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Proceedings from the 31st DRG Seminar on Robotics in the Battlefield

Defence Research Group

Actes du 31ième Séminaire sur la robotique du champ de Bataille

Groupe sur la Recherche pour la Défense

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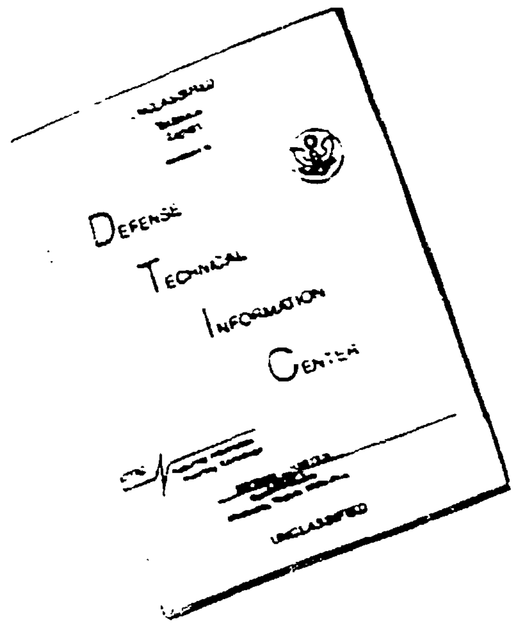

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Proceedings from the DRG Seminar on
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1. These are the proceedings from the DRG Seminar on Robotics in the Battlefield, held on 6-8 March 1991 in Paris, France.

2. This report is published in three volumes:

- Volume A (U/U) contains:
  - The Executive Summary
  - The Opening Addresses by Dr. A. Grant, M. M. Bresson and Colonel Marescaux
  - The Concluding Remarks by the Sessions Chairmen
- Volume B consists of the NATO UNCLASSIFIED presentations
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The Evolutionary Role of Humans in the Human-Robot System

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14. Abstract.

Future human-robot systems are expected to show increasing capabilities, flexibility and levels of machine autonomy. An objective of the future development of human-robot systems is incorporation of technologies such as artificial intelligence, world modeling, machine pattern recognition and automated task planning to permit increased robot autonomy and reduced human operator demands. Stages of human-robot capability were identified and criticalities of certain generic human operator functions were estimated for the capability stages. The resulting profile defines the changing role of the human operator throughout development of the capability stages. This information has implications for human factors research and development in the human-robot systems area.

THE EVOLUTIONARY ROLE OF HUMANS IN THE HUMAN-ROBOT SYSTEM

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1.0 HUMAN-ROBOT SYSTEMS

While the end of the twentieth century will be remembered as the time of the early development of modern robots, the twenty-first century may very well become known as the century of the robot. Robot technology is developing at a rapid pace. So much so that many people believe that, in the future, robots will not be considered our industrial slaves, but our virtual work partners. It will, however, take more than advanced technology to turn today's robot into a true work partner. To bring about this transition, human factors will have to make a major contribution toward defining the human's changing role in relation to changing robot technology.

The technological evolution of robots has, and will continue to have, important implications for the division of labor between humans and robots (1, 2). Today's modern robots are primarily used in well defined and repetitive tasks in the context of manufacturing. This use of robots still coincides with the origin of the word "robot." It is derived from the Czechoslovakian word "robota" which means compulsory labor and drudgery (3).

Tomorrow's robots will be used for far more than physical labor. Robots will become much more capable of emulating human sensing and cognitive processes. As this occurs, there will be a shift from viewing robots as independent machines to cognitive components, along with humans, of a Human-Robot System (HRS). The robotic metamorphosis will concurrently cause the role of the operator in the HRS to undergo a major transformation. This change will not only redefine the operators work role in relation to robots, but may well redefine our point of view toward advanced technology and science.

The purpose of this paper is to identify some general HRS functions and to estimate the criticality of those functions, in terms of system effectiveness, for first line operations personnel in the system.

2.0 STAGES OF HRS CAPABILITY

The development of HRS functional capabilities can be categorized into several stages as follows:

- Bounded autonomy
- Teleoperation
- Supervised autonomy
- Adaptive autonomy
- Virtual symbiosis

Some characteristics of these stages are summarized in Table 1. The stages are not mutually exclusive and often overlap with characteristics of one stage blurring into the next. With that in mind, the next few paragraphs briefly describe each stage.

Table 1. Capability Stages in the Development of Human-Robot Systems

Stage	Characteristics	Example	Information Processing
Bounded Autonomy	• Limited task domain • Specialized tasks • Inflexible response • No task uncertainty	• Industrial robots Production tasks Welding Painting	• Fixed prior to task execution via: Teach pendant Detailed manual inputs Fixed repertoire of movements/actions • Manipulator joint position/rate commands
Teleoperation	• Generalized platform/tools • Mobility • Flexibility • Operator in loop full time	• Shuttle Orbiter Remote Manipulator System	• Extension of human capabilities • Unprocessed sensor feedback to operator • Continuous loop closure by operator • Manipulator joint position/rate commands • Translation to object/work space coordinate frame, movement constraints
Supervised Autonomy	• World modeling • Variable degree of world structure • Variable span of autonomous control • Task orientation	• Hubble Space Telescope • JPL CARD - lunar/ planetary rover • Space Station payload servicing	• Generalized tasks and parameters defined by operator • Processed sensor feedback & local loops • Operator intervention at interval Dt • Task/argument command language • World model controlled by operator
Adaptive Autonomy	• Complex tasks and task sequences • Machine pattern recognition • Advanced world modeling • Task sequence/ mission orientation	• Pilot's Associate	• Decision making shared by operator & machine • Operator intervention by exception • Multi-sensor fusion • Machine world model updating & management • Machine extrapolation of world knowledge • Task sequence/argument dialog language
Virtual Symbiosis	• Machine functions as "co-worker" • Goal orientation • Autonomous task implementation and goal-directed learning • Periodic validation by operator	?	

Human manual labor serves as a baseline for comparison. The typical division of labor among workers in this baseline falls into such duties as direct labor, foreman, supervisor, and manager. These divisions somewhat parallel the evolution of the human role in HRSs.

2.1 Bounded Autonomy

Robotic devices in the bounded autonomy stage function with little human intervention having been pre-programmed to produce very specific movement/action sequences. Such devices are frequently used in repetitive and well defined tasks such as those on production lines. Such robots possess zero adaptability and required reprogramming if the task is changed. Once programmed by means of teach pendants or off-line programming, they execute component actions with high reliability.

2.2 Teleoperation

In the teleoperation stage, which includes subsystems such as mobility platforms, manipulators, sensors, and end-effectors, the human is an integral and full time component in the control loop. The control loop is closed only by the human operator who defines the task to be performed and operates the controls to perform that task. The operator uses feedback (usually visual, but sometimes including force or audio feedback) from the remote site but the significant point is that the operator is responsible for all of the active processing of information aside from some low-level operations such as coordinate transformations. The robot responds to the commands of the human and not directly to variables in the environment. Typically, in this stage, the remote robotic device is often used to avoid danger to the human operator or to operate at distant worksites.

2.3 Supervised Autonomy

The supervisory stage refers to the HRS level in which the robot can handle certain tasks or subtasks autonomously allowing the human to perform other tasks or control other robots. Typically, in this stage, the human is responsible for planning what to do and how to do it, teaching the computer, monitoring robot activities, intervening in robot tasks when necessary, and learning how to perform the totality of tasks better in the future (4,5). It is in this stage that true human and robot interactivity begins. This new level of interactivity warrants special attention to the safety of humans (6). In the supervised autonomy stage, the human operator defines a specific task (such as road following) with parameters (such as speed) which the remote system performs to completion with occasional operator intervention after the initial task assignment. The robotic system will typically incorporate some types of onboard intelligence (e.g., a world model) as well as primitive sensing and processing capabilities (e.g., obstacle detection sensors and avoidance algorithms). The system would still require human intervention in the cases where its capabilities are inadequate for an unexpected event or circumstance.

2.4 Adaptive Autonomy

In the adaptive autonomy stage the robot can perform many tasks independently of the human operator. The human will be needed less in the operational control loop but will be retained in the system loop (7). It is in this stage that the human functions as an information manager; one who organizes the structure of expert systems and data bases including world models, and decides what knowledge will be imparted to the data base.

Adaptive autonomy is characterized by the robot's ability to learn from experience. That is, the robot incorporates environmental and procedural knowledge learned in one task that may be used in the performance of future tasks. This presupposes machine capabilities in world model updating/maintenance and automatic programming. Human intervention will be by exception where incorrect machine proposals must be over ridden. Safety monitoring will become a critical task for humans in this stage because the human must be sure that what is learned is not detrimental to higher level goals.

2.5 Virtual Symbiosis

In the final stage there is virtual symbiosis between the human and the robot. The human and the robot will be able to exchange data, information, and recommendations at a fairly high cognitive level using languages which can express machine proposed actions and operator consent or rejection. The shared knowledge will extend to matters of planning, maintenance, and programming but the ultimate responsibility for these functions reside with the human operator.

3.0 HUMAN OPERATOR ROLES

An attempt was made to define changes in the human role in HRSs under the various capability stages by estimating the criticality for acceptable system performance of certain generic classes of operator functions for each of the stages.

3.1 Generic Operator Functions in a HRS

Seven generalized functions of human operators in an HRS were defined as follows:

- Labor intensive work
- Task planning
- Mission planning
- Monitoring and intervention
- Information management
- Interactivity

These functions are seen as being performed by the human operator who most directly interacts with the robot during mission operations. They do not address activities performed by supervisory personnel,nor do they address HRS subsystem activities such as monitoring, fault detection, maintenance and repair.

3.1.1 Labor intensive work. This factor refers to labor requirements which involve physical exertion.

3.1.2 Task planning. Planning at the task level entails development of plans which will accomplish task goals. The term task refers to short-term low level activities such as moving an object to a specified position.

3.1.3 Mission planning. Planning at the mission level entails development of plans which will accomplish mission goals. Such plans address longer term, high level objectives. Mission planning may also involve decomposition of the mission problem into parts which provide subgoals at which task planning is directed.

3.1.4 Monitoring and intervention. This function involves real-time, periodic or time sampled evaluation of processes, and current states of objects or variables in the environment to verify that plans have been completed and goals met or that plans are being executed satisfactorily. If the process is not acceptable, then some form of operator intervention will be required.

3.1.5 Information management. Information management includes processing of information to support decision making, and selection of information elements for attention, reliability evaluation, storage and dissemination.

3.1.6 Interactivity. This function refers to mutually dependent actions and reactions on the parts of both the human operator and the machine. It is not the same as workload or rate of control actuation which may be extremely high in a teleoperated HRS. Rather, interactivity involves rapid changes in allocation of functions between human and machine. Essentially, interactivity refers to rapid and frequent changes in "whose court the ball is in" with respect to each of the currently ongoing functions.

3.2 Estimation of Function Criticality

The authors attempted to estimate the criticality of each of the above generic human functions for a hypothetical HRS at each of the capability stages discussed previously. Criticality, as used here, refers to the importance of correct and timely performance of a particular function for the HRS as well as to the necessity for the appropriate supporting technology. The ratings developed do not refer to the load or time spent on the function. Criticality estimates utilized a scale from zero to ten with zero meaning that the function has no importance and ten meaning that the hypothetical system will not be feasible if the function cannot be performed. Function loadings in terms of percent of effort devoted to the function would be too system and/or mission specific to be treated in a general fashion.

3.3 Results of Evaluation

The results of the criticality estimation process are shown in Figure 1. For comparison purposes, the manual work mode without robotic involvement is included as a baseline. The Figure 1 data represent a consensus on the part of the authors with regard to the criticality of the various generic operator functions throughout the capability stages. The criticality estimates are believed to provide an approximate profile of the changing role of the human operator in HRSs as development proceeds through the several stages. The remainder of this section will evaluate the human role profile in the HRS criticality graphic. The following section will discuss some broad implications of the changing human roles in the HRS for human factors.

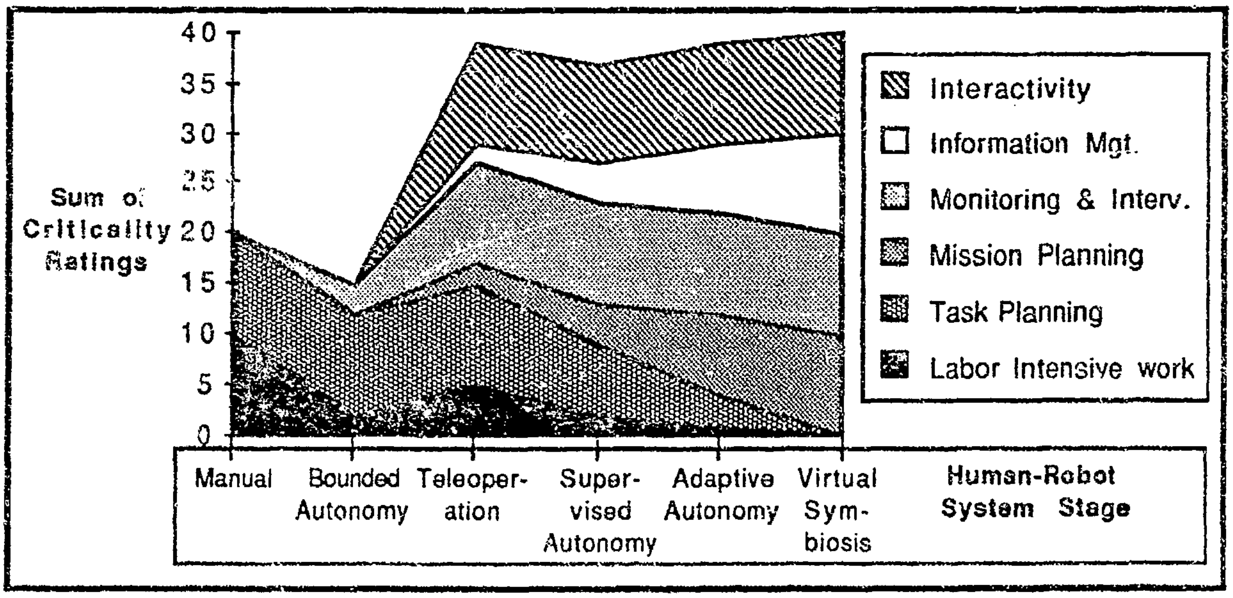

Figure 1. Criticality Ratings by HRS Stages and Generic Operator Functions

3.3.1 Interactivity. With increasing complexity there is a shift from user-display interface, which monitors unprocessed data, to a user-system interface which presents the operator with summarized data, probabilistic estimates, and extrapolations of system operational events. Human factors will play a major role in structuring and presenting the information to the operator.

3.3.2 Information management. With increasing system complexity, the operator plays an increasingly important role in managing information that is collected by the HRS. Human factors must help to design information management aides that will help the operator to make information decisions (e.g., what information to keep or purge, what level of access the robot should have to the new information, what should be shared with other HRSs, and what might be the impact of system peformance and safety of information).

3.3.3 Monitoring and intervention. With increased system complexity the criticality of human situational awareness during the monitoring process increases. This implies a definite need for a cognitive system structure representation. With increasing complexity the ability of the operator to understand what the system is doing, and why, will be limited. Human factors will have to explore methods of continually representing system functions to the operator in order to increase the likelihood that the operator will be able to play a role not only in dealing with system problems as they occur, but perhaps more importantly, in anticipating system problems.

An especially difficult problem, which already occurs in nuclear reactor control rooms and advanced technology aircraft, involves the idea of an "interval of uncertainty." An "interval of uncertainty" can be defined as a period of system operations which is characterized by rapidly decaying system integrity, accompanied by little or no information as to the cause(s). With increasing system complexity the probability of encountering an "interval of uncertainty" increases. Human factors will be instrumental in devising methods and procedures for acquiring and processing information during this time.

3.3.4 Mission planning. With increasing advanced robot technology, the robot will perform much of the task planning and execution. As a necessary step in integrating the human and robot elements of the system, the human will become more involved in concatenating tasks to the level of mission requirements. Human factors will deal with the cognitive aspect of aiding the operator to produce feasible and effective mission plans.

3.4 Implications of Results

3.4.1 Languages. Planning/operations languages will be required to support the mission and task planning functions. To a large extent, robotic programming languages support off-line programming of assembly operations and are not particularly suited for real-time, on-line control of robots. The Space Station User Interface Language (SSUIL) is currently under development to support Space Station science users in planning the operation of experiment payloads. It is object and action oriented and contains provision for a direct manipulation user interface. These language features will go far toward providing the task and mission planning capabilities required for the supervised autonomy and higher stages. It is considered that an essential development feature of the necessary robot control language will be cognitive analysis of user tasks and knowledge structures.

3.4.2 Operator-computer interface. The above discussion of robotic system planning/operations languages does not mean that a strictly command language dialog is essential or even contemplated. The user interface, whereby commands in the language are composed, might support writing commands directly but other dialog types including direct manipulation may well be more effective for on-line operator control.

3.4.3 Interaction with a world model. Task and mission planning automation in the supervised autonomy and higher stages will require a world model. Where the working environment is man-made, it is readily defined for world modeling purposes as in the case of payload servicing robots planned for the Space Station (8). Where natural objects and terrain are concerned, advances in machine pattern recognition will eventually support machine updating of a world model. In the near term, however, a human operator will have to input corrections to a world model. Three dimensional imagery and fast coordinate transformations to support multiple views are likely to be essential to the necessary interfaces.

3.4.4 Monitoring and intervention. As automated HRS capabilities increase, the frequency of operator intervention will be decreased. If this frequency becomes low enough, long periods of uneventful monitoring could result, with associated vigilance decrements etc. This could become a human factors concern. Provision will be required for "graceful stage regression" in certain cases of operator intervention. If the automated elements of the system are incapable of producing a certain evolution, the operator may have to select a lower stage (such as teleoperation). This point has been well made by Albus, McCain and Lumia (8).

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14. Abstract: Teleoperation of remote robotic systems, including battlefield systems is, cognitively speaking, a complex task. Operators of such systems are required to be 'virtually present' with respect to their perception at the sites where the teleoperated systems operate. Because of its richness in conveyed information, vision is the most important sense for such operations, providing feedback which is critical to the operator's effectiveness. A video display is the principal feedback link with the remote system. The paper discusses the operational benefits and issues of stereoscopic video in telerobotics. A new display system is then introduced. It incorporates stereoscopic views of the real world, in conjunction with various other virtual stereoscopic constructs, including graphic and text overlays. The current and future functional capabilities of the display system are then reviewed and the project status is summarized.

REAL AND VIRTUAL WORLD STEREOSCOPIC DISPLAYS FOR TELEOPERATION[1]

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1. INTRODUCTION

1. It is reasonable to project that future military operations will take place in increasingly hostile environments. The military's effectiveness in controlling people and equipment will depend on its ability to operate in such environments. Advances in mobility, firepower and communication will permit greater dispersion of soldiers and thereby reduce somewhat the effects of hazards. Even greater protection for military personnel will be provided by efficient deployment of teleoperated and telemanaged robots, however.

2. For the foreseeable future, these remotely controlled systems will make use of human facilities to achieve effectiveness in control functions, especially in such predominantly "unstructured" environments as the battlefield, where completely autonomous robotics is still far from being realisable. It is therefore essential to develop optimal capabilities for these remotely operated systems, to suit the different levels of structuring of their operational environments.

3. The effectiveness of such systems will be determined by the quality of the interactions between the operator and the remote robot. The quality of the robot-to-operator component of the interaction will be particularly important. The robot's sensing capabilities and the means of delivering the information to the operator will determine the quality of his perceptions on the status of the robot and its environment, and thereby affect the operator's decisions and resulting actions. A well developed coupling between multiple remote sensors on the robot and the operator will provide a capability approaching "telepresence". As for the operator-to-robot component, the required telepresence capabilities must be such that the operator-robot combination will be able to effectively carry out mobility and manipulation tasks, as well as use its weapons.

4. One necessary condition for effective teleoperation of weapons is that dimensional information about the target, and its distance, elevation, and bearing from the robot to the target, be accurately estimated. A similar criterion applies with respect to obstacle avoidance in

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mobility operations, and robotic or teleoperated manipulation operations. This requirement becomes particularly pronounced when the speed or rate of task execution is a critical factor. Consequently, to permit successful and effective teleoperations, it is important to provide the operator with accurate spatial information about the remote site.

5. The principal feedback link with the telerobot is the video display. Conventional video sensors alone, however, do not provide the required spatial information directly. In this paper we discuss an ongoing project to develop a hybrid display system which combines a stereoscopic video system with a stereoscopic graphics system, thereby providing operators with greatly enhanced information, both relative and absolute, about the remote worksite. The paper first presents a brief review of the benefits of stereoscopic video in telerobotics. We then point out some of the operational issues associated with manual teleoperation which remain, even after stereo video is introduced. The configuration of the new display system developed to address these operational problems is reviewed, along with some current and future fundamental capabilities. Finally, the project status is summarised.

2. OPERATIONAL BENEFITS OF STEREOSCOPIC VIDEO

6. It is now widely accepted that, for a large number of tasks, provision of a basic stereoscopic video (SV) capability can enhance teleoperator performance significantly (Merritt, 1988). An overview of visual performance research with SV systems can be found in Spain (1984). Some of the benefits of SV systems which pertain specifically to land-based military operations are summarised below.

2.1 Relative Judgement of Object Location

7. In general, the great majority of electronic display media are *monoscopic*; that is, the images which are perceived are equivalent to those which would be viewed in nature with one eye only. Such display systems do contain numerous depth cues, including: relative size of objects viewed, geometric perspective, occlusion, lighting, shading, relative motion, visual flow patterns, etc. It is nevertheless well known that, in supplying extra *stereoscopic* cues (which current research is indicating is *additive* with respect to the other (monoscopic) cues (Sollenberger et al, 1991; Dosher et al, 1986)), the ability to estimate *where* objects are in the visual field, *relative to each other,* is greatly improved. Operations which require that this be done accurately include most manipulative activities, reconnaissance, aiming of weaponry, etc. In general, accurate perception of obstacle locations and dimensions permits efficient execution of critical manœuvres and use of clearances to effect passage of a robot or its manipulator arm in a safe, collision-free manner.

2.2 Enhanced Image Interpretation

8. In addition to providing a significant improvement in seeing *where* things are, stereoscopic viewing can also enhance the ability to perceive *what* things are, especially in unfamiliar or complex visual environments. This is especially important for reconnaissance, camouflage detection, logistics planning, ordnance management, etc. For example, a camouflaged vehicle stationed in front of a forest may be completely inconspicuous using a monoscopic display, yet may stand out dramatically on a stereoscopic display.

2.3 Enhanced Task Performance

9. Some of the remote handling tasks for which stereoscopic viewing is particularly helpful are those which involve ballistic movement, recognition of unfamiliar scenes, analysis of three dimensionally complex scenes, and the accurate placement of manipulators or tools within such scenes (Dumbreck et al, 1987). Results of other studies suggest that stereoscopic viewing is critical when tasks are unpredictable or constantly changing, when visibility conditions are poor, or when precise positioning in depth is critical for success.

2.4 Enhanced Slope and "Negative Obstacle" Perception

10. Experiments in off-road driving have shown that it is very difficult to perceive terrain slopes and to detect "negative obstacles", that is, sudden dips or drop-offs, with monocular viewing. Stereoscopic viewing can enhance perception considerably under such situations. This is especially important in battlefield telerobotics, where it is quite common for teleoperated vehicles to roll into hidden gullies and topple over on inclined slopes.

2.5 Enhanced Training Regimes

11. The eye-body relationship has a strong bearing on human spatial perception, as a consequence of life-long experience and learning. In remote viewing, therefore, the operator's own frame of reference tends to dominate over the camera-robot frame of reference. For those systems in which the camera is mounted on the robot platform to retain a constant point of view with respect to the end effector, perception is also affected by frequent movement of the camera system during operations of the robot arm. The consequences of such factors do not manifest themselves in slow, simple operations relative to a distant horizon. However, they do become particularly evident in busy environments involving rapid critical operations. Any inadequacies in the operator's perception of spatial information can therefore severely limit the efficiency of some teleoperated activities. At the same time, a trial-and-error approach to compensate for these inadequacies will not be acceptable under operational settings.

12. Most research with stereoscopic displays has concentrated on showing either improved depth resolution or improved task performance relative to monoscopic viewing. In some situations, operators with two orthogonal single camera views can be as effective as those with one stereoscopic view, with sufficient training. For highly repetitive tasks, furthermore, it is possible for skilled operators to perform well-rehearsed teleoperation tasks as effectively using a single monoscopic view. Most teleoperation tasks are rarely repetitive, however, and especially not battlefield teleoperations.

13. As with other operational systems, one of the most important aspects of managing a telerobot system is the investment needed to train operators to use it. Operators of current explosive ordnance disposal robots are subjected to extensive and costly practical training toward proficiency in teleoperation. Periodic refresh training is also common, to maintain their operational readiness. Preliminary research has shown that transfer effects arising from early exposure to manual teleoperation using stereoscopic video are positive (Drascic et al, 1989), implying that the use of stereoscopic viewing may significantly reduce operational training requirements.

3. OPERATIONAL ISSUES ASSOCIATED WITH STEREOSCOPIC VIDEO

14. In the preceding section, several of the advantages of stereoscopic viewing systems have been reviewed. It is our contention, however, that further operational enhancements can be achieved by extending the SV capability to encompass stereoscopic computer graphics and machine vision technologies. The issues addressed include the following:

3.1 Estimation of Absolute Distances / Locations

15. In general, when using monoscopic video systems it is very difficult and it requires a great deal of training and practice to estimate object sizes and distances accurately. In unfamiliar or obscured environments, this can be almost impossible. Users of stereoscopic video systems, on the other hand, benefit from a greatly enhanced ability to discriminate *relative* distances, depths and object sizes; that is, the relative locations of objects in space are immediately obvious to most observers. Unless observers are very well trained, and very familiar with the objects in the remote location, however, they are still somewhat limited in their ability to make ***absolute*** judgements of distance and depth. In other words, whereas it might be easy for an observer to determine that object A is farther away from the cameras than object B, for example, it is generally more difficult to estimate *how far away* the two objects are from the cameras, or from each other. The ability to make such estimates can be of importance for tasks involving remote surveillance, assembly, telerobotic path planning, obstacle avoidance, weapon deployment, etc.

3.2 Specification and Adjustment of Stereoscopic Camera Parameters

16. The essence of a stereoscopic display system is that images from equivalent left and right eye views are displaced with respect to each other when presented on a monitor. The viewer-monitor geometry determines to what extent the resulting binocular disparity is interpreted as depth. If lines were drawn along the optical axes of the viewer's eyes to corresponding points of left and right images on the monitor, and then extended until they intersect, this would determine the effective convergence point of the observer's eyes.

17. Relating this to natural vision, human eyes can typically converge to a point as close as 15 cm and as far away as infinity. That is, with natural vision one sees what is actually present at distances as close as 15 cm from one's face. When using stereoscopic video, however, what the observer sees at that apparent distance, called the "near point", is a function of the separation, convergence angle and focal length of the cameras, as well as the size of the monitor and the observer's position relative to it. These same parameters also determine what appears at "infinity" for the observer, known as the "far point". If the near point and the far point are close together, observers are limited in what they can comfortably see; however, what they *can* see, they see with much higher depth resolution than would typically be possible with natural vision (despite the degradation of image quality due to the video medium). This is similar to the function of binoculars, which move the near point further away, leaving the far point at infinity, and so effectively increase the depth resolution within that range.

18. In terms of stereoscopic video systems, for object distances which appear very close relative to the screen depth, the viewer's eyes are forced to converge excessively, resulting in possible eyestrain. Conversely, for very far distances relative to the screen depth, the eyes might even be forced to diverge. In addition, problems may develop because the observer's

eyes tend to focus at the depth of the monitor screen, while converging at a virtual depth point which generally is on a different depth plane. This may also result in possible eyestrain, fatigue and, in many cases, inability to fuse the stereo image. Consequently, a pair of stereoscopic cameras with a fixed separation and convergence angle can in practice severely limit the operator's ability to perform effectively over a broad range of viewing conditions and scenarios.

3.3 Manipulator Orientation and Alignment Problems

19. With most military robotic platforms, the camera assembly is typically placed somewhere on the arm of the robot. This placement of the camera package prevents feedback of information on the specific orientation of the manipulator with respect to the platform, however. This limitation can be a serious handicap for the operator, who needs to be able to visualise how the various system and environmental components are aligned with respect to each other. In some instances it is possible for the cameras to be situated on either a different manipulator link, or on a platform which is not attached to the arm at all. Nevertheless, even in these cases problems can arise, as the operator must be able to transform what he sees from his own camera frame of reference to the task frame of reference. For some tasks, such as pick and place, insertion tasks, etc., critical errors may result from this need to work with these different frames of reference.

3.4 Operator Workload

20. Accurate teleoperation involves significant attentional demands. The perceptual limitations of the remote viewing system can intensify the severity of these demands. In addition, the memory load on the operator can be quite high, in cases for which retention of control actions performed during the mission can be essential to identify the state, location, and direction of the remote system at any stage in the operation. This may be critical to the success of the mission, particularly when the operator has little or no direct visual contact with the remote system. The stress imposed by this requirement is further exacerbated when operating in physically complicated environments, under high time pressure, or even when the periods of required vigilance are unduly long, e.g. when controlling very slow systems. Such enforced attention requirements not only limit the number of concurrent activities which the operator is able to handle, but can also lead to increased likelihood of error, and may ultimately endanger the mission.

4. CONFIGURATION OF SV+SG DISPLAY SYSTEM

21. A generic block diagram of the system under development is given in Fig. 1. It consists of four basic elements, as follows:
- Stereoscopic Video Camera System,
- Stereoscopic Viewing System,
- Pointer Positioning Device,
- Control Computer.

22. The first and second elements comprise the basic functional components of the stereoscopic video system, based on *alternating-field*, or *time-multiplexed*, stereoscopy. The fundamental principles of this system have been described elsewhere (Milgram et al, 1989,

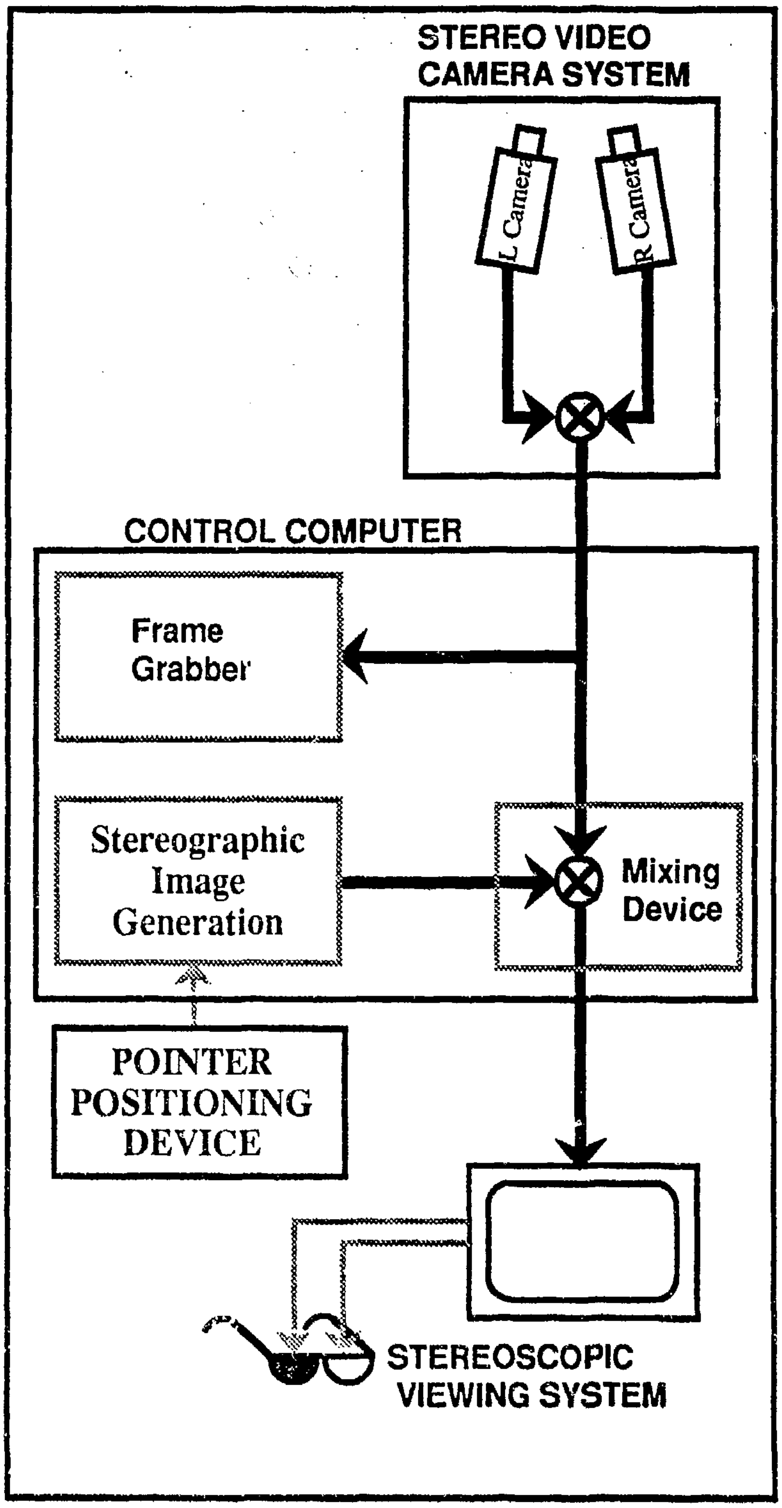


Fig. 1 Block Diagram of Stereoscopic Video + Stereoscopic Graphic Display System

1990; Milgram & van der Horst, 1986). Briefly, this class of stereo-pair displays involves rapidly alternating left- and right-eye viewpoint images on a video or computer monitor. When the stereoscopic images are generated as live video pictures, the signals from each of the left and right cameras are electronically combined, such that one is transmitted as the *odd* field and the other as the *even* field of a single interlaced video signal. When this signal is viewed directly on the monitor, it is perceived as a flickering double image. When viewed through special purpose synchronised liquid crystal spectacles, however, a single stereoscopic image is perceived. This is because the spectacles act as a shuttering device, which alternately blocks and unblocks the view of the display from each eye, in synchrony with the alternating display images. The result is that the left eye is blocked whenever the right eye image is displayed and unblocked whenever the left eye image is presented, and vice versa.

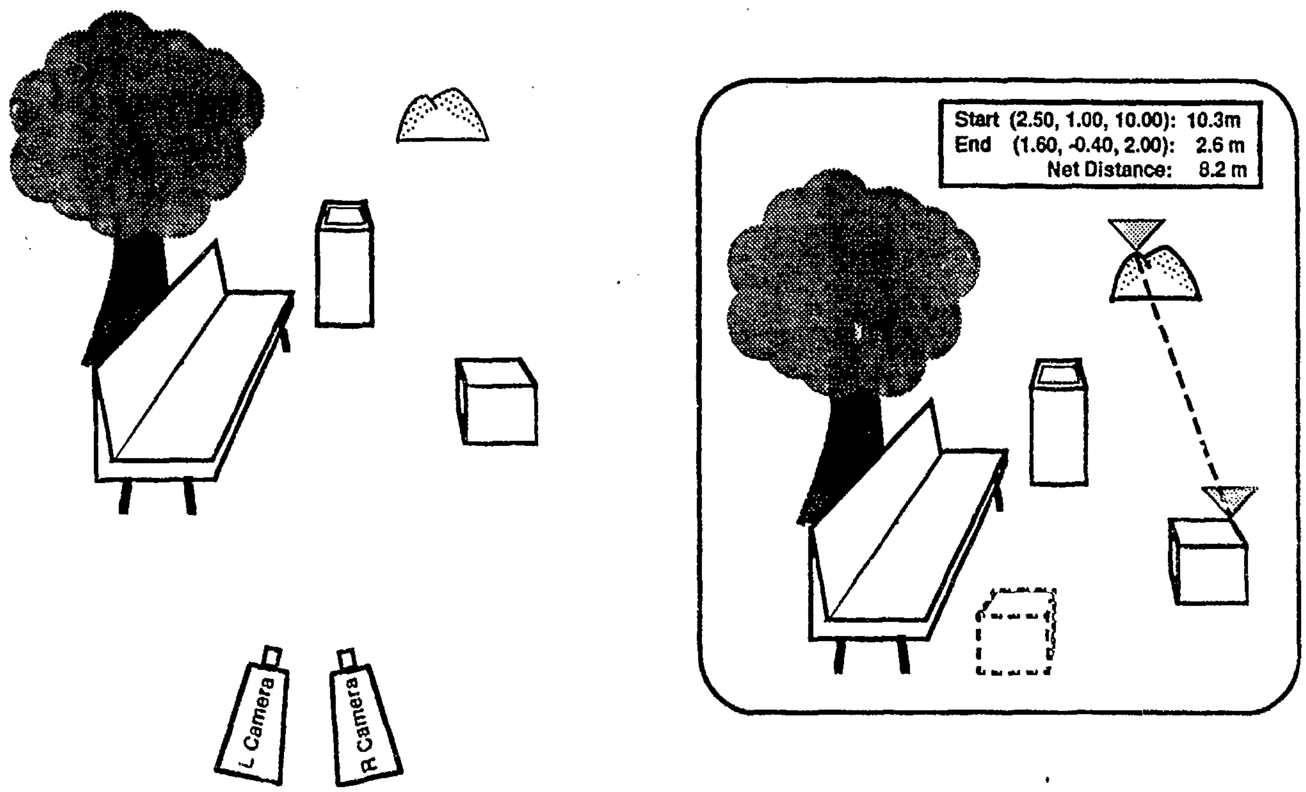
23. Stereoscopic images can be created by a computer using a similar technique. The stereographic image generation system, shown in Fig. 1 as a sub-function of the Control Computer, is responsible for generating pairs of alternating images which are analogous to corresponding left and right camera images.

24. The unique aspect of our system, as described thus far, is its ability to *combine* stereoscopic video (SV) and stereoscopic graphic (SG) images and view them on a single monitor. This is accomplished with the Mixing Device, shown in Fig. 1, which combines the synchronised video signals from both the computer and the cameras. The net result is a three dimensional image within which *virtual* SG objects generated by the computer appear within the *live* SV video world.

25. An illustration of the capabilities outlined thus far is given in Fig. 2, in which a park scene, on the left hand side, is depicted as being viewed via the (dual camera) SV system. The reader is requested to imagine that this scene, observed with the help of the shuttering spectacles, is perceived stereoscopically on the monitor, shown on the right hand side. The tree, the bench, the dustbin, the rock and the box all represent "live" objects, which are provided by the video cameras. The virtual objects in the picture, that is, the "V" shaped triangles and the line joining them, as well as the second box drawn with dashed lines, are generated by the SG computer and appear to the observer to be actually present among the real objects in the video world.

26. Because they are computer generated, it is clearly possible to cause the virtual SG objects to move around freely within the SV world, by making use of the Pointer Positioning Device (a three degree of freedom trackball in our case), indicated schematically in Fig. 1. This is accomplished by scaling the size and position in depth of a superimposed SG object so that it appears realistically within the SV scene. This means that, if a particular object is drawn graphically and then moved to the same location in (x,y,z) space as a corresponding real world object with identical dimensions, the two should coincide exactly on the screen. To accomplish this all virtual images are calibrated so that any (x,y,z) input from the pointer positioning device is interpreted directly in terms of real world units. The physical parameters which enter into those calculations include the following:

- camera separation,
- camera convergence angle,
- alignment of camera optics,
- positions of the centroids of the lenses,
- mapping between the video sensors and the computer display.



Real-world Scene Stereoscopic Display Monitor Image

Fig. 2 Example of "Virtual Pointer" + Overlaid Wireframe Image

27. If all of the parameters listed above have been computed or measured correctly, system validity can be verified by superimposing and visually comparing SG object images with corresponding real objects. For our purposes, it is sufficient that these be aligned only to an extent that is within the resolution capabilities of the visual display system. In order to enhance the overall reliability of the system, however, we are currently extending it by adding frame grabbing hardware, as shown in Fig. 1, which will serve as a basic component of our ultimate "virtual control" capability. This and other functional capabilities are discussed in the following section.

5. FUNCTIONAL CAPABILITIES -- CURRENT AND FUTURE

28. In this section we refer to the operational issues outlined in section 3 and discuss how the current functional capabilities of our SV+SG display system address those problems. In addition, we present our planned enhancements of the system, and discuss their relevance to practical telerobotic operations.

5.1 Stereographic Pointer / Tape Measure Capability

29. In Section 3.1 operational aspects of the problem of being able to make absolute distance or location measurements are outlined. That problem has been the principal motivation for our development of the virtual pointer capability. Because humans are very sensitive at making *relative discriminations*, but are *not* very good at making *absolute judgements* (van Cott & Warrick, 1972), it is logical to try and convert all such estimation tasks to relative discrimination tasks, wherever possible. This is the same general principle that is employed in supplying *anchoring* stimuli in practical display design, to assist people in absolute judgement tasks (Wickens, 1984).

30. The stereographic pointer is generated by the graphics computer and can be moved throughout the three dimensional space by the multi-degree of freedom Pointer Positioning Device. The pointer must be readily visible on the screen and must have an obvious characteristic single-point vertex for alignment purposes. Pointer formats with which we have experimented thus far have included cross-hairs, an open or filled letter V (as shown in Figure 2) and upward or downward facing arrows. It has become clear that the "best" pointer format should be determined by the particular operational circumstances, including such factors as predominant orientation and density of objects at the remote site, ambient illumination, etc. The great advantage of employing a computer generated tool such as this, of course, is that pointer shape and orientation, as well as brightness and colour, can be selected by the operator during usage, to suit the situation.

31. The three dimensional pointer location on the screen is calibrated in absolute real-world units, as a function of the basic physical characteristics of the stereoscopic video system, which are listed in Section 4. Using the Pointer Positioning Device, the pointer can be aligned with any feature of the real-world scene. The corresponding real-world position coordinates {x,y,z} can then be computed and, using the SG option, can even be displayed alphanumerically at the same depth plane of the pointer in 3-D space.

32. If two such points are identified at the remote site, the distance between them is readily calculated. This is the basis of the *"tape-measure"* capability, which is graphically depicted in Figure 2. To implement it, the viewer/operator triggers the pointer at one location and "drags" a virtual line along a three dimensional trajectory to a second point in the scene. The computer then calculates and displays or announces the absolute distance between the two registered points, as illustrated.

5.2 Hybrid Pointer Alignment System

33. As emphasised above, the capability of making absolute 3-D measurements of target locations is potentially very useful in practical telerobotics. It is important to recognise, however, that, using the SG pointer alone, the final measurement is subject to two possible sources of error. One derives from the procedure for calibrating the SG software relative to the camera system, while the other is the result of the operator's limitations in matching the perceived location of the virtual pointer with the real-world location of target objects.

34. In response to the second problem, the SG pointer concept is being incorporated into an enhanced *hybrid* pointer alignment system, involving a higher level of automation. The advanced SG pointer system, which is being implemented on a more sophisticated graphics workstation, makes use of frame grabbing hardware that allows digital recording of the real-world scene. This will facilitate computational analyses, including machine vision detection of edges or corners, to be used for objective determination of location, dimensions and orientation of objects in the environment.

35. This system will enable the operator to use the SG pointer to perform initial designation of points or objects of interest and then allow the computer to carry out automated processing to generate an objective image of the remote scene in the vicinity of the SG pointer. The display system will then communicate to the operator, *also by means of overlaid graphics*, its version of which points or objects it believes the operator has selected. If this does not coincide with the operator's intention, the procedure is repeated until the two system components, the human and the computer, come to an agreement.

36. The philosophy behind this hybrid system is to utilise optimally the strengths of both the human and the computer. With the original SG pointer system outlined in Section 5.1, even though the computer knows *where* in the real world, relative to the video cameras, it has drawn the *pointer*, the computer possesses no knowledge at all about *what* is in the real world being viewed by the video cameras. The human must therefore perform the high level function of recognising and designating operationally strategic targets, as well as the low level function of precisely aligning the SG pointer with those objects. With the enhanced system, the human will be spared a portion of the low level aligning task. Even though the computer will still have no knowledge of *what is in the real world* (which is an important contradistinction with most Artificial Intelligence applications), it will have access to detailed quantitative information about *where things are in that world*. This will permit the computer to perform the low level computations necessary for specifying points in space, while the human operator is able to concentrate more on strategic planning and decision making.

37. It is important to point out that this process will reduce, but not completely eliminate, the operator's labour-intensive task of manually aligning the virtual SG pointer with real-world points in the 3-D video space. What it will provide, however, will be a *faster* and *more reliable*

system, which will result in *more efficient* teleoperation, with a significantly *reduced operator workload*, which in turn will permit the operator to turn her attention to other concurrent control activities.

5.3 "Virtual Control"

38. The logical extension of the hybrid system outlined above is one which permits "virtual control" of the telerobot. What this involves is a system which enables the human operator to rise above the low level function of continuous manual control of the teleoperator, and allows her instead to designate intermediate robot states, or "way points", which can subsequently be achieved by the control computer. This concept is consistent with Sheridan's well known model of supervisory control of telerotic systems (Sheridan, 1984). A similar concept has been proposed by Conway et al (1990), using a somewhat different technological approach.

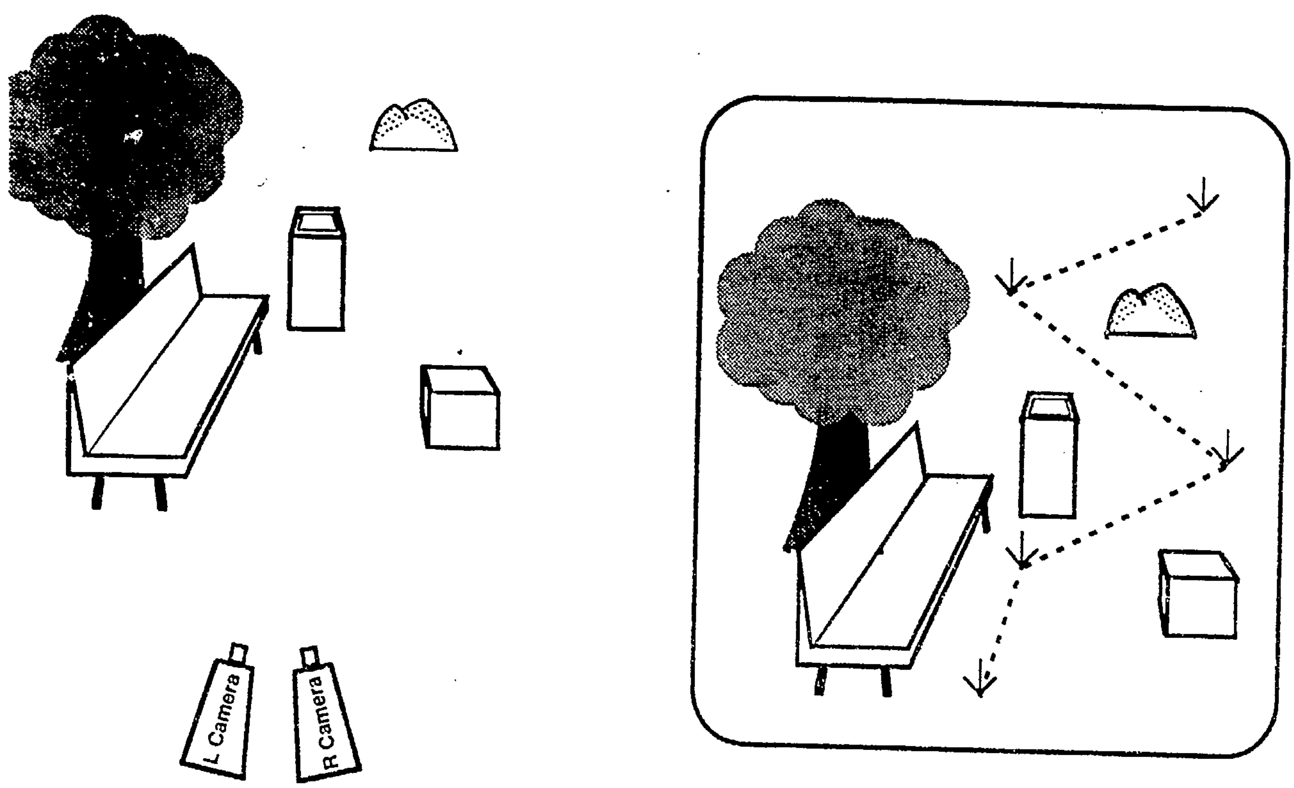
39. As a simple example of virtual control, the pointer could be used to design a collision-free pathway for a teleoperated vehicle, which would then be programmed to follow that pathway. An example of such an application is shown in Fig. 3. In the same context as Fig. 2, the operator has used the pointer here to designate to the control computer a set of way-points along a desired trajectory. In the figure the computer is also displaying stereoscopically to the operator how this 3-D trajectory will appear within the real-world site.

40. With knowledge of certain dimensional parameters of the robot, this pathway planning function, together with the local world mapping function, could become more sophisticated; that is, the computer could carry out checks on the operator-designated pathway to ensure that vehicle-obstacle clearances allow for a collision-free route. Path smoothing/optimisation is another possibility. The same principles and techniques could be applied to manipulator movement/path planning in a congested environment. Another important application domain involves systems with very long dynamic time constants and/or with significant time delays. In all cases, the operator's control workload should over the long term be reduced considerably, allowing more attention to be allocated to high level planning and decision making tasks.

5.4 Generalised Stereographic Superposition

41. The 3-D graphics techniques used to generate the SG pointer described above have been extended to allow generation of more complex *wireframe* images, which can be drawn both stereoscopically and in perspective. This general capability is illustrated by the wireframe box drawn with dashed lines at the bottom of the right hand side of Fig. 2.

42. Data for such three-dimensional wireframe images can be derived from digital analysis of real-world objects or from available computer models of those objects. The images of the targets can then be superimposed onto the real-world video scene to simulate or enhance target visibility. This capability could be particularly useful, for example, for teleoperation in the vicinity of partially visible or partially obscured objects with known characteristics, which permits generation of an accurate virtual wireframe construct. It could also be useful for teleoperation with totally invisible objects with known characteristics in a structured or partially structured environment.



Real-world Scene

Stereoscopic Display Monitor Image

Fig. 3 "Virtual Pathway" Example

43. Such wireframe images can be also used to generate virtual objects and thereby create totally virtual scenarios. This "simulation" capability is anticipated to be most useful for training purposes, including safe and effective teleoperation in a complex, partially structured environment. Wireframe constructs could be used in such cases to provide graphic displays, for example of a recommended trajectory for a teleoperated vehicle in an environment with obstacles. A one-dimensional example of this is shown in Fig. 3; however, there is no reason why more complex formats, such as heads-up "path-in-the-sky" types of displays (Stokes et al, 1990) could not be used here.

44. One potential application of this technique is for simulating and displaying predicted manipulator movements or predicted projectile trajectories. When combined with the "spread" characteristics of the projectile, for example, it could also be used to display a "cone of danger" associated with the weapon. Another anticipated application is as a means of graphically superimposing coordinate reference frames, which can be used in the context of a heads-up display for complex alignment operations in multi-degree-of-freedom telemanipulation tasks.

5.5 Dynamic Optimisation of SV Camera Configuration

45. It was shown in section 3.2 above that a pair of fixed base stereoscopic cameras can potentially limit the effectiveness of teleoperations, especially if surveillance or manipulations are to be carried out within a relatively large dynamic range, or if enhanced depth resolution is necessary for precision or detection purposes. However, adjustment of camera separation and angle of convergence to match the observer's focus of attention and operational needs is a time-consuming and inexact procedure. Although such a function is clearly a prime candidate for automation, the difficulty of making such adjustments automatically, and especially dynamically, i.e. on-line, is compounded by the necessity of communicating to the control computer *what the observer's operational needs are* and *where the observer's focus of attention is.* In response to this issue, an automated dynamic camera base optimisation system is being implemented.

46. Using the arrangement shown in Fig. 4, the cameras are mounted on supports whose orientation is controlled by two roman screws, each with both left and right hand threads, allowing symmetrical translations of the camera supports. Simultaneous rotation of the screws is accomplished through the use of motors controlled from the computer supporting the vision system. Based on a particular region of operational interest, either prescribed independently or indicated on-line via the SG pointer, the computer is able to adjust the camera alignment to optimise the depth range and resolution of the stereoscopic video system. A similar procedure can be used to control the focus and zoom of the camera lenses.

6. CONCLUSION

47. The SV+SG display system described here was implemented originally using an Amiga 2500 as the graphics computer. That platform is currently being transferred to a Silicon Graphics 4D/310 graphics workstation, which will permit near real-time animation of complex solid images, in addition to the wireframe images discussed above. In this section we outline a number of operational issues experienced thus far with the SV+SG display system described above.

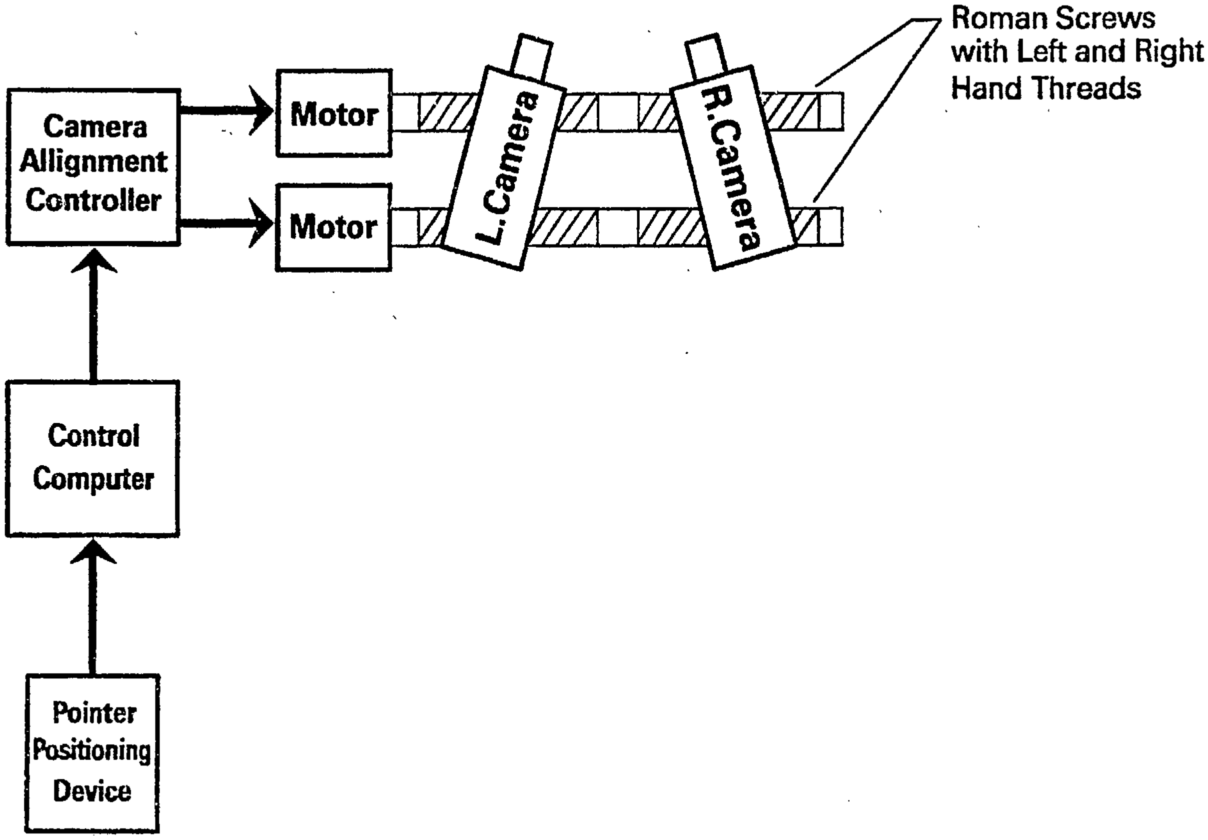


Fig.4 Schematic Diagram of Camera Drive System

48. The setting up and use of stereoscopic video for teleoperation is associated with a number of specific problems associated with the system itself. Many camera models are unsuitable for use in a stereoscopic pair due to their large physical size. This makes it difficult to obtain orthostereoscopic conditions, which generally corresponds to that which is perceived by an average human, with an interpupillary distance of about 62 mm. In addition, commercially available video cameras are typically not designed or manufactured to meet other stringent requirements of satisfactory performance in a stereoscopic pair system. For example, most cameras exhibit significant variations in the offset of the optical axis of the sensing element with respect to direction and point-of-intersection at the sensor and the optical axis of the lens system and the body of the camera. If the variations are slight, this problem is not a major one for stereoscopic video alone. However, when mixing stereoscopic video (SV) with stereoscopic computer graphics (SG), this *"nonmisalignment problem"* can have major detrimental effects.

49. A preliminary experiment has been conducted to evaluate the accuracy with which the SG pointer can be aligned with targets in the real world (Drascic & Milgram, 1991). This work has found that the pointer can be positioned with a precision close to human stereoacuity perceptual limits (approximately 20 seconds of arc disparity), and with a reliability comparable to that of aligning a real pointer remotely. (The stereographic pointer has a standard deviation of approximately 90 seconds of arc disparity, while the real pointer had a standard deviation of approximately 60 seconds of arc disparity.)

50. The stereoscopic video camera mount described above has been constructed and interfaced to the micro-computer. Software to permit the manual control of the separation and convergence angles of the cameras has been developed. The heuristics necessary for automatically adjusting the camera parameters based on the operator's control of the SG pointer have been specified and are currently being implemented. An experimental investigation of a number of operational tradeoffs among various camera configuration parameters is about to begin.

51. Software has been developed to generate arbitrary stereoscopic wireframe graphics from a database of objects. These wireframes can be animated to indicate moving items. Planned for the near future are graphics tools to aid in the creation of the object database. The objective is for the animating computer to be able to generate an appropriate wireframe image of a particular object in any location and with any orientation within the remote view. The minimum specification for this function is that it be possible for the SG object to be perfectly superimposed upon a corresponding real-world object of the same dimensions.

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14. Abstract:

The Human Engineering Laboratory (HEL), in partnership with the Combat Systems Test Activity, is developing facilities at Aberdeen Proving Ground to support research and test robotic systems. These facilities include an indoor and outdoor test couse instrumented for automatic data collection. A remotely-controlled golf cart is among the tools used by the HEL to study human factors design and interface issues associated with teleoperation. This platform, along with a teleoperated High Mobility Multi-Purpose Wheeled Vehicle, is currently being used in a program of research in low data rate driving. This program seeks to optimize soldier/operator performance under tactical conditions requiring reduced bandwidth transmissions. During this research the influence of various image compression and enhancement techniques on remote driver performance will be measured.

REMOTE OPERATION USING A LOW DATA RATE COMMUNICATIONS LINK

1.1 INTRODUCTION

1. Although the technology for constructing robotic systems exists, the knowledge base needed to support cost-effective design decisions is still lacking. Current research in robotics at the Human Engineering Laboratory (HEL) is geared toward identifying visual display and control device design characteristics required for teleoperation, particularly as they apply to the quantity and quality of sensory input actually needed by the remote operator to perform a given task effectively. This paper describes some of the tools and facilities developed to support these current study efforts as well as a program of research in low data rate remote driving called ROAD RUNNER.

1.2 RESEARCH FACILITIES

2. In November 1988, with the signing of a Memorandum of Understanding, the HEL and the U.S. Army Combat Systems Test Activity (USACSTA) embarked on a cooperative endeavor to establish facilities at Aberdeen Proving Ground that would support the Army's effort to effectively apply robotic technology to combat, combat support, and combat service support materiel. Since that time, several indoor and outdoor test courses have been developed specifically to support research and test of robotic systems. One such course, located within a former aircraft hangar, provides a controlled environment for assessment of remotely operated vehicles. Another outside course enables the researcher to collect similar data under more variable, real-world conditions. Both courses are instrumented to facilitate automatic data collection.

1.2.1 Indoor Test Course

3. The indoor test course is housed in a 3200-square-meter aircraft hangar. Its black macadam roadway is 2.7 meters wide and approximately 400 meters long (see Figure 1). The area surrounding the road is painted a lighter shade to define path boundaries. The course consists of six segments that include straightaways, serpentine, right- and left-hand turns, a figure 8, and an obstacle avoidance segment. Driving performance on each of these segments is scored automatically, and summary statistics are available immediately after each run. These performance data include vehicle speed and accuracy.

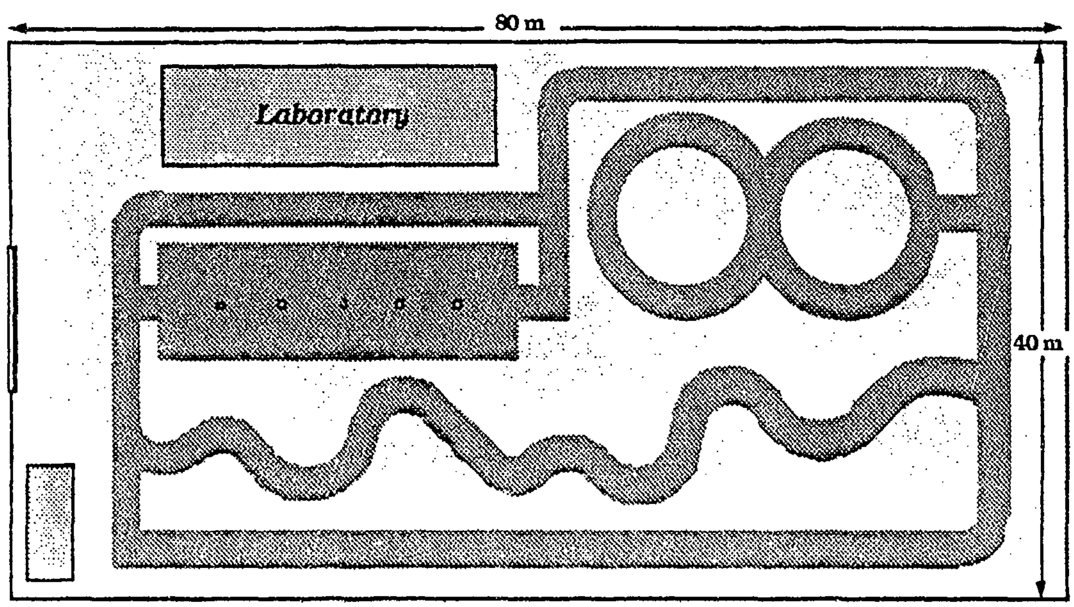

Figure 1. CSTA-HEL Robotic Test Facility

4. The measure of accuracy for all course segments, except for the obstacle avoidance segment, is the amount of absolute deviation from the centerline of the road. This centerline, along with four other stripes, are painted on the roadway's surface. Each stripe is approximately 1.3 centimeters wide. The stripes are spaced 68.5 centimeters apart and run parallel along the length of the course. A fluorescent light, video camera, and transmitter are mounted within a hood attached to the front of the vehicle. The fluorescent light illuminates the stripes on the road directly beneath the hood for the video camera (see Figure 2). The video image of these stripes is transmitted to the data acquisition center for processing by two contrast trackers. These trackers lock onto the right edge of the right-most stripe in the field-of-view (FOV) of the camera and compute the position of that stripe relative to the camera's horizontal FOV. Data pertaining to deviations from road centerline can be collected within 2 to 5 centimeters of accuracy at a rate of 60 times a second. This measure also enables computation of distance traveled with one, two, three, or four wheels off the road.

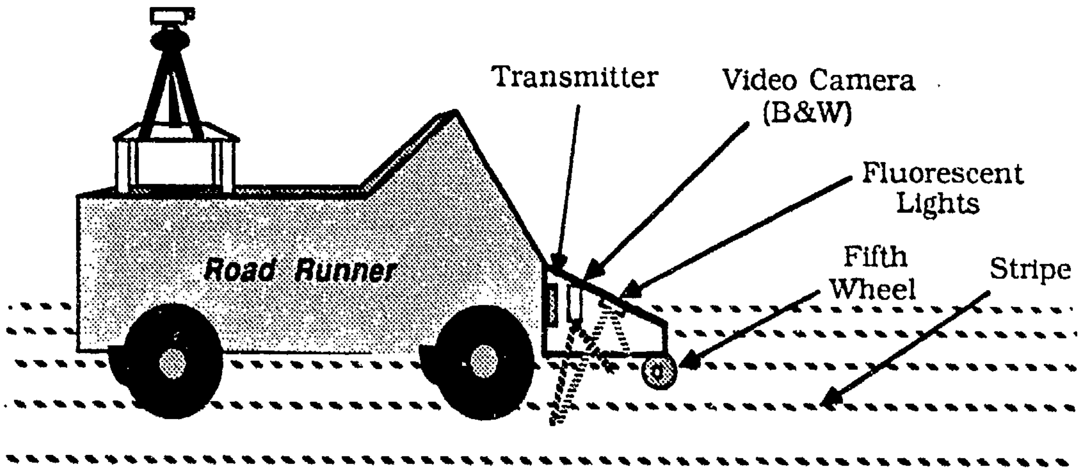

Figure 2. On-board instrumentation for measurement of deviations from road centerline.

5. The obstacle avoidance segment, located at the end of the course, is the last maneuver to be performed. The number of pylons hit is used to determine the level of accuracy for this segment. These data are provided by normally open contact switches which are incorporated into each pylon and linked to the computer.

6. A microswitch, located at the start of the course, senses the commencement of a run and data collection is initiated automatically. Data collection is terminated in a similar manner. Microswitches are also located at the beginning and end of each course segment. If the vehicle should temporarily stray off the course to a point where there are no stripes within the FOV of the camera, microswitches located every 4.9 meters within each segment identify the vehicle location upon its return and reinitiate data collection. Vehicle speed can be computed within each of these intervals based on time and distance traveled. A fifth wheel is used to provide an accurate measure of distance traveled.

1.2.2 Outdoor Test Course

7. The Rolling Road course is one of several outdoor courses that comprise the 60.7-hectare Munson Test Range at Aberdeen Proving Ground (see Figure 3). The course is 3.7 meters wide and approximately 2 kilometers long. It is composed of a variety of terrain features including gravel and macadam road surfaces, open and tree-lined areas, flat and rolling terrain, and assorted straight and twisting paths. The course consists of three segments. One segment includes left and right turns of varying severity. The two remaining segments are both straightaways. One straightaway is composed of a flat, macadam surface; the other is more rugged rolling terrain consisting of hard packed gravel with numerous potholes. These straightaways are of equal length. Three types of obstacles, six of each type, are located at surveyed points throughout the course. The three types of obstacles used are pylons, railroad ties, and man-made rocks.

The course is reconfigured by changing the location of the obstacle types. For all configurations, the obstacles are equally distributed on both left- and right-hand sides of the roadway and the number of each type of obstacle remains the same within each course segment.

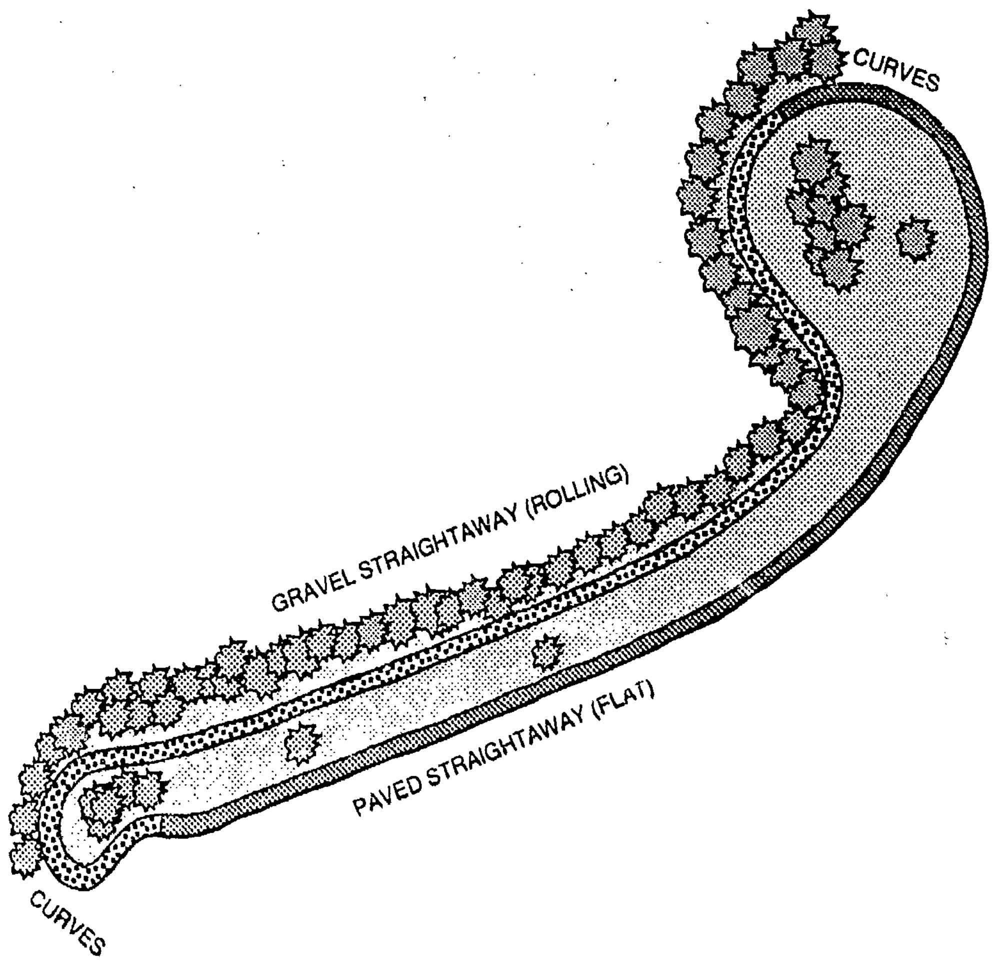

Figure 3. The Rolling Road course.

8. Driver performance is scored based on vehicle speed, deviations from the "perfect path", and obstacles hit. The "perfect path" is defined as the surveyed centerline of the road and the minimum deviation the vehicle must take from this centerline to avoid hitting an obstacle (see Figure 4). The Radio Frequency Navigational Grid (RFNG), developed by Kaman Sciences Corporation, is used to locate the position of the vehicle. These data are used to compute vehicle speed and deviations from the "perfect path" as well as the number of obstacles hit. Position location is obtained by phase differencing using a hyperbolic grid. The RFNG can compute the X and Y coordinates of the vehicle at a rate of one per second and, according to the manufacturer, can locate the position of the vehicle within 10 to 15 centimeters.*

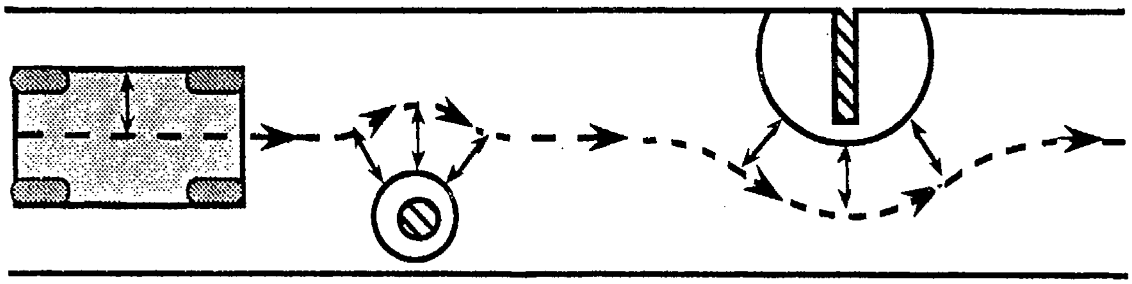

Figure 4. The perfect path

* Validation tests are under way to ascertain position location accuracy.

9. Vehicle position location data, provided by the RFNG, are also used to estimate the distance from the obstacle upon its identification by the test participant. This technique employs a data collector who depresses a button upon hearing a correct verbal identification from the test participant. This button is linked with the computer which flags the location of the vehicle at that moment during the run and calculates its distance from the obstacle.

10. Two additional driving segments are located just off the main course. They include an obstacle avoidance segment similar to that of the indoor test course, and a segment called "parking." As on the indoor test course, the obstacle avoidance segment is comprised of a row of equally spaced pylons. The remote driver's task is to maneuver the vehicle between and around these pylons as quickly as possible without hitting them (see Figure 5). Driving performance is scored based on time to complete and the number of pylons hit. The "parking" segment is also comprised of pylons arranged to form a rectangle with an opening at one end (see Figure 6). In this segment, the remote driver must maneuver the vehicle into the rectangle without hitting any of the pylons and stop as close to those which form the rear of the enclosure as possible. Performance measures include time to complete and the number of pylons hit. Normally open contact switches are used to identify pylons hit in both of these driving tasks.

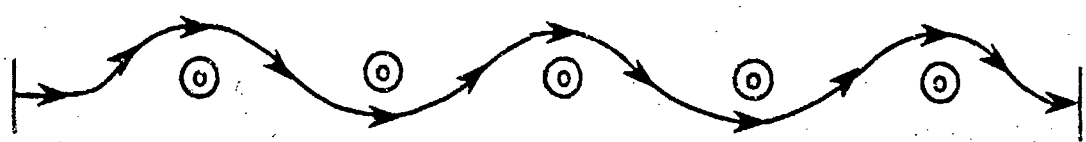

Figure 5. Obstacle avoidance segment.

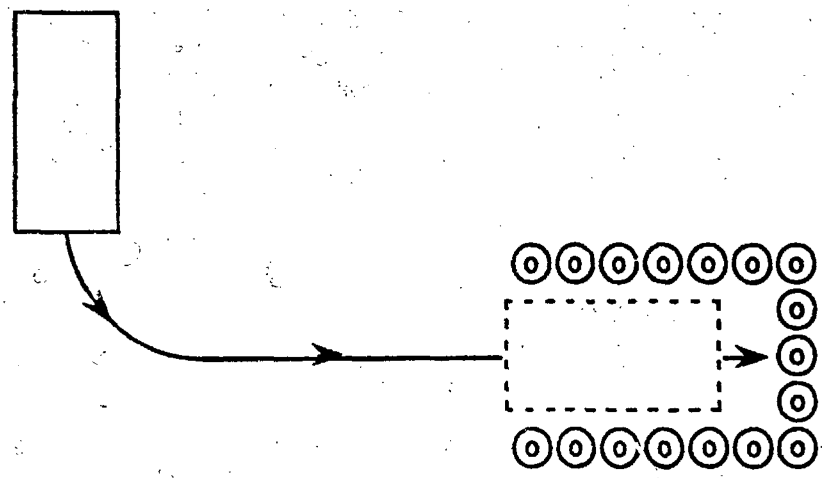

Figure 6. Parking segment.

1.3 RESEARCH PLATFORMS

11. The Road Runner vehicle is one among a number of remotely controlled platforms currently being used by the HEL to study human factors design and interface issues associated with teleoperation. These platforms range in size from the smaller explosive ordnance disposal vehicles to the High Mobility Multi-Purpose Wheeled Vehicle (HMMWV). The Road Runner is a simple, low cost, highly reliable teleoperated golf cart converted for remote operation for the HEL by Tooele Army Depot in Salt Lake City, Utah (see Figure 7). This vehicle was developed specifically to serve as a research platform for examining control and display design and information requirements for teleoperation. The vehicle is powered by six 6-volt rechargeable batteries and is capable of speeds of up to 19 kilometers per hour.

12. The vehicle controls consist of a steering wheel, brake, and accelerator pedals. Information on vehicle speed, wheel direction, and system voltage are transmitted from the Road Runner vehicle and displayed on dial-type gauges at the operator's remote control panel. The vehicle is capable of being operated from an on-board driving position as well as remotely using the same control station. In the remote driving mode, the vehicle's control station is seated within a frame containing both a 12-volt battery pack and electrical connector. The control station is attached to the frame by four bolts and a power hook-up cable. The station is easily removed as a unit from the frame and reinstalled on board the vehicle. This unique design feature enables the researcher to measure and more reliably compare on-board versus remote driving performance.

13. The Road Runner incorporates numerous safety features. These include front and rear bumpers which, upon contact with an object (8.9 newtons of force or more), shut down the motor and apply the brakes. The brakes are fully activated within 1.5 seconds. A large emergency stop button on the instrument panel to the right of the steering wheel performs the same function. The vehicle can be restarted by depressing the initialize button to the left of the steering wheel. Shutdown procedures will also be initiated automatically if for any reason the radio frequency signal to the vehicle is interrupted. If the throttle should stick, application of the brakes will remove the signal to the motor. The brake and throttle must be fully released before the system can be reactivated.

14. Since its arrival at the HEL in August 1989, the Road Runner has provided numerous visitors hands-on experience in remote driving, both indoors and out. It has proven to be a sturdy and highly reliable platform. The vehicle is currently being employed in a research program in low data rate driving similarly titled ROAD RUNNER. Verification and extrapolation of the performance data base

Figure 7. The High Mobility Multi-Purpose Wheeled Vehicle (top) and the Road Runner research platform (bottom).

generated with this research platform will be obtained through selective field trials with teleoperated tactical vehicles such as the Army's HMMWV.

1.4 RESEARCH PROGRAM

1.4.1. General Description

15. The ROAD RUNNER program is one of many HEL research efforts examining human factors design and interface issues associated with teleoperation. The ROAD RUNNER was established to support the Robotic Testbeds program - a major cooperative effort among laboratories within the U.S. Army Laboratory Command (LABCOM). The HEL has the lead role for Robotic Testbeds within LABCOM. The major objective of Robotic Testbeds is to demonstrate practical supervisory control of robotic combat vehicles operating with realistic mission requirements, including use of a low data rate tactical communications link for command and control of the remote platform.

16. Although fiber optic tethers are envisioned to serve as the primary communications link between the teleoperator and the remote platform, their survivability on the battlefield remains a concern. If the fiber optic link is severed, a secondary radio frequency (RF) link would enable the teleoperator to retrieve the remote platform or continue its mission. RF transmission of a standard broadcast quality black and white video image from the remote vehicle to the teleoperator, however, requires a wide communications bandwidth of approximately 62 megabits per second. If RGB colour and stereovision are added, the data rate requirement is more than tripled. High data rate RF transmissions would consume most of the bandwidth allocated for communications on the battlefield and preclude use of existing tactical radio systems.

17. The ROAD RUNNER program seeks to optimize soldier-operator performance under tactical conditions

requiring reduced bandwidth transmissions. The primary objective of this research is to minimize the time to emplace a remotely driven ground vehicle while minimizing the bandwidth required for transmitting the video imagery to the remote driver. Our bandwidth goal is 16 kilobits per second. This goal corresponds to the bandwidth capabilities of the Single Channel Ground-Air Radio System (SINCGARS), a secure tactical radio which is currently in the U.S. Army's inventory.

1.4.2. Methodology

18. Driving a vehicle is a visually intensive task. Enhanced resolution, stereovision, and colour are anticipated to provide valuable cues for optimizing teleoperator performance. Ideally, we would like to compress all this visual information down to 16 kilobits, transmit it over a single data channel and reconstruct the full video image with no loss in visual quantity or quality at the teleoperator's control station (see Figure 8). This, however, is not currently within the state of the art. Therefore, we must identify the minimum amount of visual information required for remote driving and find ways of reducing the bandwidth of the video transmission that preserve or synthesize that visual information essential to the performance of this task.

19. Before examining the influence of degraded imagery on remote driver performance, it is necessary to select a lens focal length for the video camera that will provide the teleoperator vision forward of the vehicle. Although shorter focal lengths will increase peripheral vision, resolution will decrease and distortions will be induced. The lens focal length will also effect relative distance judgment at varying distances from the vehicle. As focal length decreases, objects appear farther away than they are; as focal length increases, objects appear closer than they are.

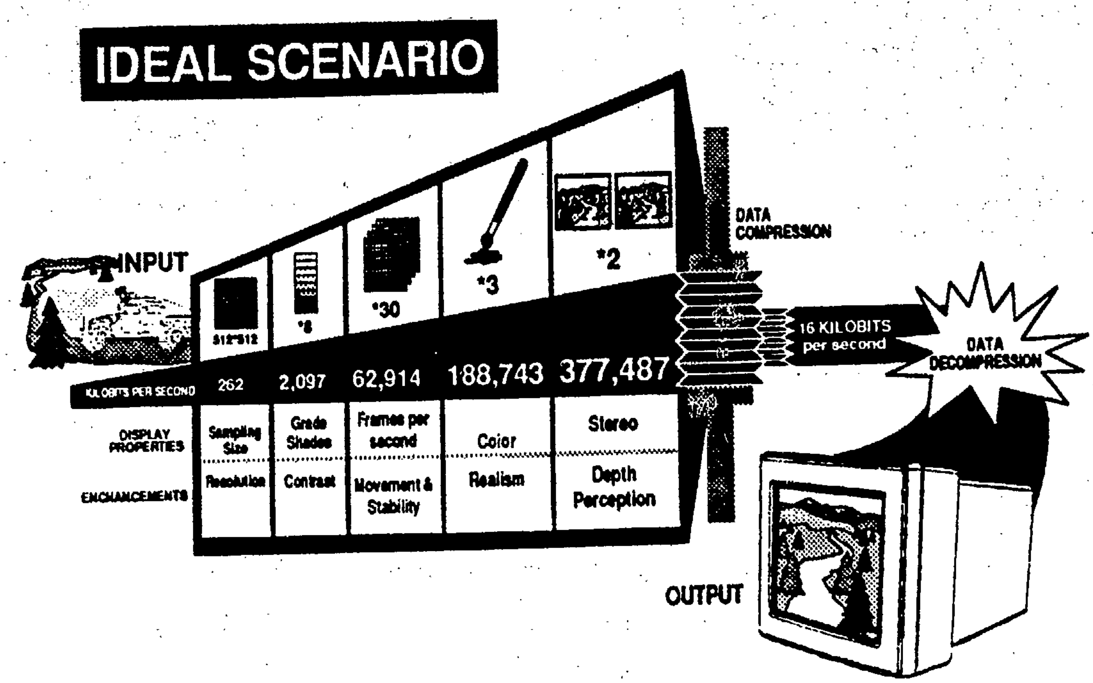

Figure 8. The ideal scenario.

20. The first in the series of ROAD RUNNER investigations began in July 1990. The purpose of this study was to select a lens focal length for the fixed, black and white video camera which would serve as a baseline during follow-on investigations. The study was conducted on the indoor test course using the Road Runner research platform. During this investigation remote driver performance was measured under three focal length or FOV conditions: 12 mm (29°), 6 mm (55°) and 3.5 mm (94°). Driver performance in the on-board mode was also measured. A major technology exposition held within the indoor facility and subsequent

construction of laboratory workspace forced postponement of study completion until this coming spring. To date, 9 of the 18 study participants have completed test. Although the data collected at this point are insufficient to perform an analysis, the trends appear to favor a focal length of 6 mm which provides a 55° horizontal FOV.

21. Follow-on studies will seek to define that point where reductions in video quality critically impact the soldier-operator's ability to control the vehicle under field conditions. These studies will involve a systematic assessment of the effects of reductions in the number of pixels, gray shades, and frame rate on remote driving performance. An initial examination of the influence of colour and stereovision will also be conducted. The information obtained during these investigations will assist in the selection of hybrid image compression and enhancement techniques for subsequent assessment.

1.4.3. Image Compression and Enhancement Options

22. The HEL is a member of a low data rate working group established to support the Robotic Testbeds program. This group meets periodically to review contractor proposals and the status of efforts in the development and assessment of the various signal processing approaches. As a group, they maintain current knowledge in the field of image processing. They become intimately familiar with those approaches that are currently being developed and choose which techniques should proceed or be terminated.

23. Table 1 is a list of signal processing approach options. These approaches fall into two basic categories: spatial and temporal. During initial studies conducted by the HEL, the individual and combined effects of two spatial techniques (resolution and gray scale reduction) and one temporal technique (frame rate) will be assessed.

Table 1
Signal Processing Approaches

SPATIAL	Image Sampling	Resolution Foveal/Peripheral Interpolation
	Quantization	Gray Scale/Colour Contrast Enhancement Histogram Slicing
	Discrete Cosine Transform	Frequency Domain
	Encoding	Run Length Encoding Variable Length Encoding (Huffman)
	Pyramid Coding	
	Blob & Contour Analysis	
	Fractal Compression	
	Predictive	DPCM
TEMPORAL	Frame Rate Reduction	Interpolation
	Prediction	Image Differencing Motion Compensation
	Simulation	Image Warping

24. Follow-on studies will examine the influence of colour. Within the colour domain, red, green and blue may be manipulated to achieve the effect of colour at less cost in bandwidth. This variable set may be transformed into hue, chroma and value (see Figure 9). Only those colours that are important in that domain need be selected and transmitted.

25. Another spatial technique planned for evaluation is called foveal-peripheral or foveal window. This approach imitates human vision creating an area of high resolution at the center of the image surrounded by an area of lower or gradually degrading resolution around the periphery. The high resolution portion of the image may be maneuvered to a point of interest in the display by either an eye scanner (occulometer) or a hand-controller.

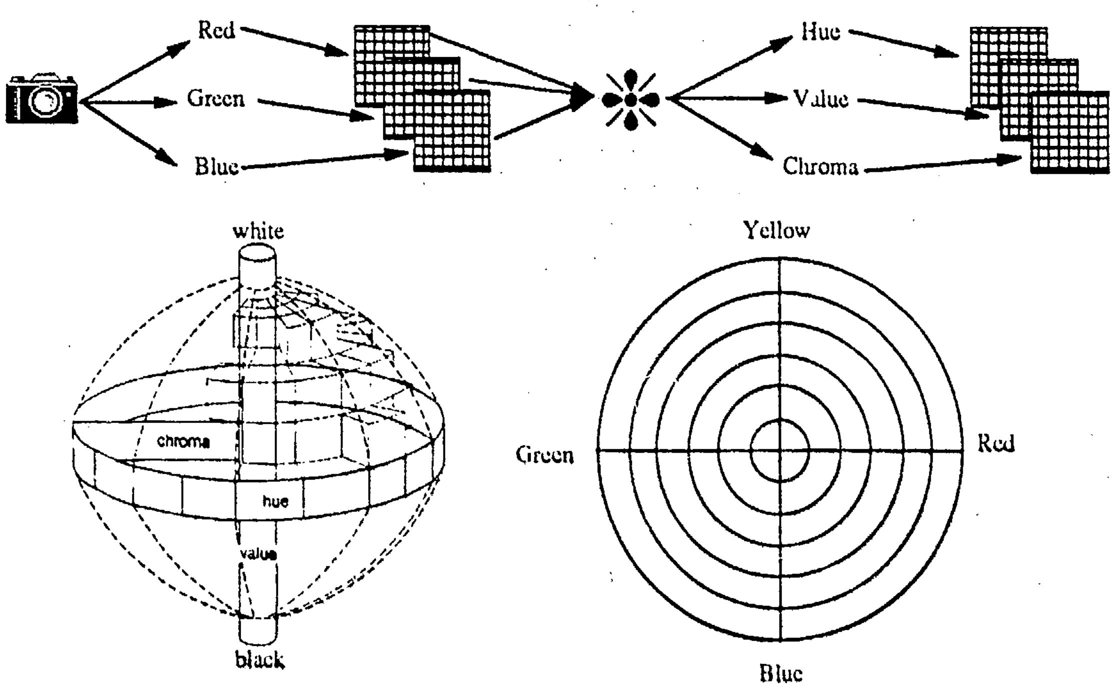

Figure 9. Colour: another world

26. Image warping is a geometrical mapping technique that uses information such as camera angle and vehicle speed to predict how the information in the picture will change over time. This temporal technique could be used to fill in missing frames and possibly minimize the effects of frame rate reduction.

27. Not all processing techniques that may be used to reduce bandwidth will effect a loss in image quality. "No loss" techniques include frequency domain and encoding. There are currently two "no loss" methods of encoding: run length encoding and the "Huffman" technique. In the run length encoding technique, the value of a pixel and the number of those pixels within a given run may be transmitted instead of the individual pixel. The Huffman technique is a coding schema wherein most frequently used gray shades (or colours) are assigned a different coding with fewer bits and the least frequently used gray shades assigned the full 8 bits. Both of these techniques, however, are time consuming and may introduce some lag in the transmitted image.

28. Some image processing techniques will work more effectively than others depending on the type of knowledge to be compressed. For example, an image containing only edges (high frequency) could be compressed by coding only the edge knowledge. However, an image with reduced gray shades (low frequency) would use an entirely different approach to achieve maximum compression. These different pieces of knowledge may be compressed individually to achieve the optimum effect and transmitted at lower cost in bandwidth by sending them separately and recombining them at the remote operator's station.

29. These various processes will be performed by the HEL using Versa Modular European (VME) based boards that may be pipelined to effect the desired compression technique or enhance the image artificially. Most of this hardware is

manufactured by DataCube. The software package, used as the real-time operating system, is called Vx Works, developed by Wind River System Incorporated.

1.5 SUMMARY

30. The HEL, in partnership with the USCSTA, is developing facilities at Aberdeen Proving Ground to support research and test of robotic systems. These facilities include an indoor and outdoor test course instrumented for automatic data collection. A remotely controlled golf cart is among the tools used by the HEL to study human factors design and interface issues associated with teleoperation. This platform, along with a teleoperated HMMWV, is currently being used in a program of research in low data rate driving. This program seeks to optimize soldier-operator performance under tactical conditions requiring reduced bandwidth transmissions. During this research, the influence of various image compression and enhancement techniques on remote driver performance will be measured. In April 1992, the results of these studies will be demonstrated during low data rate driving of remotely operated ground vehicle.

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14. Abstract:

Mobile robots which have to move, survey and achieve interventions in hostile conditions need perceptual functionnalities that allow them to intelligently interpret the evolution of the environment.

Redundant and complementary sensors together with a complete library of data processing are all necessary to build reliable and safe robotic systems. The hardware and software resources are managed by an intelligent perception system which controls all the choices and parametrizations.

The following paper presents the GESPER system (GEStion de la PERCEPTION) being developed at the LETI laboratory of CEA. This system is based on Artificial Intelligence concepts. According to the mission assigned to the robot, it carries out the perceptual resources control, the management of the perception strategies and the interpretation of the sensors data.

1) INTRODUCTION

Although many works were devoted to path planning systems, few concerned perception control systems. This is probably due to the fact that navigation is the main problem for a robot. Therefore, there are many algorithms for path planning and testbeds to validate them. But the perception is a real problem which has to be approached.

The first question one can answer is : why does a robot need to control its perception? The essential reason is the need for adaptability of the robot. A robot has to move according to the constraints of the environment and the assigned mission. It has to optimaly schedule its perceptual resources which are managed by an intelligent controller.

1.1 Constraints :

In general, robots move in complex environments that can be unstructured, unknown (robots have few a priori knowledge about their environment). They are also not pre-equipped which excludes the use of sensors based on the recognition of active beacons. But the most important characteristic of the environment is its changing evolution. Robots have to detect any changes and unexpected events like moving obstacles, smoke, changing in the lighting, fog,... and to react intelligently.

Because of these constraints, a mobile robot cannot be pre-programmed. It must be a non-deterministic real-time system resolving on line perception resources conflicts.

1.2 Perceptual resources :

The perceptual resources of a robot are the sensors and the associated data processing. The sensors acquire information in the environment and the associated data processing help the robot to interpret this information.The number and the type of sensors and functionnalities depend on the missions assigned to the robot.

As any single sensor is imperfect, a reliable perception system must include a set of redundant and complementary sensors and must be able to handle errors and uncertainties.

The perception control system analyzes the mission and answers the four questions : what is to be perceived, where, when and how must perceive the robot in order to complete this mission. Therefore, the mission has to be divided into perceptual tasks. The perceptual tasks are then planned and put into execution by the system. This is done by an intelligent controller.

1.3 Intelligent perception control :

As the sensors are redundant and complementary, each perceptual task may be performed using one of several perceptual resources and data processing. So the first functionnality of an intelligent control is the choice and the parametrization of the sensors. The sensors should be perfectly characterized as the perception system uses the sensors models to manage the perception.

But it is not the only functionnality of the perception system. The interpretation process is another important functionnality. Having acquired data from the sensors, the system has to use this data to localize the robot and to build representations of the environment.

The localization process supplies the absolute or relative position of the robot.

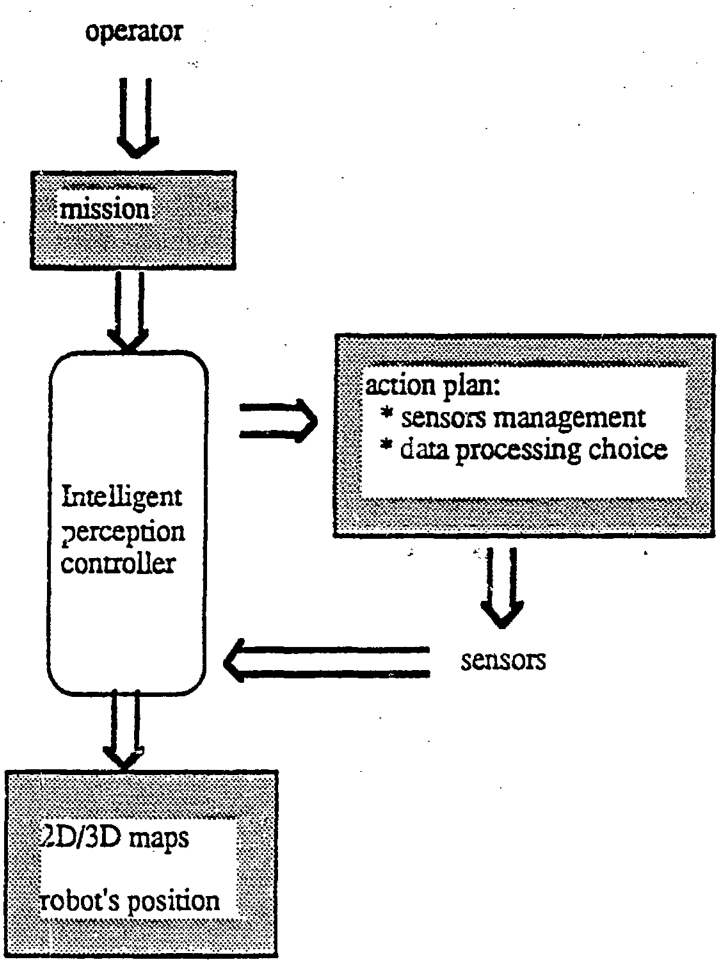
As for representations, there is not a single representation of the environment : it may be fine or coarse, on all the surroundings of the robot or only on small areas of interest... The type of representation depends on the levels of description needed by the decision level of the robot. The more complex the decisions the robot has to take, the more complete the representation must be. Three hierarchical levels are usually considered : symbolic, topologic and geometric.

In fact, the characteristics of a good perception system controller are :

- reliability : the mission must always be completed,
- adaptability : the controller makes the robot react to any event,
- modularity : it must be as modular as possible to add or exclude sensors and data processing,
- real-time,

in order to manage the complexity of the different alternatives :

- choice and paramerization of the sensors,
- choice and parametrization of data processing,
- choice of the multisensory fusion method,
- choice of the perception strategies.



Intelligent perception controller

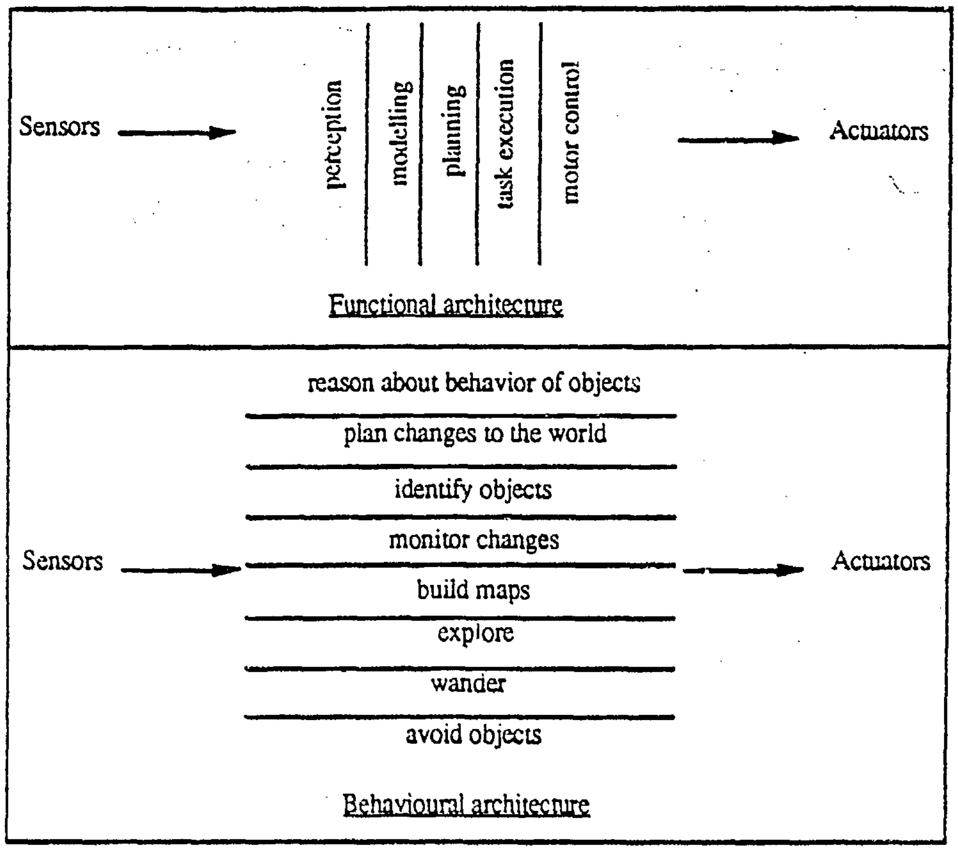
And it is important to note that the perception system is closely linked to the decision system and the term perception control must include perception and decision processes.

In this section, the aim and functionnalities of a perception control system were defined. The following sections deal with the different architectures suitable for a perception system. The architecture of our system is then presented.

2) PERCEPTION SYSTEM ARCHITECTURES

As the robot has to work and reason on imprecise and evolving information, a control system needs to be a knowledge-based system mixing symbolic and numerical representation of the environment.

Several artificial intelligence architectures have already been put forward to organize and structure the intelligent controller of a mobile robot. These architectures belong to two main groups : the behavioural ones (Brooks...) and the functional one (Meystel, Albus ...).



2.1 The functional architecture :

The functional architecture seems more natural because it divides the problem into sub-problems, data flows between modules are simple and solutions are not detailed too early during planning. But it is a rigid system and it is difficult to integrate new modules in this type of architecture. In most cases, this architecture produces very complex systems that provide global solutions even for a simple problem.

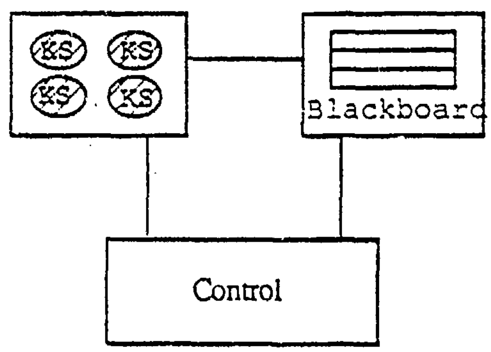
2.2 The behavioural architecture :

In a behavioural architecture, modules are independant and asynchronous. The structure is flexible but the difficulty is to make the different modules communicate and it is more and more difficult as the number of modules increases. And the control of the whole system is the main problem.

So, the tendancy is to mix those two approaches. This is true for the global control system of a robot but also for the perception control system which in fact is integrated in the former. The approaches based on blackboards are particularly interesting as a robot is a set of agents which must be controlled by a supervisor. In the coming section, we are going to detail the blackboard approach.

3) BLACKBOARD ARCHITECTURES

Blackboards are distributed structures which have the advantages of the behavioural architecture (modularity, flexibility, asynchronism) but the communications are much easier : they are made through a hierarchical data base. They also take advandtage of the natural hierarchy of the system.



Blackboard architecture

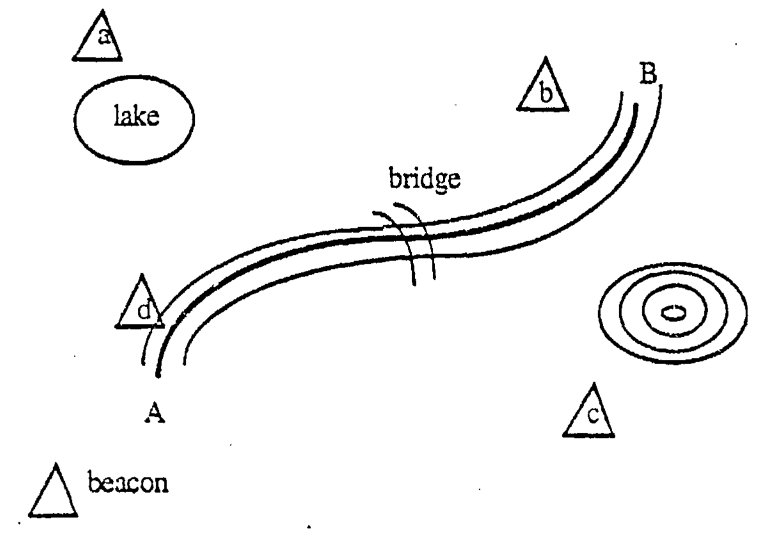
Blackboard is the name of the architecture and the name of the hierarchical data base. Knowledge Sources (KS) are independant processes that place and retrieve data from the blackboard. They communicate and interact only via the blackboard data base. The execution is so event driven and the blackboard architecture contains synchronisation primitives that determine when knowledge sources are to be executed.

We have developed an intelligent perception controller based on this blackboard architecture and we are going to give details about our implementation.

4) THE GESPER SYSTEM

GESPER (acronym for GEStion de la PERception) is the name of our perception control system. It is connected to the navigation module : the path followed by the robot is planned thanks to the representation of the environment supplied by GESPER and GESPER needs the path to plan its perception.

GESPER receives one or several missions from an operator with execution constraints (quickness, safety ...).



Example of mission

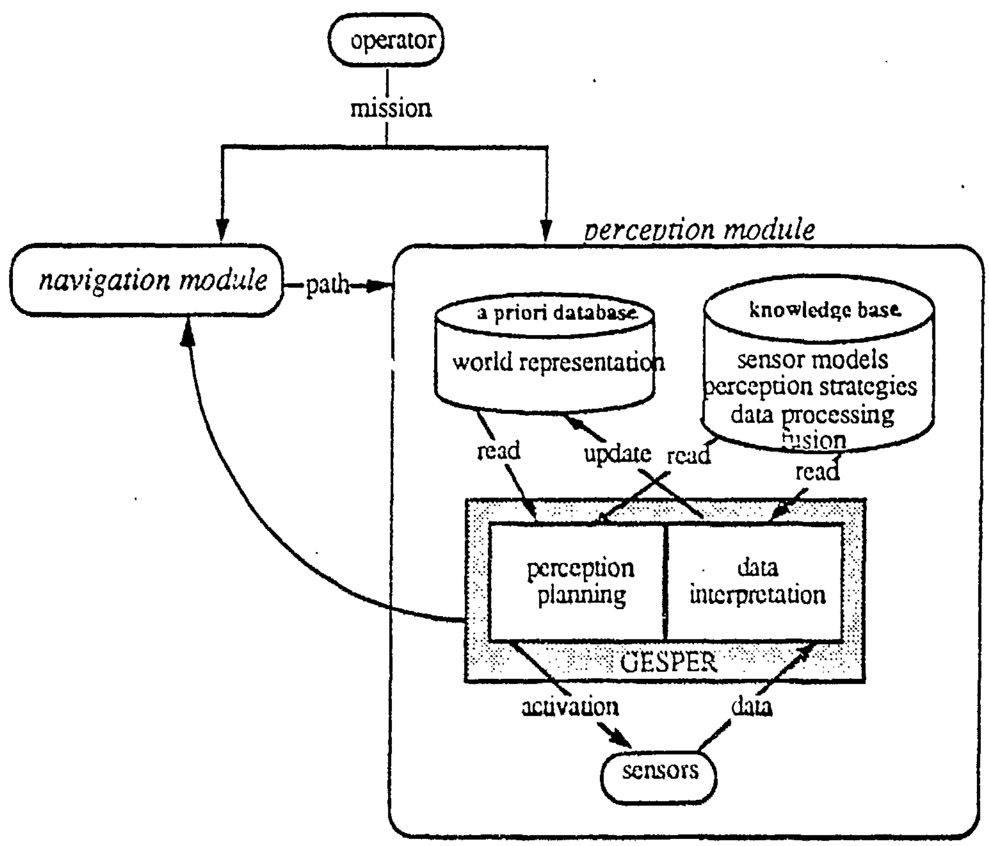
go from A to B localizing thanks to the beacons a, b, c and giving a representation of the environment

GESPER is implemented on TRAM, a blackboard tool developed in LETI (in C language). The events deduced by GESPER are recorded on two blackboards corresponding to the two main processes : the perception planning blackboard for the planning process and the perception interpretation blackboard for the data interpretation process.

The top-down perception planning process analyzes the mission and provides perception plans for the sensor activation description (which sensor has to be used, at what time and place and how it must be parametrized), the parametrization of data processing and the choice of the way to fuse sensory data. The perception planning module also carries out the execution control of the generated plans. It reacts dynamically to any unexpected change in the environment or in the robot (operator intervention, sensor failure...). It replans if possible or sends information to the navigator if not.

The perception actions are sent to the actuators and GESPER gets back raw data from sensors. The bottom-up data interpretation process makes them interpreted by the relevant processing and selects the right fusion algorithm according to the perceptual goals.

The two processes communicate with an a priori database (read/update) and a knowledge base (read).The a priori database records all the knowledge about the environment (maps for example). It is matched with the information extracted by the data interpretation module. It includes beacons and landmarks positions and models if existing. The knowledge base records all knowledge required for the choice and the parametrization of sensors and data processing. For example, sensor modelling consists in the description of characteristics such as orientation, field of view, ... Fusion and data processing algorithms are described in terms of : CPU time, type of information on which they can be applied, accuracy ... Perception strategies are also part of the knowledge base (best position to perceive landmarks for example)



The GESPER architecture.

GESPER has got four perceptual resources :

- a set of three wide field cameras,
- a time-of-flight range finder (2D scanning),
- a camera associated with a structured strip light (which can be oriented)
- a localization camera.

It also takes into account odometer data to estimate the robot position.

The data processing are related to the perceptual resources. Data processing are high level algorithms which chain pre-processing, primitives extraction, primitives interpretation... They are used for free-space detection, map building (2D and 3D), landmark recognition and localization.

5) CONCLUSION

In this paper, we have explained the need of an intelligent perception control, we have described the different existing approaches and the perception control system GESPER based on the blackboard approach.

GESPER will be used for an indoor robot equipped with a stereo-vision system, a telemeter and two cameras. It is of great interest for all robotic applications as it is capable to autonomously plan, trigger acquisitions, integrate and interprete multisensory data.

GESPER provides a generic development architecture : new sensors and/or new data processing can be easily integrated depending on the application. It is a modular, flexible and asynchronous architecture able to cope with either outdoor or indoor environments.

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14. Abstract:
We present an approach that allows the activities of multiple robotic vehicles to be controlled in such a way that each vehicle is capable of responding to unanticipated circumstances in a highly opportunistic manner while still adhering to the constratins of high level plans. We show how this may be accomplished by using the notion of plans as resources for action. We then present an architecture that embodies this notion by representing plan guidance as sensory input to a behavior-based vehicle control system.

Cooperative Control

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1. INTRODUCTION

We describe in this paper an approach that allows the activities of multiple robotic vehicles to be controlled in such a way that each vehicle is capable of responding to unanticipated circumstances in a highly opportunistic manner while still adhering to the constraints of high level plans. Our experience has shown that conventional approaches to plan representation and plan execution have serious weaknesses when applied to any system that must operate in a dynamic environment. Autonomous vehicles cannot be controlled in a purely top-down manner if they are to be truly responsive and opportunistic. Using a bottom-up approach, we show how each vehicle may be provided with the competence needed to perform the basic functions required for obstacle avoidance, pursuit and evasion, and coordination with other vehicles. High level plans are then employed as an additional source of sensory input to improve the performance of those capabilities already in place. By developing representations that allow multi-agent plans to be expressed in terms of constraints and advice rather than as explicit instructions, we show how a single plan may be used to guide the activities of many vehicles. Many aspects of multiple vehicle control are thus greatly simplified using this methodology.

Previous work has addressed the problems of coordinating multiple cooperating agents both in a purely top-down plan-based manner and a purely bottom-up behavior-based manner. Plan-based approaches are generally concerned with generating a plan that will completely specify the actions of each agent. In behavior-based approaches, coordination is obtained as an emergent property of many simple and local rules of interaction. Our work seeks to establish a common ground between these two extremes.

In purely plan-based approaches, all actions and interactions are planned in advance. The plan is then a script for action that all cooperating agents must follow faithfully. Assuming that the agents can each execute their plan correctly, then an overall coherent activity will take place. Plans are usually expressed either logically or geometrically. Using a logical description of the environment and the ways the environment can change when actions are performed, logical proofs can be used to determine a sequence of actions for each agent that will result in an intended goal state [1]. In more spatially oriented multi-agent path-finding problems, geometric reasoning and search techniques can be used to provide reasonable path descriptions [2]. In both cases, the plans are assumed to provide a complete description of all required actions. Uncertainties in the environment must be accounted for by contingency actions within the plan. This assumption leads to brittleness should the original problem description fail to capture all the uncertainties of the real-world environment.

In behavior-based approaches, intelligent action is a manifestation of many simple processes operating concurrently and coordinated through the context of their environment. Work by Brooks, for example, has resulted in a variety of robots that can perform complex tasks without using plans at all [3]. These systems exhibit a great deal of robustness because their actions are in direct response to immediate sensory input. Control decisions and representations are determined relative to each specific task, so that environmental uncertainties can be managed on a task by task basis.

A behavior-based approach can produce coordinated multi-agent actions in the same way it produces meaningful action in a single agent. Franklin, for example, has shown in simulation how three predators can be made to chase, encircle, and close in on a prey using only local information [4]. Each agent in this simulation knows only its relationship to other agents within a very limited range. A very simple set of decision rules is used by each agent to evoke actions in response to the actions of others nearby. Surprisingly, while the resulting actions appear very well orchestrated, no explicit communication between agents is required. More recently, Miller [5] has suggested a number of simple local strategies that could be used by a team of agents for exploration and sample recovery on Mars. Again, no explicit plan is used, and only minimal communication is required. Much of the work in Artificial Life [6] also exemplifies this approach. By giving each agent the same set of procedures for how to behave in response to the actions of others, a variety of interesting and useful group behaviors can emerge [7].

Our intent is to take advantage of the robustness of a behavior-based approach while also providing a plan-based means for controlling a team of agents. Given a team of agents with built-in competences for various forms of cooperation, we wish to be able to direct the actions of this team such that long-range objectives may be accomplished. Explicit control of each vehicle will not suffice in this case, because we would lose the robustness inherent in the behavior-based control strategy. Instead, we apply the notion of using plans as resources for action [8]. As resources, plans serve as sources of information and advice to agents that are already fairly competent at dealing with the immediate concerns of their environment. Consequently, plans are used to bias the natural actions of agents so that they conform more closely to achieving some global objective.

2. INTERNALIZED PLANS

In the case of a single agent, we have found that classical plan representations serve poorly as a resource for action because they lack much of the information needed to allow flexible and opportunistic response to unanticipated events. We have developed the concept of internalized plans to address this problem [9]. An internalized plan is fundamentally a plan representation that allows the information obtained during look-ahead and search to be used directly within the decision-making processes of a behavior-based agent. The plan is not intended to specify all actions of the agent. Rather, the agent is expected to already have the built-in competence needed to deal with common situations. The plan is merely used as a supplementary source of information within the agent's decision-making processes.

To clarify how internalized plans are used, we must first clarify the nature of an agent's built-in competence. In our approach, all responses of an agent to its environment are controlled through a set of loosely coupled control processes we call reflexive behaviors [10]. These behaviors each consider only particular aspects of the environment through specialized sensory processing units we call virtual sensors. Each virtual sensor and behavior pair serves as a direct sensory-action control loop. In Figure 1, shows a simplified example of behaviors for obstacle avoidance combined with behaviors for road following and navigation. Despite the fact that these behaviors do not share a single coherent representation of the world, the appropriate fusion of behavior commands [11] allows coherent actions to result.

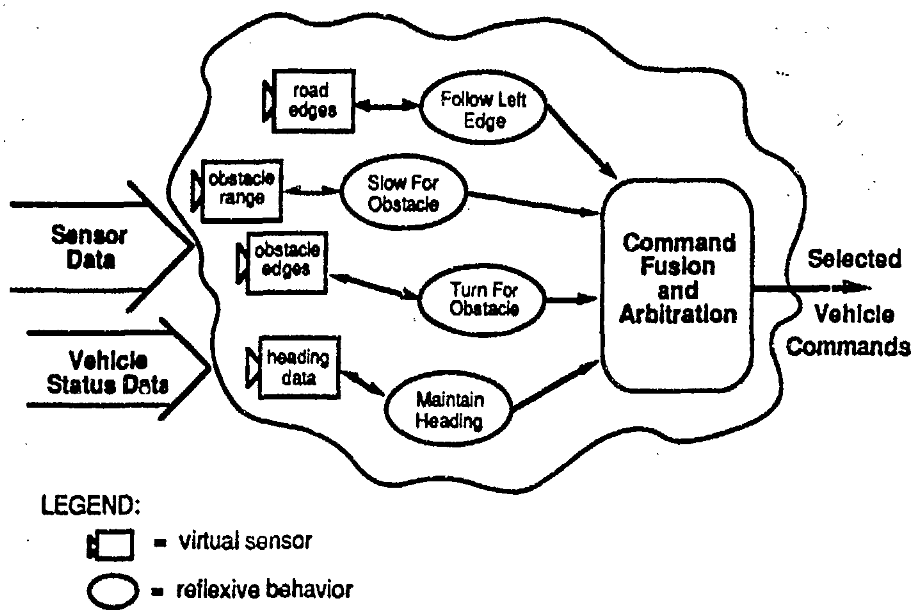

Figure 1: Reflexive behaviors and virtual sensors provide the basis for an agent's fundamental competences.

The importance of a behavior-based approach is that it allows us to construct an intelligent agent in terms of progressive levels of competence [12]. Using behaviors, fundamental levels of competence such as basic movement and survival skills are implemented first, with more sophisticated skills added incrementally as needed. Our agents, therefore, do not require plans to deal with most issues in their environment. All capabilities for movement and avoidance of sensed obstacles and threats are implemented directly within the basic control processes of the agent.

At some point, even the most competent agent can benefit from a-priori knowledge and planning. Behavior-based responses based solely on sensed data have the potential perform immediate actions that could lead to long-term difficulties. When choosing between two candidate paths, some knowledge about where each path will lead is usually quite helpful. However, if this kind of knowledge is to be used effectively by a competent agent, then it cannot be used to control the agent directly. Plans must serve as sources of information to the agent, having no more influence over the agent's actions than the sensory inputs.

Internalized plans provide a means to bias the actions of a competent agent. As shown in Figure 2, a gradient field is one form of internalized plan. Note that the plan does not indicate an explicit path to the goal. Instead, the plan provides advice about desirable headings to get to the goal. Given any vehicle location, the plan will provide a suggested heading. The behavior-based control system has the responsibility to use this advice in a way that is appropriate for the current situation. The vehicle can never be expected to follow the advice of the plan exactly because unknown obstacles will inevitably appear in its path. While the obstacle avoidance behaviors have the built-in competence to handle such circumstances, they can do a better job overall if they also take the advice of the plan into account.

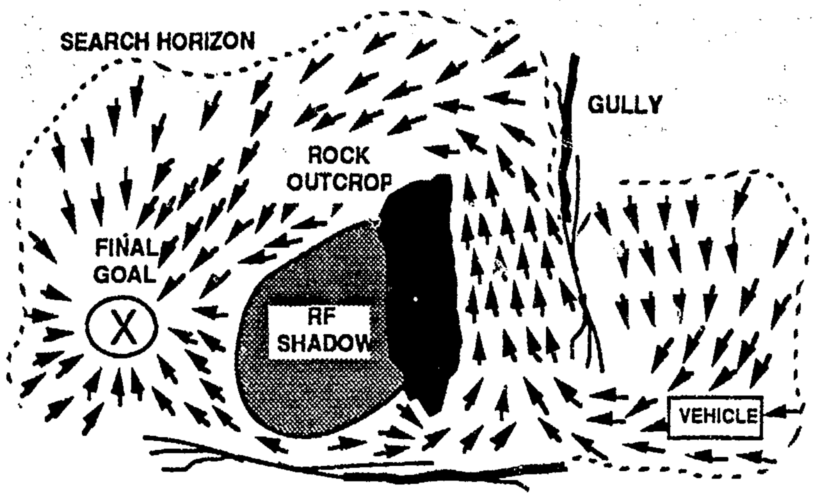

Figure 2: An Internalized Plan for a Single Vehicle Route

Internalized plans are generated with search and are used by indexing into the results of that search at run time. In the example above, the search was performed as a shortest path computation in a map [13]. The state-space for this search is simply vehicle locations. Transitions between states are determined from estimated costs of moving between neighboring locations. The resulting gradient field associates with each location state, a pointer to the best subsequent state. In order to use the internalized plan, the vehicle's location relative to the map must be known. The current location becomes an index into the map, with the resulting advice being a suggested heading.

An important issue in the design of internalized plans is the sensitivity of the indexing functions. In the case of gradient fields, small errors in position usually have only a small effect on the resulting advice from the plan. Only when significant discontinuities in the terrain exist will the plan advice be highly sensitive to position error [14]. Therefore, estimated position is usually a robust function for indexing into a gradient field. In evaluating internalized plan representations for multi-vehicle control, the robustness of the indexing function will be a major concern.

In effect, internalized plans are used as supplementary sensory inputs to the behavior-based agent. The gradient field, for example, can be thought of as a phantom compass that always gives a general idea of the right way to go. The behaviors that use this information operate in the same way that sensor-based obstacle avoidance behaviors perform.

3. EMERGENT COOPERATION

The concept of internalized plans can be applied directly to a multi-agent domain. Using a team of behavior-based agents, a single plan can be used to guide the actions of the whole team. Again, each agent must have appropriate competences for both individual and group coordination. Given these competences, the internalized plan need only provide biases to each agent's actions to keep the team properly coordinated toward achieving a desired objective. Because internalized plans can associate a bias with each possible situation, multiple agents using the same internalized plan can each receive unique information relevant to their own particular situation or state.

Many fundamental competences required for cooperative interaction such as moving in groups and staying in formation can be supported through an appropriate set of behaviors that respond only to the local relationships between a vehicle and its neighbors. By designing agents to specialize their actions according to their local interactions with other members of their team, they will be able to automatically adapt to the loss of team members, and will be able to assume roles that were previously handled by others. Internalized plans may then be used to guide these competent teams toward achieving long-range objectives.

Figure 3 shows an example of how the combination of internalized plans and behaviors for local interaction can be used to achieve mission goals. In this example, it is desired that three vehicles reach a specified ridge while maintaining a linear formation. The internalized plan for this problem is indicated by the small arrows. Note that the plan specifies the best direction to head from any location in order to reach the ridge, and therefore is applicable to each agent. Meanwhile, each vehicle is given behaviors that try to maintain a constant distance between them. Because the internalized plan is used as advice to these behaviors, the overall actions taken by each vehicle will be determined as a combination of these influences. Therefore, the vehicles will approach the ridge, but if one is diverted to avoid an obstacle, the others will adjust their relative positions to maintain proper spacing.

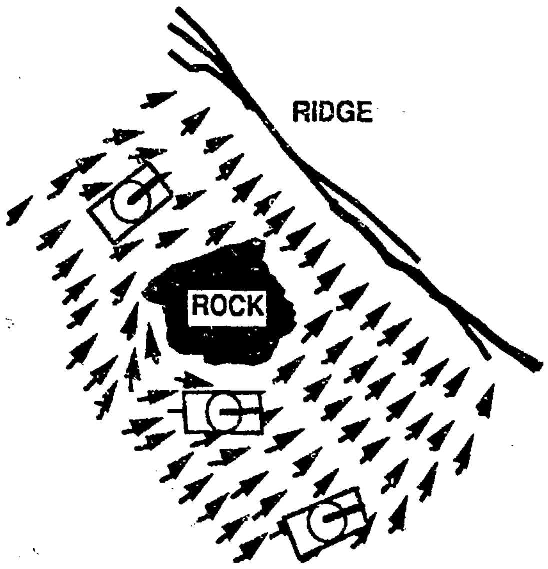

Figure 3: An internalized plan to guide three vehicles to a ridge.

By providing each agent with an appropriate level of competence, we are free to represent plan information in forms that can augment the performance of each agent and of the group as a whole. The behaviors provide competence to each individual agent, defining local interactions between agents in such a way as to establish and maintain tactical formations within groups of agents in a robust distributed fashion. Internalized plans may then be used to guide the actions of these agents toward user defined goals, thereby achieving a balance between local autonomy and supervised control.

4. MARKERS AS SENSORY INPUT

In complex multi-agent domains, internalized plans will need to provide far more information than just a desired heading. The relationships between a vehicle and its neighbors as well as between a vehicle and the surrounding terrain may all provide relevant influences on vehicle actions. Because of the potential complexity of these relationships, plans may be needed to provide advice regarding which aspects are most relevant in the current situation. Because we desire this advice to be expressed in a form that is equivalent to other sensory input, we seek a common representation that is suitable for both real sensory input and plan advice.

We have found that the concept of markers as proposed by Agre and Chapman [15] [16] provides a powerful and flexible representation that is ideally suited for our behavior-based architecture. Markers may be used within a retinocentric reference frame to keep track of important features in the environment. As shown in Figure 4, a marker may be associated with visible objects such as neighboring vehicles and critical points along ridge lines. As visible vehicles move relative to the observer, the observer's perception system will automatically keep the markers co-located with the observed vehicles. Over time, each marker will acquire information about its associated object's range and estimated motion.

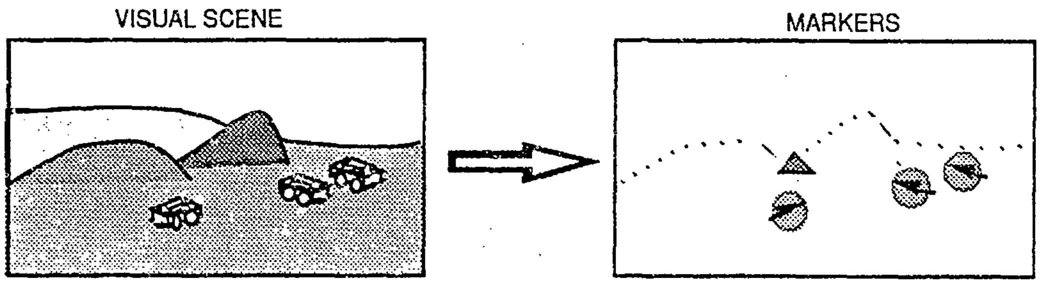

Figure 4: Markers track features within the visual scene.

In our architecture, we make a distinction between markers that are associated with objects in the visual scene, and markers that may be moved about between objects to identify causal relationships between these objects and the observer. The first type, we call sensory markers. The second, we call deictic markers.

Sensory markers are produced directly from our virtual sensors. They relate to aspects of the environment that are directly sensed and that can relate directly to behavior actions. Sensory markers track various aspects in the environment. For example, a sensory marker may be associated with each observed vehicle. These markers will track the observed vehicles in the visual scene. Upon initial observation of another vehicle, a marker will be established and perception resources will be devoted to tracking that vehicle within the visual scene. The marker will follow that track. Should a range estimate are obtained, the associated marker will acquire this range data as part of its state.

Deictic markers are markers that may be moved from one sensory marker to another. They represent causal relationships between the agent and aspects of the observed environment. Once associated with a sensory marker, they will move in correspondence with the sensory marker. Deictic markers provide a powerful mechanism for focusing the attention on relevant aspects of the environment. For example, sensory markers may identify several nearby vehicles. Deictic markers can then be used to identify relationships such as "THE-VEHICLE-THAT-SHOULD-STAY-TO-MY-LEFT," "THE-VEHICLE-THAT-SHOULD-STAY-TO-MY-RIGHT," and "THE-VEHICLE-I-AM-FOLLOWING." Chapman has described how the manipulation of markers such as these can simplify reasoning processes by focusing attention only on relevant aspects of the environment [17].

5. INDEXING STATE INTO ADVICE

Markers provide an ideal means for representing the advice from internalized plans. If an internalized plan can influence marker relationships as a function of vehicle state, then it will have a direct influence on the vehicle behaviors. In this way, the plan will truly be treated on an equivalent basis with real sensory input. To understand how plans should be used to manipulate markers, we must first examine the kinds of information that may be needed from plans.

In our previous examples, sensory markers are associated with objects in the perceptual field of a vehicle, and deictic markers are moved into correspondence with sensory markers to effect behavior. However, vehicle behavior often should be contingent on data that is not present in the perceptual field. For example, in Figure 5a, we see that there is a vehicle hidden behind a hill. Normally, this hidden vehicle would not be known to the observing vehicle. However, a variety of features of the current situation might provide just cause to suspect the presence of the hidden vehicle. Observations such as tracks in the dirt, or the actions of other nearby vehicles may be sufficient cues in this case. Using only deictic and sensory markers, it would not be possible for any behaviors to respond to this object. We therefore require a means for creating new markers for hypothesized objects.

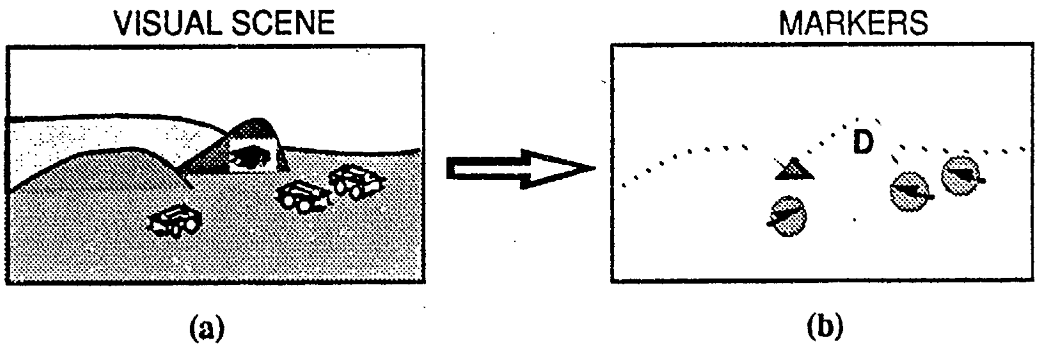

Figure 5: A scenario requiring hypothesized markers

We call the markers created for unobserved objects *hypothesized markers*. These markers will be generated from an internalized plan. In essence, the plan embodies the advice that says "when you see three vehicles in this configuration, watch out for another behind the hill." The advice, however, is more specific to the situation than this, in that it identifies the approximate location of the suspected vehicle with a marker. Such advice could be obtained from projection and search, or it could be retained from past experience. Like the simple gradient field, the current state has a significant impact on the advice obtained. In this case, though, the state is far more complex than a mere location. The state is represented by relationships between all sensory and deictic markers.

Merely hypothesizing undetected objects is not sufficient. We also require a means to establish the causal relationships between both detected and undetected objects. Again, the current state of the vehicle relative to its surroundings should provide information relevant to establishing these relationships. This state will include past reports from other team members, relative positions of other vehicles, and characteristics of the local terrain. The advice that results will involve the manipulation of deictic markers.

As an example, Figure 5b shows recognition of a potential ambush. The agent viewing this scene does not really know whether or not there is a vehicle hiding behind the hill. Its internalized plan, however, has identified this possibility by creating a hypothesized marker behind the hill. The internalized plan has then recognized the possibility that such a vehicle could play the role of an ambushing vehicle. It therefore has placed the deictic marker "D" on top of the hypothesized marker. The specific deictic marker used might be an "AMBUSHING VEHICLE" marker, thereby capturing the causal relationship between the hidden vehicle and the observing agent. In response to the placement of this marker, vehicle behaviors can now respond with caution as if a real vehicle were known to be in that location.

Clearly, the problem of generating suitable markers from the current state is far more complex than that of merely following a gradient field. Sill, the basic concept remains the same. Even the gradient field can be thought of as generating a simple marker. For example, we could use the gradient field to produce a hypothesized goal marker. This marker would move as the vehicle moved because the vehicle's state would constantly be changing. The resulting action would be similar to that of a horse attracted to a moving carrot. The plan moves the carrot, but the vehicle behaviors are still fundamentally in control.

In order to deal with complex multi-agent plans, we must be able to support a much higher dimensionality of state. In the gradient field example, state was represented merely by two numbers: a longitude and a latitude. Indexing is simple in this case. The gradient field may be represented by an array, and indexing is performed by a simple array look-up. When sensory and deictic markers are used to represent the current state, then representation and indexing become a serious problem. In multi-agent plans the location and status of every other agent is relevant. Even if we could compute such a large dimensional plan, an agent does not have access to information about all the other agents. Therefore we need a plan representation that allows us to retrieve advice given partial state descriptions.

The technology of case-based reasoning (CBR) gives us just such a capability. CBR systems can take a partial state description and efficiently retrieve a closely matching full state description [18]. However, states predicted during planning will not be exactly the same as states actually encountered in the world. Fortunately, CBR systems can also take a full state description and adapt it to the current state [19],[20]. Therefore we propose, as our internalized plan representation, the case-based internalized plan (CBIP).

Figure 6 shows our overall architecture using the CBIP. The retrieval indices of the CBIP are all of the markers, including hypothesized markers, that are examined by the behaviors. The output of the CBIP is commands or advice to a set of modules we call virtual operators. Virtual operators are responsible for managing all hypothesized and deictic markers. They are similar to the virtual sensors except their input data consists only of the sensory markers produced from the virtual sensors. An example of commands sent to the virtual operators might be "Create a hypothesized vehicle behind the hill in the middle of the perceptual field."

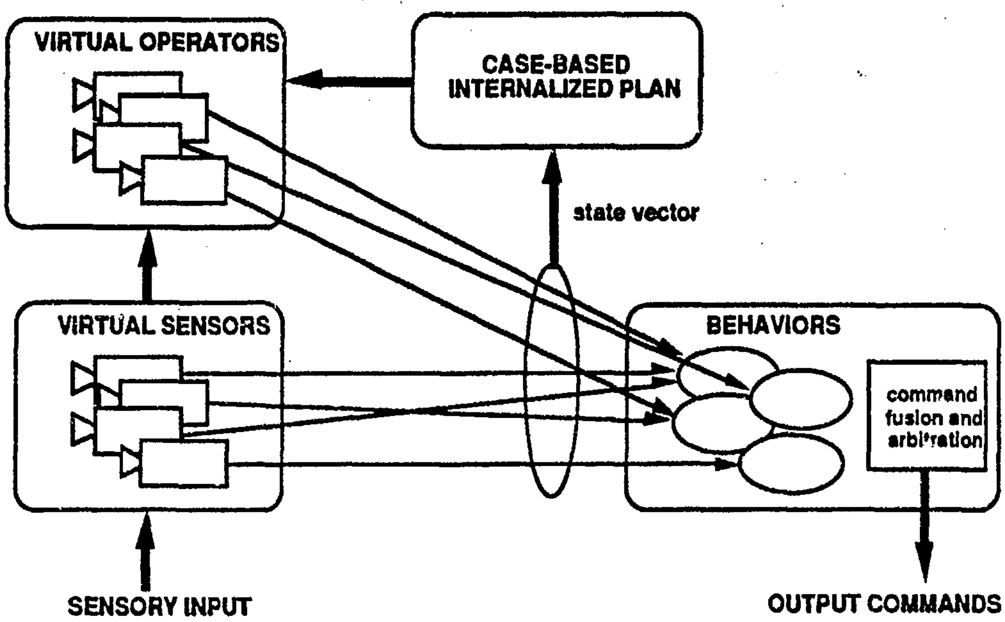

Figure 6: CBIP Architecture

Note that we have decomposed the problem somewhat differently from previous marker based approaches [15],[17]. Agre, for example, has proposed a central system that directs a perceptual system [16]. The functions of our virtual sensors are intended to be similar to Agre's "visual routines." The visual routines, however, do not create markers in Agre's system. The only markers created are equivalent to what we have called deictic markers. We have added the notion of sensory markers to provide the needed state information for the CBIP. Further, we have added the notion of hypothesized markers. Because deictic and hypothesized markers are managed differently from sensory markers, we have split the perceptual system into two distinct components. A limitation of our approach that remains to be addressed is the inherent inability of the virtual sensors to detect all objects that may be relevant to the behaviors.

6. GENERATING PLANS

The generation of internalized plans places constraints on the type of planning algorithms that can be used. First, an internalized plan encompasses all the states examined during planning. Therefore, algorithms that are postulated on re-using memory, such as depth-first iterative deepening, are not applicable.

Second, the current state of the agent is used as an index to retrieve advice for the behaviors. Because perceptual cues are used as indices, the planner must search in the space of operators and states that correlate well with actions that may be taken by the agent and with perceptual information that will be available as a result of these actions. For example, some planning systems search in the space of task orderings, incrementally adding constraints to the ordering of tasks. Such plans are difficult to use as internalized plans because it is difficult to create a function that indexes world states into task ordering constraints.

Even so, the planner may have to perform extra computations during planning to compute indices from marker states to plan states. The extra work may be required because operations on markers may not be the most natural search space. However, if the state space corresponds well to the environment sensed by an agent, creating marker indices should not be problematic.

The last constraint is the choice of abstractions. As noted before, the search space for multi-agent plans has many dimensions, and therefore abstraction will be necessary. However, because we have the constraint of being able to index the plan using perceptual cues, we would like to be able to index the abstractions in the same manner. A good example of an applicable abstraction approach was demonstrated using the SOAR program [21]. In this very general abstraction approach, abstractions are formed by dropping parts of the state description. In our mutli-vehicle example, this would correspond to dropping markers from the state description, or dropping marker attributes.

7. CONCLUSION

We have presented an approach for using plans as resources to bias the actions of behaviors rather than to force a particular course of action. As a result, each vehicle is given sufficient flexibility to respond to unexpected changes in its environment. In formulating this concept of using plans as resources, we have developed a methodology for representing plans as visual input to vehicle behaviors. This allows plan data to be considered on an equal basis with sensory input from the outside world. Plans are communicated to behaviors through the instantiation of markers within the visual field of the robot. These markers may be as simple as indicators of a goal direction or as complex as indicators that track potential threats and targets. Markers also provide a unique mechanism for human operators to provide advice to a semi-autonomous system. Because markers can be made to track visual features, a human operator may be able to augment the performance of a robotic vehicle by manually indicating important features that were not found automatically.

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14. Résumé:

A partir de l'analyse des missions de l'armée de Terre et de l'état de l'art en robotique, téléopérations, capteurs et armements, cette étude a défini des concepts de robots du champ de bataille. Une analyse de la valeur a ensuite été effectuée sur ces concepts, et des tendances à moyen/long terme ont été dégagées.

ETUDE DE CONCEPTS DE ROBOTS DE COMBAT

1/ INTRODUCTION

Le CEA et GIAT Industries ont décidé de coordonner leurs efforts dans le domaine de la robotique militaire. Leur accord vise à développer les effets de synergie pouvant résulter de l'expérience de recherche du CEA et de la pratique de conception et d'intégration de matériels militaires de GIAT-Industries.

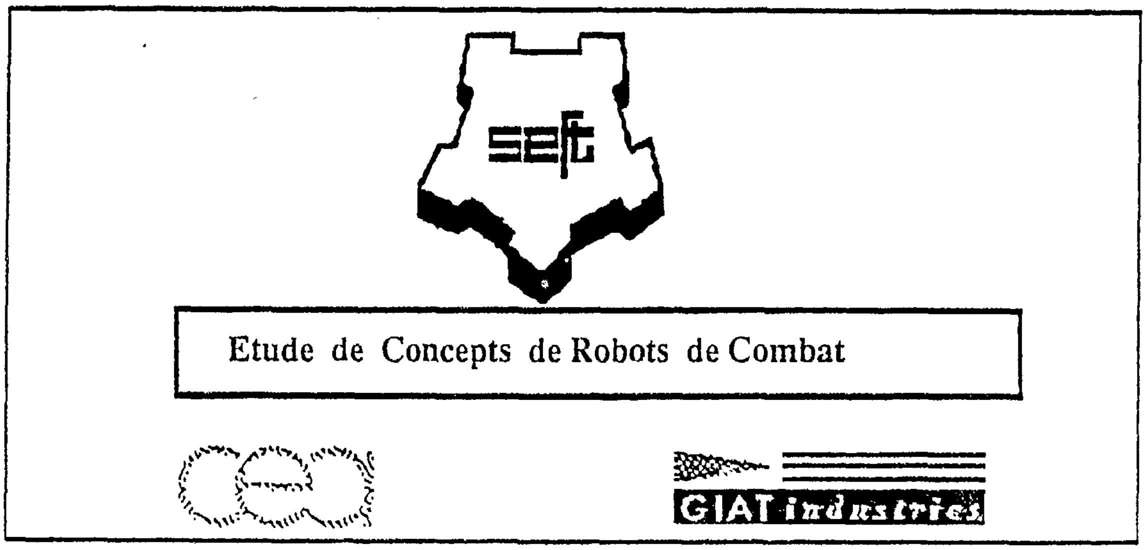

Figure 1

Le CEA (*Commissariat à l'Energie Atomique)* et GIAT-Industries (*Groupement Industriel des Armements Terrestres*) ont été retenus ensemble par la DAT / SEFT (*Direction des Armements Terrestres, Sections d'Etudes et Fabrications des Télécommunications*) pour une "Etude de concepts de robots de combat". Cette étude de dix-huit mois a débuté mi 1989. Son objet est l'établissement de plans d'actions à moyen terme et de lignes d'actions à long terme pour le développement de robots de combats parmi les plus utiles.

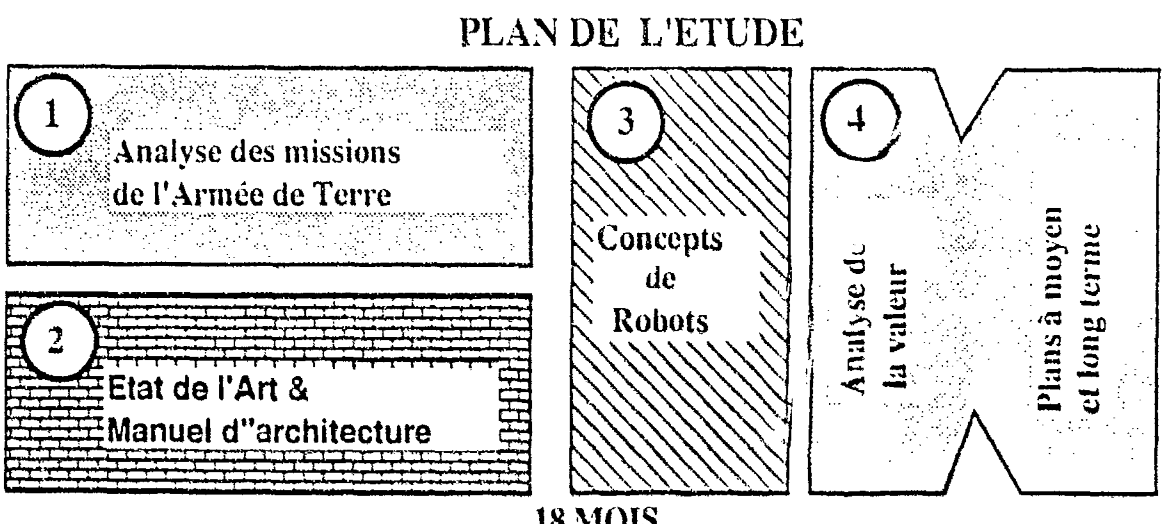

Figure 2

Cette étude comprend quatre phases. Les deux premières d'entre elles ont été effectuées en parallèle; elles ont pour objet de déterminer les actes militaires robotisables d'une part, et de réunir la documentation utile aux phases suivantes d'autre part. La troisième phase a pour objet la conception des robots soumis à la sélection de phase 4, dont l'objectif final est l'élaboration de plans d'action à moyen terme et de lignes d'action à long terme.

2/ ANALYSE DES MISSIONS DE L'ARMEE DE TERRE

Cette analyse comprend une revue générale des missions, leurs décomposition en procédés, puis en actes élémentaires répétitifs.
Les activités militaires ont été divisées en huit domaines:

ABC (Arme Blindée Cavalerie)
Infanterie
Artillerie
ALAT (Aviation Légère de l'Armée de Terre)
Génie
Train
NBC
Logistique.

Dans chacun de ces domaines ont été établies des listes des modes d'action, des procédés et des actes élémentaires, une activité d'un niveau étant composée d'une ou plusieurs activités du niveau inférieur, exception faite pour les actes élémentaires qui constituent le niveau le plus bas.

Une liste de critères a été établie: limitations dues à l'homme, coût en personnel (nombre incluant les risques et qualité) ou en matériel, possibilité de robotisation, fréquence d'occurrence de l'activité considérée. Parallèlement ont été définies des conditions d'environnement et des dominantes pour permettre de déterminer les situations particulières pour lesquelles les besoins de robotisation seraient les plus importants.

Chaque acte élémentaire a été noté en fonction de chacun de ces critères, conditions d'environnement et dominantes. Le résultat de ce travail a été soumis à des opérationnels qui ont fait un certain nombre de remarques sur les activités étudiées, sur certaines activités absentes et sur les notations effectuées.Ces remarques pertinentes ont été prises en considération et les documents modifiés en conséquence.

Une méthode de tri à partir des critères, conditions d'environnement et dominantes a été élaborée et appliquée à l'ensemble des actes élémentaires pour ne retenir que ceux qui, pour la robotisation, présentent un intérêt opérationnel, qui paraissent robotisables et dont la fréquence d'occurrence est suffisante.

ACTION RETARDATRICE

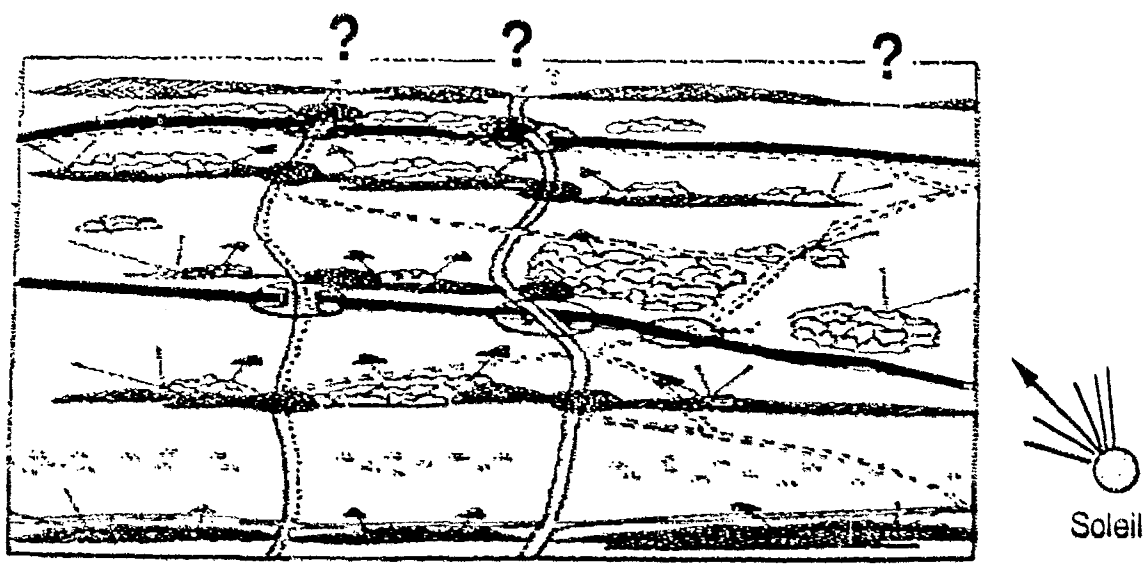

Figure 3

Des spécifications ont été rédigées pour chacun des actes élémentaires retenus après ce tri. Des scénarios tels que celui illustré par la figure ci-dessus ont été élaborés de façon à situer les actes élémentaires retenus dans un environnement opérationnel réaliste pour satisfaire les besoins de ingénieurs chargés de la conception des robots.

3/ ETAT DE L'ART ET MANUEL DE DIMENSIONNEMENT.

En parallèle avec l'étude des missions, a été établi un "Etat de l'Art" rassemblant les éléments d'informations regroupés par "Briques technologiques" d'intérêt:

Locomotion, mécanique, énergie.
Capteurs
Electronique
Transmissions
Architecture
Procédés et technologies d'armement

Cet état de l'art a été conçu sous forme de base de données informatique contenant des fiches signalétiques de matériels et contenant des photographies ou des croquis tels que celui du robot "VERI", véhicule d'Exploration Reconnaissance Inspection (de zones contaminées).

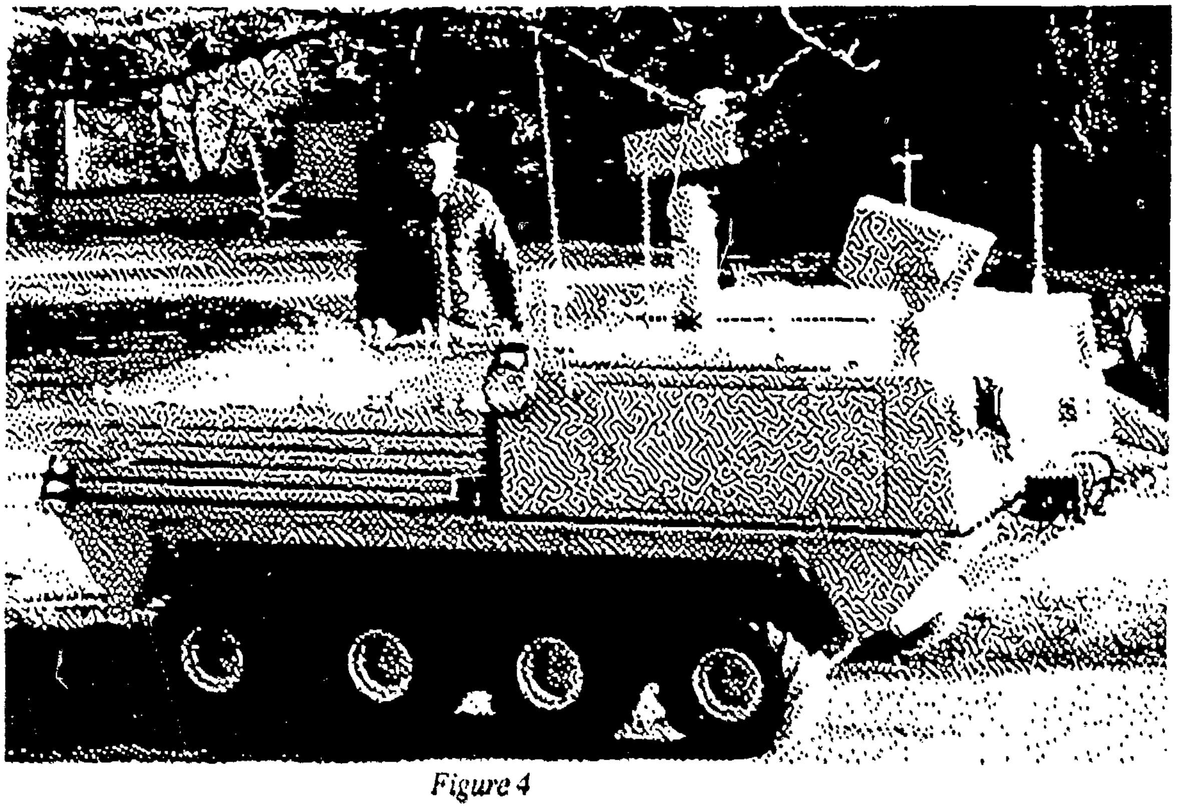

Figure 4

Cet état de l'art, qui rassemble des objets typiques, constitue un rassemblement d'exemples illustrant le manuel de dimensionnement permettant de prévoir les dimensions des matériels futurs, en s'appuyant sur des statistiques relatives aux matériels existants, traduites en formules à chaque fois que possible. Il traite essentiellement:

- des sources d'énergie à conversion directe et indirecte
- des plateformes mobiles, roulantes, flottantes et volantes.
- des sous systèmes robotiques: capteurs, tourelles de vision, manipulateurs, système de contrôle commande portables, portatifs, en shelter.
- des transmissions hertziennes ou à laisse et des questions de discrétion associées.

- des procédés spécifiquement militaires tels que la vision militaire et certains systèmes d'armes jugés d'intérêt.

4/ CONCEPTION DES ROBOTS

Les actes élémentaires retenus en fin de première phase ont été examinés en utilisant les renseignements rassemblés au cours de la deuxième: des projets de robots spécifiques plus ou moins satisfaisants ont été proposés pour réaliser chacun d'entre eux.Ces projets couvrent des actes aussi divers que la transmission d'alerte, le chargement et déchargement de véhicules et d'hélicoptères, le combat rapproché, diverses opérations de déminage et neutralisation d'explosifs, le balisage d'un itinéraire, diverses opérations de reconnaissance, la décontamination, le franchissement des cours d'eau, les travaux de terrassement... etc
Souvent, plusieurs solutions ont été proposées pour un même problème comme le montre l'histogramme ci-dessous:

Histogramme donnant le nombre de solutions différentes proposées pour les 68 actes élémentaires.

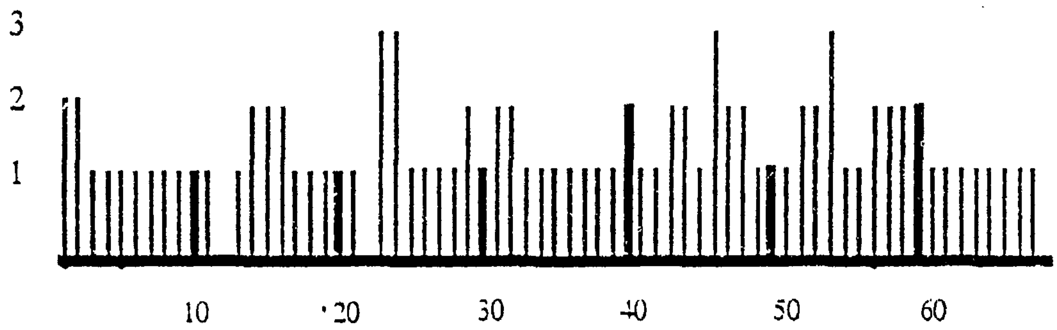

Fig 5

Une analyse fonctionnelle et statistique effectuée sur les paramètres suivants:

Déplacement
Manipulation
Capteurs
Autonomie
Retour vidéo
Télécommande.

a permis de préciser les points communs des différents concepts de robots spécifiques, en vue de la conception de robots plus polyvalents. Les conséquences de cette analyse ont été doubles:

- On s'est rendu compte que le rôle de certaines techniques, telles que par exemple la télémanipulation, était moins important que prévu.

- A l'inverse, certaines techniques ont vu leur poids relatif augmenter considérablement. C'est par exemple le cas de la téléopération par objectifs*[1] qui apparaît dans un grand nombre de cas, comme le montre la statistique suivante portant sur 68 cas repérés par leurs numéros:

[1] * *Système de téléopération permettant de ne transmettre au mobile contrôlé que des commandes raréfiées. Ce système devrait aussi s'accommoder d'un retour d'images ralenti. Les projets de robots envisagés dans l'étude prennent en compte cette nécessité.*

Observation reconnaissance	23, 31, 32, 46, 47, 52, 53, 54
Combat	05, 11, 24, 25, 39
Aménagement du terrain	20, 01, 38
Mines et explosifs	14, 15, 16, 42, 43
Franchissement	29, 02, 37, 56, 57
NBC	35, 51
Actions actuellement aéroportées	68, 58, 59, 60, 49, 66
Logistique	08, 09, 28, 50, 40

Ainsi a été constitué, pour compléter la liste des robots spécifiques à chaque acte élémentaire, un catalogue descriptif de "robots polyvalents" capables de plusieurs actes élémentaires.

Tous les actes élémentaires n'ayant cependant pas pu être couverts par les robots polyvalents, la liste finale des robots soumis aux opérations d'analyse de la valeur objet de la phase suivante comporte à la fois des robots spécifiques tels qu'un véhicule de transport de blessés et des robots génériques: véhicule d'attaque, véhicule ouvreur de brèche,robot lance flammes, robots désignateurs d'objectifs... ces quelques exemples montrant l'apparition de "filières techniques" entrant en concurrence en vue de la réalisation d'opérations relativement analogues.

A ce niveau ont été rédigés à nouveau des scénarios d'emploi illustrant les nouveaux concepts Ces scénarios ont été choisis de manière à illustrer et valider les demandes de performances demandées par les responsables de l'étude opérationnelle.

Scénario No 13

Véhicule ouvreur de brèche.

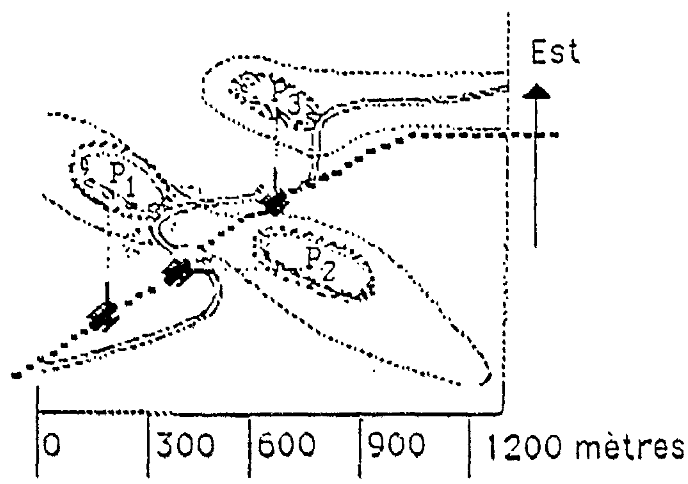

Figure No 6

Chaque scénario comporte quatre parties principales:
- Situation,
- Mission
- Déroulement comprenant mise en place, fonctionnement, répartition.
- Conclusion comportant un premier jugement de valeur, indiquant les autres emplois possibles et les limites d'emploi, évaluant les raisons d'échec possibles.

A titre d'exemple, la conclusion relative au robot ouvreur de brèche indique:

" Le franchissement des positions ennemies sans le robot aurait posé des problèmes relativement longs à résoudre: mise en place d'appui feu d'artillerie ou de mortiers, attaque des positions, probablement nécessité de les nettoyer.

Le robot ouvreur de brèche, pour échapper aux tires de l'ennemi, doit être très mobile et puissamment blindé, pouvoir neutraliser l'adversaire par des tirs massifs, savoir placer des fumigènes aux endroits nécessaires.
La consommation de munitions étant forcément très grande, il faut pouvoir la moduler selon les objectifs à traiter: là où la menace est plus grande, il faut pouvoir diriger un tir plus dense.
L'emploi de ce robot nécessite une nette séparation entre positions amies et positions ennemies pour éviter toute méprise."

5/ PLANS D'ACTION A MOYEN TERME ET A LONG TERME

La conception de ces plans a été précédée d'une phase d'analyse de la valeur comportant un grand nombre d'opérations de notations ou de chiffrage se rapportant à chacun des concepts de robots retenus pour le criblage final.
Au cours de cette analyse, la plupart des concepts ont été légèrement optimisés de manière à pouvoir réaliser les missions prévues au moindre coût, chaque responsable de concept ayant pour objectif d'obtenir la meilleure notation possible en fonction des critères utilisés pour classer ces robots. Ces critères, eux mêmes divisés en sous-critères, sont essentiellement les suivants:

- *Critères opérationnels*: performances, nouvelles possibilités opérationnelles, contraintes, taux d'utilisation, sécurité, vulnérabilité.
- *Critères humains:* Danger, pénibilité, gain en personnel, gain en personnel qualifié, stress.
- *Critères techniques:* complexité, délai de recherche, développement, industrialisation.
- *Critères financiers*: coûts récurrents, coûts de possession liés à la complexité.

Chacun des robots a été soumis à une série de notations ou de chiffrages pour pouvoir qualifier son niveau.
L'intérêt général opérationnel ou humain est représenté par la moyenne des notes obtenues pour chacun des critères.Les coefficients attribués à ces notes avaient été préalablement soumis à un panel d'une dizaine d'officiers.

On a réussi à attribuer à chaque robot les mêmes questions, mais il s'est trouvé nécessaire d'attribuer des grilles de notations différentes à chacune d'entre elles: les hélicoptères téléopérés de reconnaissance et les engins de franchissement du Génie ont dus être notés en utilisant des barèmes différents.

Le premier tri, qui présente un caractère éliminatoire, a été effectué en utilisant la grille de la figure 7:

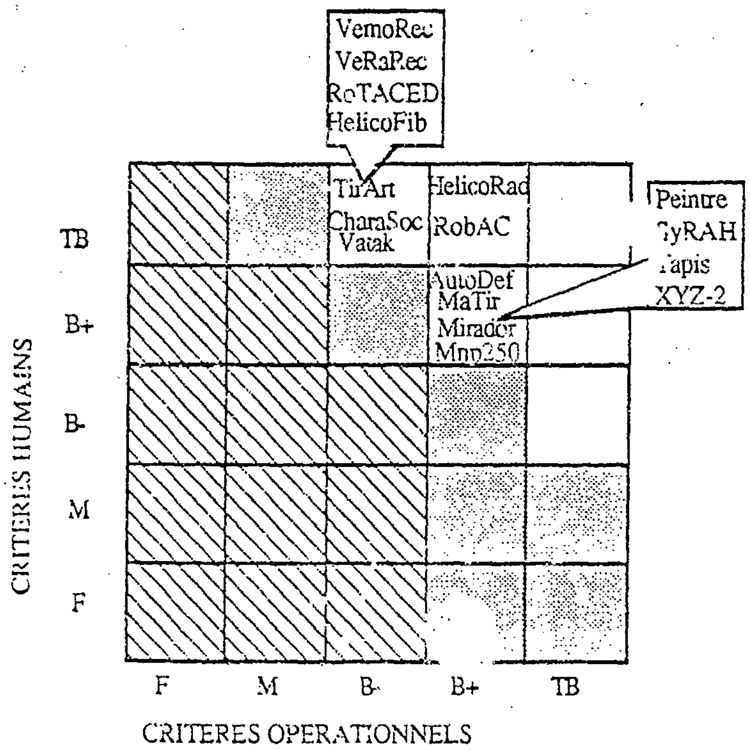

Figure 7

Des symboles appréciatifs ont été préférés aux notes pour rendre le tableau plus parlant:

F= faible
M= moyen
B- = relativement bien
B+ = franchement bien
TB = très bien.

La figure 7 indique les noms des principaux robots sélectionnés. Il s'agit essentiellement d'engins de combat, de reconnaissance et observation, de logistique.

Deux modèles se distinguent particulièrement. Il s'agit d'un hélicoptère radiocommandé de reconnaissance (HélicoRad) et d'un robot antichar (RobAC).

La faisabilité économique a été vérifiée au moyens des paramètres apparaissant figure 8.

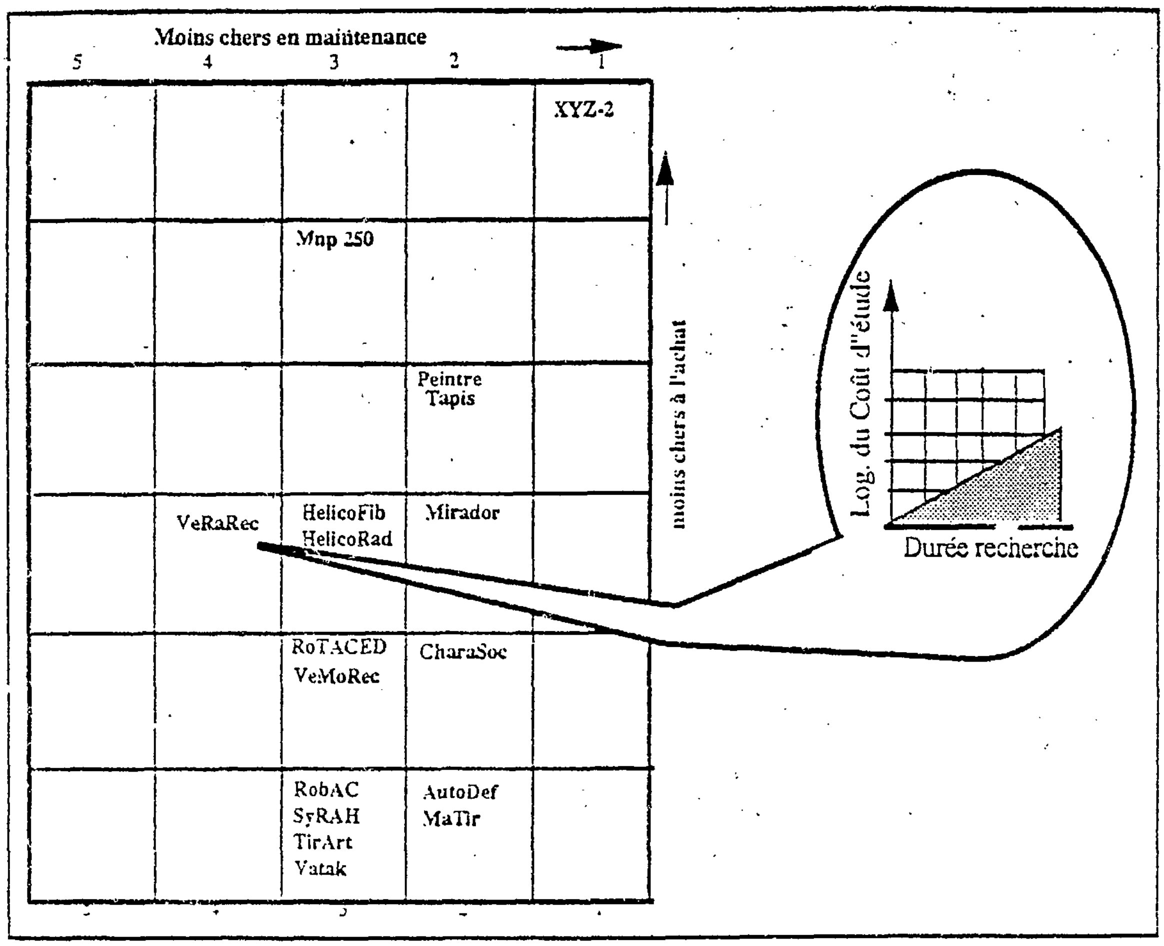

Figure 8

Les coûts figurant sur la grande grille sont des coûts marginaux qui ne prennent pas en compte l'amortissement des recherches et des études. Les coûts de maintenance n'ont pas été évalués directement: on a admis qu'ils étaient proportionnels à un facteur de complexité ayant également été utilisé lors de l'analyse opérationnelle.
Les coûts et délais de recherche, développement et industrialisation l'ont été à partir de plannings types reproduisant l'expérience acquise lors de la réalisation de robots mobiles civils, avec certains aménagements pour prendre en compte les exigences particulières aux fabrications d'armement.
Ces diagrammes permettent d'orienter les premiers choix, à condition de se souvenir que le coût d'un programme est normalement plus faible que la somme des coûts de ses constituants, les recherches et les investissements étant susceptibles de s'épauler mutuellement.

Parmi les concepts proposés, certains sont réalisables à relativement court terme: il s'agit essentiellement de machines existant déjà sur le marché tels que par exemple les robots de désamorçage d'explosifs ou des robots de nettoyage susceptibles d'être utilisés pour faire de la décontamination.

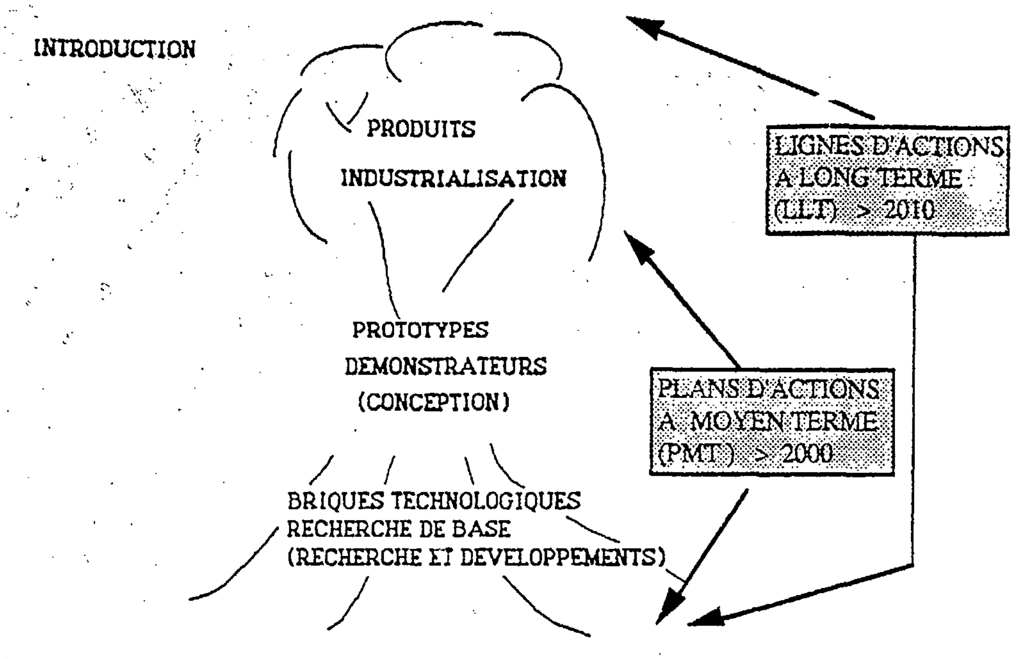

Fig. 9

Mais l'objectif de l'étude couvre avant tout le moyen et le long terme. La figure 9 présente la méthodologie d'établissement de ces plans.
La recherche à moyen terme a pour but essentiel l'acquisition des technologies nécessaires pour atteindre les objectifs retenus. Lorsque ces objectifs de connaissance seront atteints, il faudra engager des développements industriels adaptés aux produits.

La figure 10 fournit des informations plus détaillées sur la méthode de détermination des programmes de recherche. Il a été considéré que la validité des recherches devait être vérifiée grâce à des démonstrateurs physiques venant en complément des recherches papier. Ces démonstrateurs ne doivent pas être confondus avec des maquettes souvent utilisées par les chercheurs pour valider leurs méthodes de prévision. Ils seront beaucoup plus orientés utilisation et ressembleront déjà à des robots de combat, mais ils ne représenteront pas encore des robots optimisés prêt à l'emploi.

DEMARCHE DE DEFINITION DU PMT

(1) ROBOTS RETENUS — SOUS SYSTEMES ROBOTIQUES (2)

	S1	S2	S3	S4	S5				Sn	
R1			*			*		*	*	D2
R2	*		*	*				*		D1
R3	*	*			*	*			*	D1
R4	*			*			*	*	*	D1
		*	*	*	*	*	*	*		D2
			*	*				*		Dn
Rn	*	*	*	*		*		*	*	D3

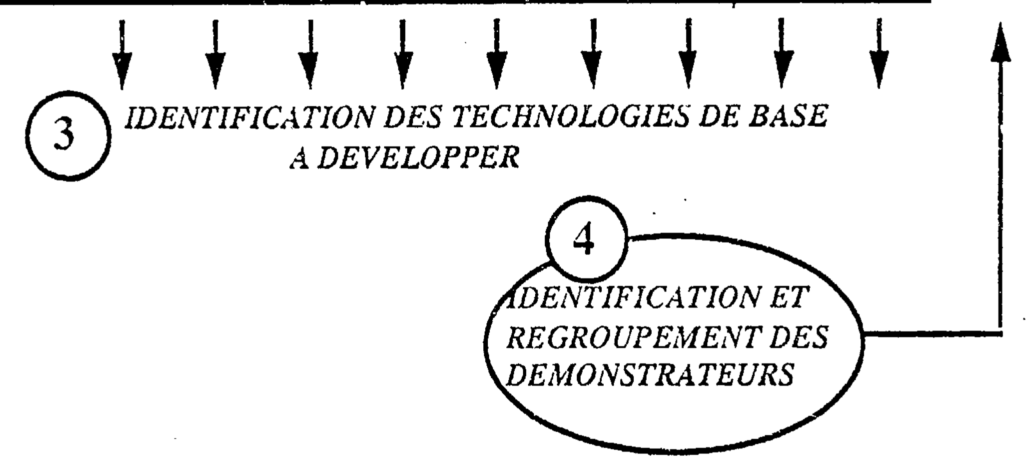

Figure 10

La figure 10 montre comment quelques démonstrateurs permettent de couvrir la gamme des technologies sans pour autant construire la totalité des systèmes envisagés. Les fonctions et sous systèmes sont listés pour chaque robot suivant les colonnes d'une matrice comportant une ligne par robot retenu. Ainsi, certains systèmes appartenant à deux types de robots, ne seront pas étudiés deux fois: le système de téléconduite d'un robot de combat peut par exemple convenir au char lourd de déminage dont les performances en vitesse sont moins élevées. Les systèmes d'autodéfense de véhicule sont adaptables aux robots fixes, les systèmes de transmissions, certains capteurs particulièrement difficiles tels que les télémètres imageurs etc... ne seront étudiés qu'une seule fois, mais seront essayés sur quelques engins différents dans des conditions différentes.

Parmi les recommandations qui figureront dans le rapport final, se trouveront très probablement les suivantes:

* Circonscrire les études aux robots vraiment les plus intéressants, les recherches prévues étant souvent lourdes et susceptibles de révéler des difficultés imprévues diminuant l'intérêt des concepts concernés: une marge d'intérêt est nécessaire pour éviter les impasses.
Cette recommandation n'exclut pas, au contraire, une vérification périodique du bien fondé des objectifs.

Elle n'exclut pas non plus la réalisation immédiate par l'industrie des robots utiles et faisables à court terme, tels que les "Minirobots".

* Introduire une certaine modularité dans les concepts pour limiter les études spécifiques, les moyens industriels nécessaires et la quantité de matériels à emporter par les utilisateurs.

* Attacher une grande importance aux études de transmissions d'une part, aux études d'autonomie d'autre part, pour faciliter l'emploi de nombreux robots dans un même compartiment de terrain.

* Les développements concernant l' "armement" sont de loin les plus lourds en prix, mais ils ne conditionnent le délai que dans deux cas importants concernant un robot d'autodéfense et un robot de tir. Par contraste, les recherches concernant la téléconduite des véhicules sur objectifs mettent en oeuvre des budgets relativement faibles mais ne peuvent pas être réalisées en un temps très court, le franchissement d'une étape nécessitant le succès soigneusement vérifié et consolidé de l'étape précédente.Il est donc recommandé de commencer immédiatement ces recherches peu chères mais essentielles pour la grosse majorité des projets.

* Une compétition entre filières techniques existe entre les moyens de reconnaissance: véhicule chenillé classique, véhicule rapide à créer et hélicoptère télécommandé, le véhicule classique se présentant à la fois comme le plus coûteux et le plus difficile à réaliser. Il n"est pas proposé de résoudre ce dilemme avant les cinq années à venir, les études de base étant les mêmes et exigeant au moins ce laps de temps.

* Un démonstrateur de téléopération sur objectifs de véhicule tout terrains sera indispensable pour prolonger les premières études VERI jusqu'à un niveau d'applicabilité au problèmes militaires.

* Différents robots antichar correspondant aux mêmes besoins opérationnels mais réalisés de façon très différente pourraient être développés. Trois axes de recherche apparaissent nécessaires:

- Tir déporté compatible avec transmission ralentie des images.
- Chaîne d'identification et de riposte
- système d'identification des amis utilisable par les engins terrestres.

* La téléopération des armes utilisera des procédés spécifiques, ne reprenant qu'en partie les technologies de téléopération. de plus ces procédés devront être couplés de façon active avec les procédés de conduite des véhicules. Un couplage "passif". par l'intermédiaire de capteurs enregistrant simplement les mouvements du véhicule ne suffira pas dans tous les cas pour obtenir les vitesses d'action et les précisions souhaitées. La prise en compte des ordres du système de pilotage par le système d'armes permettra seule d'obtenir les performances souhaitées.

* L'analyse de la valeur opérationnelle a montré que la taille des systèmes de commande était un facteur important pour les opérationnels. Un gros travail de développement de ces interfaces de masse réduite est nécessaire. Les techniques dites de "téléprésence", non appliquées aujourd'hui aux véhicules terrestres devront faire l'objet d'une attention particulière.

6/ CONCLUSION

Cette étude de concepts de robots de combat nous a permis de cerner les besoins de l'Armée de Terre tels que connus aujourd'hui et de jeter les bases d'un programme de recherche tendant à rendre réalisables des concepts relativement futuristes.
Les programmes proposés nous paraissent valides pour une période d'environ 4 à 6 ans suivant les points concernés.Les causes de modifications prévisibles sont les suivantes:

Modification des besoins perçus par les opérationnels
Apparition de nouvelles technologies modifiant les faisabilités et les coûts.

Nous proposons donc une remise à jour de la présente étude dans trois ans.

C7

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14. Abstract:

The use of mobile surveillance and intervention robots is necessary in a hostile environment where human beings cannot complete a mission without danger. In few years, one may expect that a robot will be intelligent, as far as it, or he, will be able to react with and against its environment.

However, and for many reasons, a robot must be robust. Reliability of equipments, survivability in an agressive an dhostile environment are the keywords. But how test, and certify, this robustness? Advanced technologies in robot's world could imply use of symbolic computing, neural nets, genetics algorithms, just for today ... The probably non short term deterministic behaviour of the robot may not be convenient for massive testing at integration and trial phases as far as the robot do have to react against the outside world.

ROBOT TRIALS: DARDS TEST-BED an APPROACH for ROBOT'S TESTING

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ABSTRACT

The use of mobile surveillance and intervention robots is necessary in a hostile environment where human beings cannot complete a mission without danger. In few years, one may expect that a robot will be intelligent, as far as it, or he, will be able to react with and against its environment.

However, and for many reasons, a robot must be robust. Reliability of equipments, survivability in an agressive and hostile environment are the keywords. But how test, and certify, this robustness? Advanced technologies in robot's world could imply use of symbolic computing, neural nets, genetics algorithms, just for today... The probably *non short term* deterministic behavior of the robot may not be convenient for massive testing at integration and trial phases, as far as the robot do have to react against the outside world.

So far, this document does not describe existing solutions for such a challenge, but do expose what real problems could be encountered during the testing phases.

DARDS TEST-BED

DARDS, an acronym of ***Démonstrateur Autonome à Rapidité de Déplacement pour la Surveillance***, is a French's DoD major program. It is mainly funded by DRET and is designed to be a test-bed for advanced complex functions and sensors.

It is not designed to be a fully operational system. However the robot include methods and technologies already existing in others "off the shelf" systems and provide many room for future experiences: power supply, standard mechanical interface, wide-band digital and video links... Fig 1 & fig 2 present DARDS.

During the trials, DARDS is fully supported by a separate mobile control center. It is integrated on a stand-alone 25 ft truck, equiped with four control stations. These workstations are designed for real time control and easy-to-use system. The control center is backuped by an autonomous power supply.

ELEMENTARY TESTS

A common method of qualifying a system consists in performing elementary tests which become increasingly complex. Mobility, Agility, Intervention effectivess... This classic methodology is already used for robot integration (fig 3).

These initial tests are essential for checking, both simply and without confusion between parameters, the quality of the various algorithms employed. Each trial must be designed to answer a question concerning the correct execution of a specific function.

The tests of the basic functions must therefore be combined in a dynamic and coherent manner to make an in-the-lab evaluation of the future product. The definition of basic action in the integration process and trials, in a more open world, is a fundamental question.

DEFINITION of TRIALS

With an environment which, by definition for a mobile autonomous robot, is poorly known, the exploration of possible cases is difficult and of course costly. It can also be inachievable.

Several methods may be considered as a random approach, where the operator imagines complex cases of intervention. A combination approach, all possible cases are described with all possible problems to write it and keep it...A statistical approach for which cases apparently more significant are extracted from the previous analysis (fig 4).

These methods are effective in the case of elementary tests, but are difficult to apply in the case of weighted combinations of these tests. By the end, there is a danger of subjective bias linked to the operator.

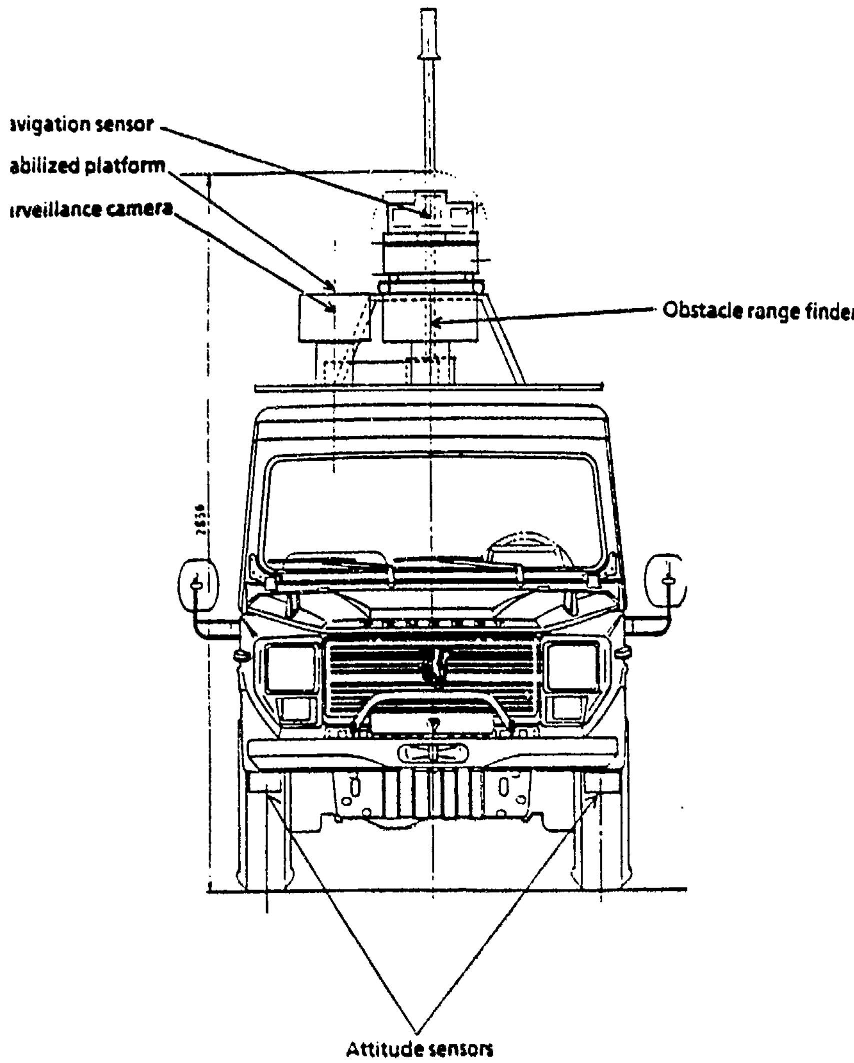

ıvigation sensor
abilized platform
ırveillance camera
Obstacle range finder
Attitude sensors

FIGURE 1

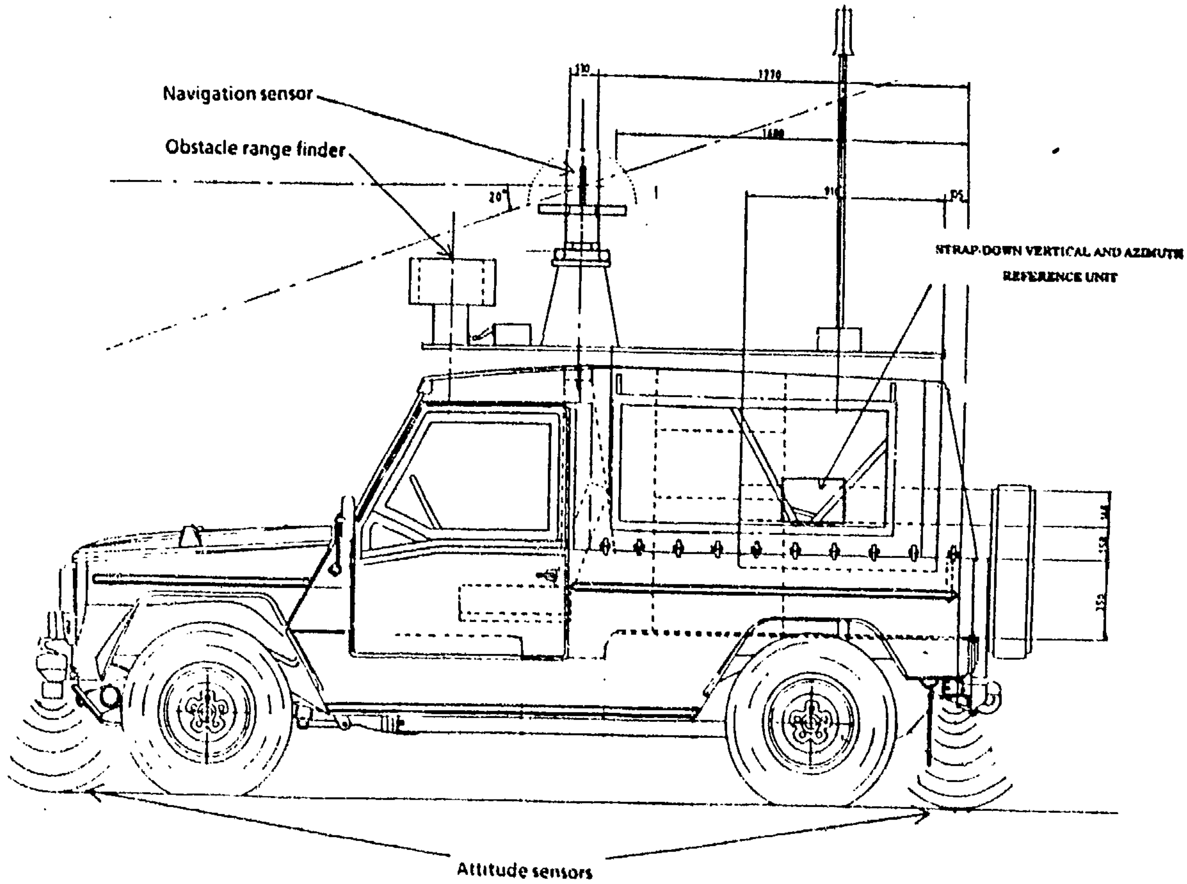
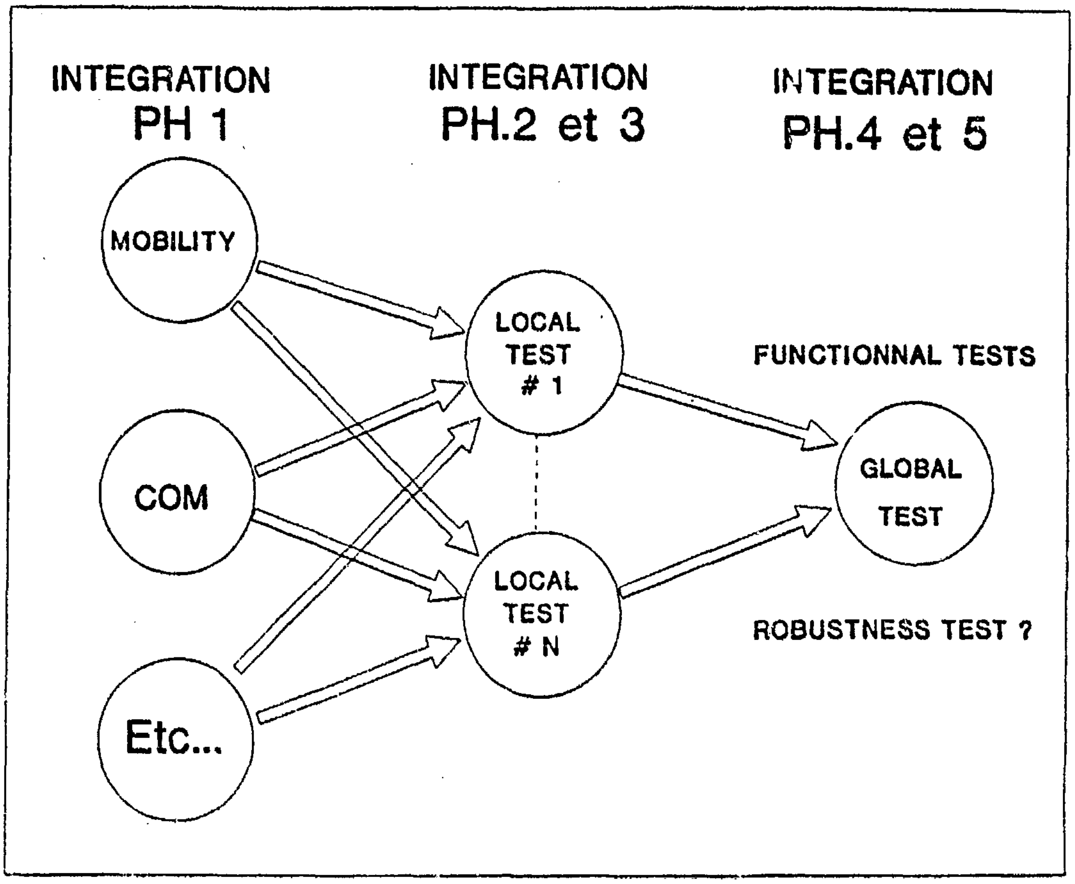

Navigation sensor
Obstacle range finder
STRAP-DOWN VERTICAL AND AZIMUTH REFERENCE UNIT
Attitude sensors

FIGURE 2


INTEGRATION
PH 1
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FUNCTIONNAL TESTS
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TEST
ROBUSTNESS TEST ?

FIGURE 3

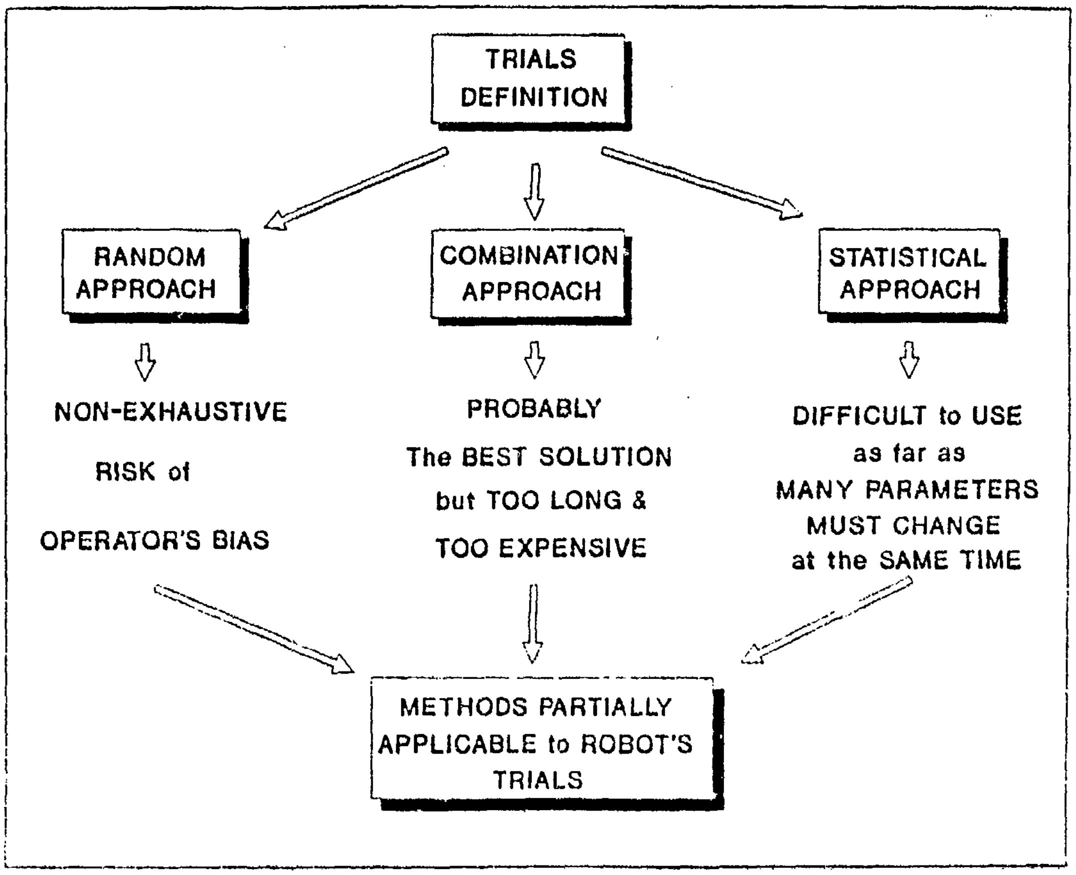
TRIALS DEFINITION
RANDOM APPROACH
COMBINATION APPROACH
STATISTICAL APPROACH
NON-EXHAUSTIVE
RISK of
OPERATOR'S BIAS
PROBABLY
The BEST SOLUTION
but TOO LONG &
TOO EXPENSIVE
DIFFICULT to USE
as far as
MANY PARAMETERS
MUST CHANGE
at the SAME TIME
METHODS PARTIALLY APPLICABLE to ROBOT'S TRIALS

FIGURE 4

AI and future techniques

AI techniques are more and more introduced to achieve appropriate "intelligence" in a robot. The actual human intelligence can be approached by a three-part synthesis of symbolic process, connectionist process and genetic algorithms (fig 5).

In the olden time, the classical feature of a system was based on deterministic algorithms. AI, or symbolic process, knowledge based system, can replicate human expertise within narrow domains. But this approach is a human-related process, subject to a human bias and human ability to foresee the environment that the robot will encounter. Moreover, expert system are often non-deterministic in time.

Connectionist process, implemented in neural networks, could be suited for bug's intelligence. Actual works on such technology is in progress. The results may be non deterministic if an imperfect, or incomplete, learning is made.

Genetic algorithm is a very promising technique. It is based on self-modifying algorithm with a feed-back mechanism.

All these techniques seem to be the future of intelligent robot, allowing it to learn from and adapt to uncertain and changing environments. But integration and trials are quite more complicated as far as it costs a lot to test a robot on a proving ground, and it costs much more to test a system with an unpredictable answer to its environment (fig 6).

SIMULATION of TRIALS

A trial specification aid tool may partly solve the problem raised. This approach consists in modelizing robot functions and modelizing the environment together with protagonists and factors present therein (fig 7).

Complete modelization includes simulation of robot mobility, of reception sensors and associated processing and finally, simulation of the terrain and elements on the terrain, wether fixed, pseudo-mobile and mobile. The knowned behavior of these objects, or actors, must be included in the simulation.

SIMULATION of the ROBOT

The mobility function may be simulated by a dynamic vehicle model taking into account the mechanical characteristics of the vehicle. The navigation and localization function may also be simulated. But the most complex is the simulation of the perception.

Fig. 8 show how could be built the simulation for perception. It is of course the most complex simulation, and it can be achieved in three different ways:

* by direct use of operational algorithms on a real image. This solution, theorically the most accurate, has the main disadvantage of generation of an image as close as possible to the robot's environment.

* by considering that most image processing, at a low pre-processing level, is based on simple algorithm (SOEBEL filter by example). A synthetic image may be built

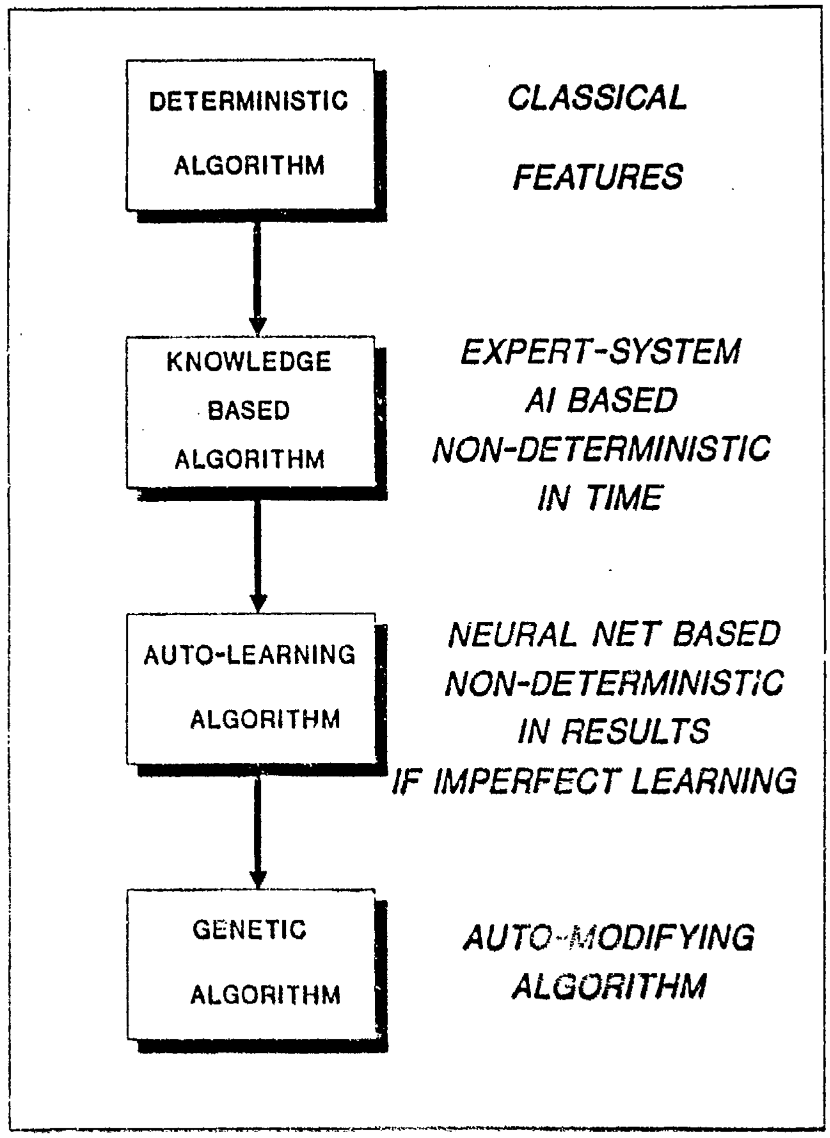
DETERMINISTIC ALGORITHM
CLASSICAL FEATURES
KNOWLEDGE BASED ALGORITHM
EXPERT-SYSTEM AI BASED NON-DETERMINISTIC IN TIME
AUTO-LEARNING ALGORITHM
NEURAL NET BASED NON-DETERMINISTIC IN RESULTS IF IMPERFECT LEARNING
GENETIC ALGORITHM
AUTO-MODIFYING ALGORITHM

FIGURE 5

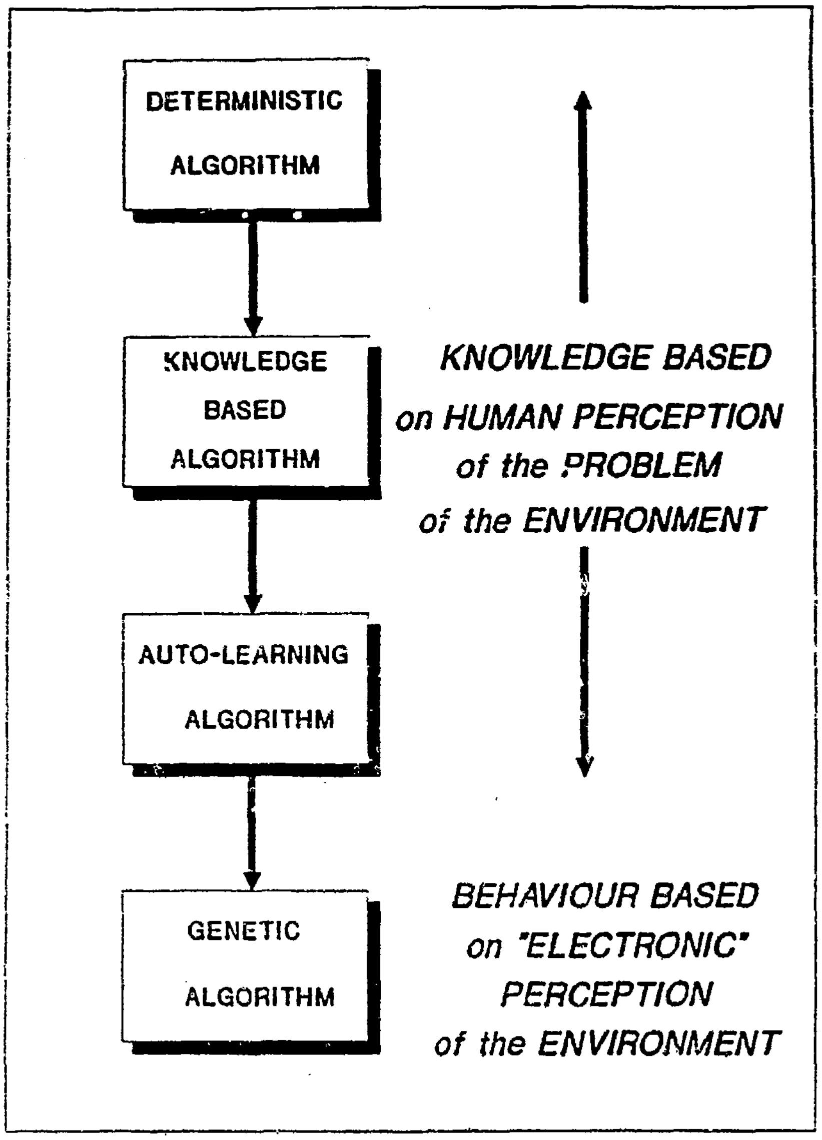
DETERMINISTIC ALGORITHM
KNOWLEDGE BASED ALGORITHM
AUTO-LEARNING ALGORITHM
GENETIC ALGORITHM
KNOWLEDGE BASED
on HUMAN PERCEPTION
of the PROBLEM
of the ENVIRONMENT
BEHAVIOUR BASED
on "ELECTRONIC"
PERCEPTION
of the ENVIRONMENT

FIGURE 6

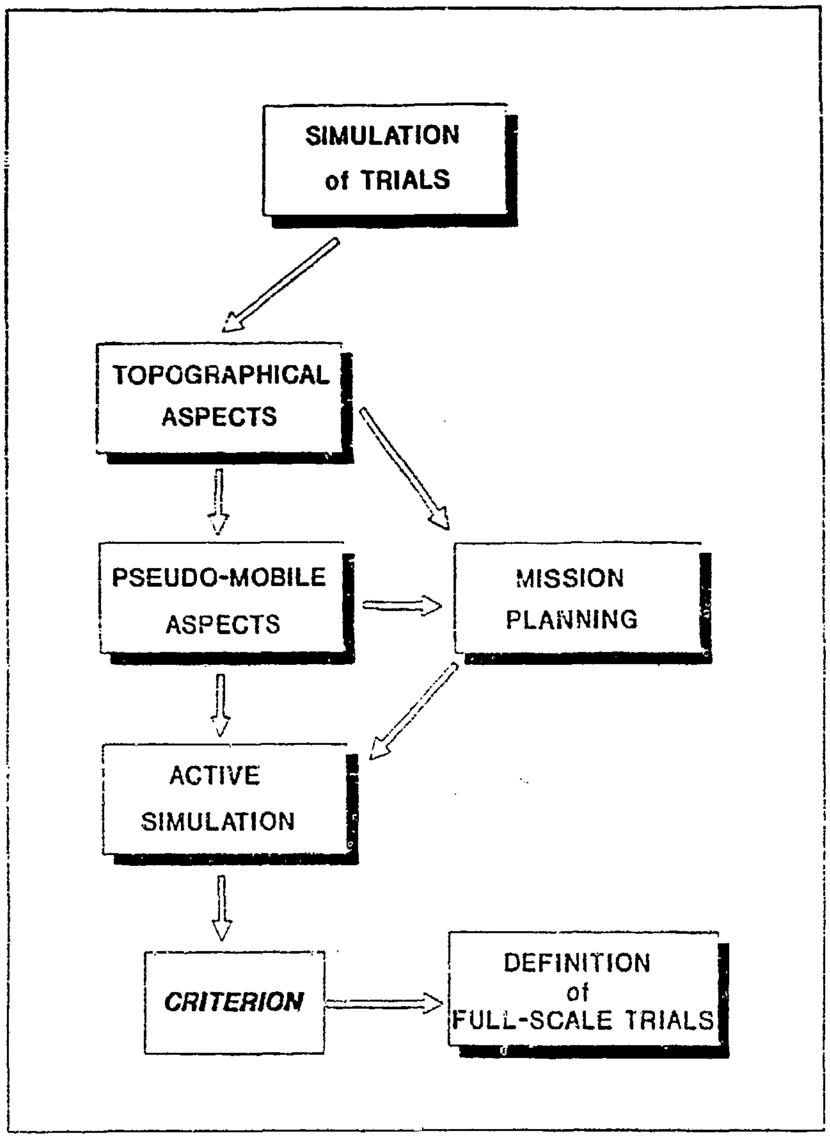
SIMULATION of TRIALS
TOPOGRAPHICAL ASPECTS
PSEUDO-MOBILE ASPECTS
MISSION PLANNING
ACTIVE SIMULATION
CRITERION
DEFINITION of FULL-SCALE TRIALS

FIGURE 7

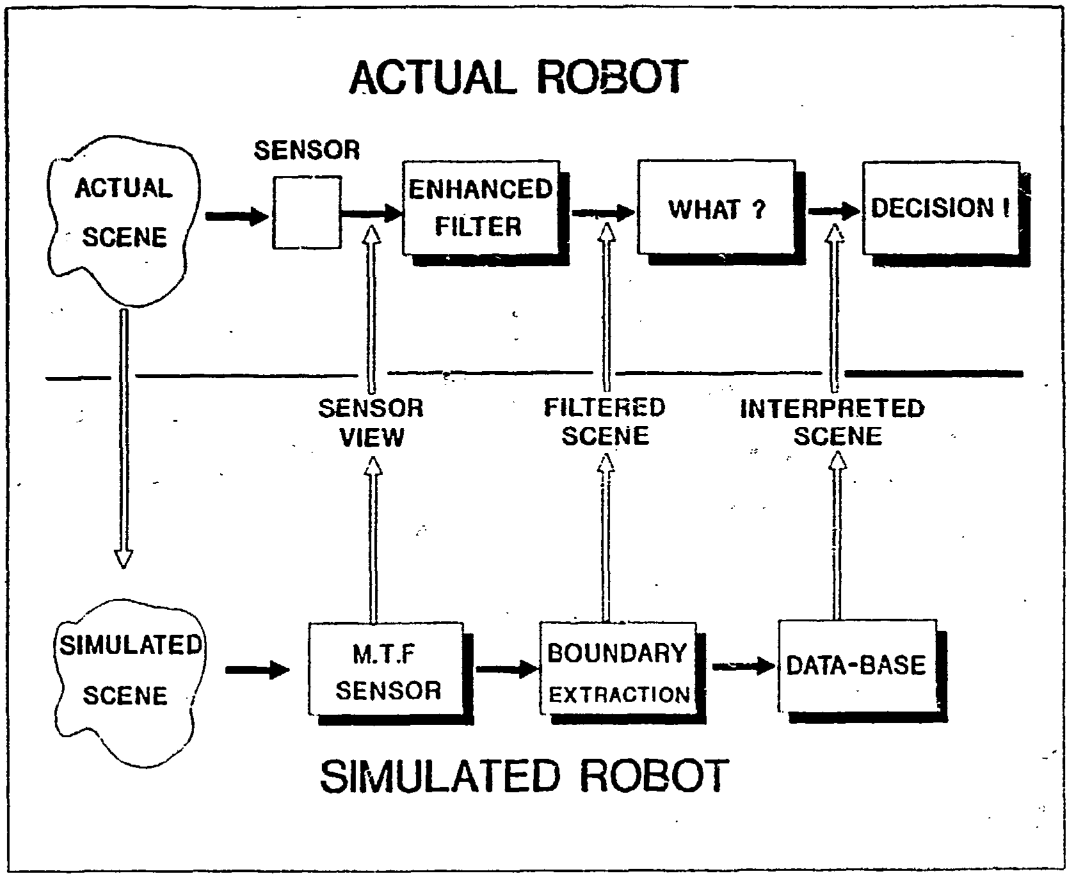
ACTUAL ROBOT
SENSOR
ACTUAL SCENE
ENHANCED FILTER
WHAT ?
DECISION !
SENSOR VIEW
FILTERED SCENE
INTERPRETED SCENE
SIMULATED SCENE
M.T.F SENSOR
BOUNDARY EXTRACTION
DATA-BASE
SIMULATED ROBOT

FIGURE 8

identical to a filtered image thereby allowing the application of processing and interpretation algorithm.

* by indicating to the robot how it could or should perceive and interpret the various objects in the scene. Of course, this last solution is less costly in calculation time, but can generate an artefact.

The robot could learn the way the operator detect the objects by using a neural network.

Fig 9 and fig 10 shows the organization of terrain simulation.

CONCLUSION

Simulation of the trials to be performed in order to qualify mobile robots does not eliminate the basic testing of each function. New techniques, connectionist and genetic algorithms, make the system far more difficult to test and can generate non-deterministic features. However, the robustness of the robot must be qualified and quantified. This a new challenge in integration and test process.

1 ROBUSTNESS for AUTONOMOUS VEHICLES, Robert FINKELSTEIN, AUVS, Spring'90.

2 ROBOT TRIALS: an approach to simulation by object langage. Dr C.FARGEON, J.Ph QUIN, IROS 90.

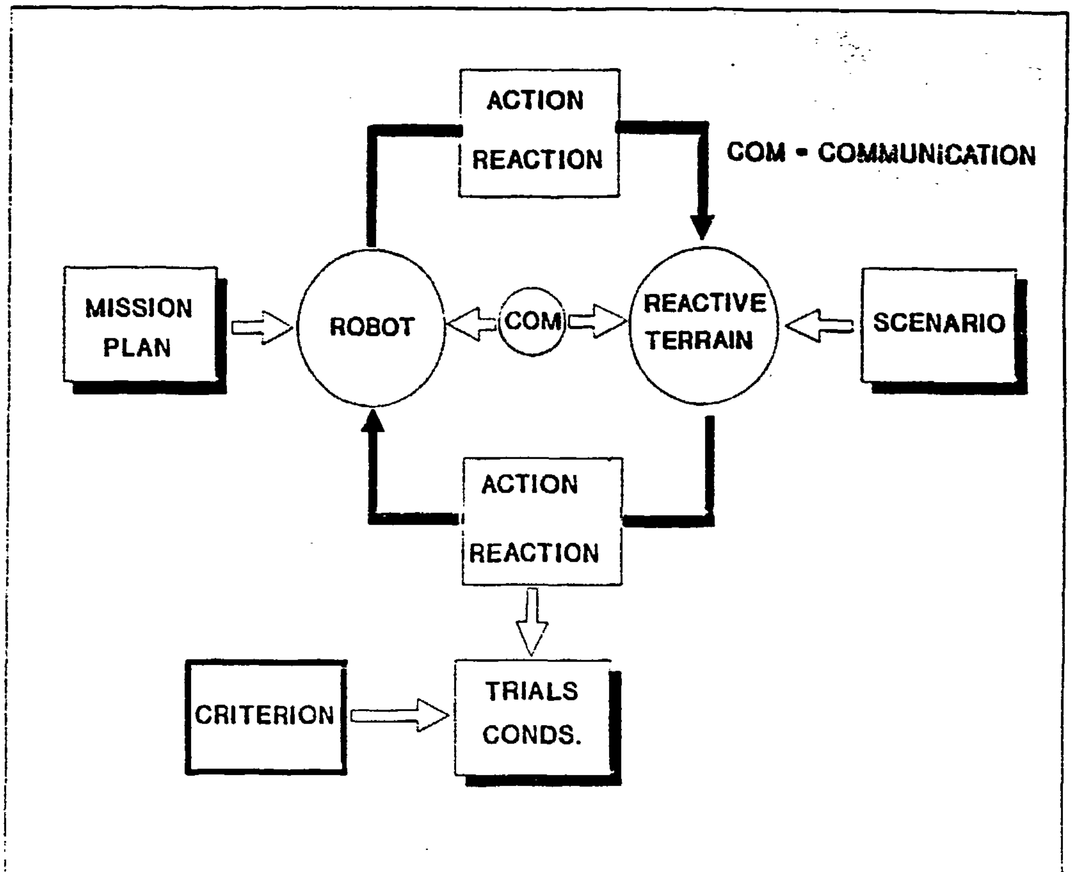
ACTION
REACTION
COM = COMMUNICATION
MISSION PLAN
ROBOT
COM
REACTIVE TERRAIN
SCENARIO
ACTION
REACTION
CRITERION
TRIALS CONDS.

FIGURE 9

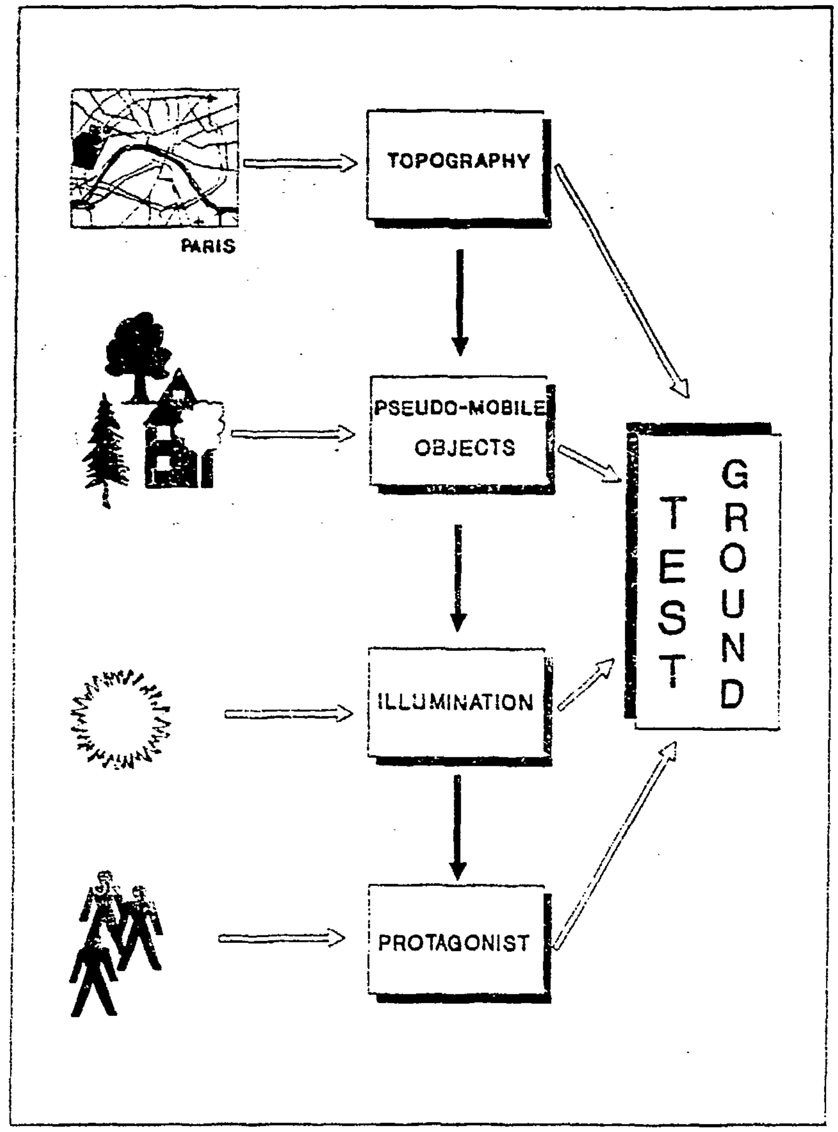
PARIS
TOPOGRAPHY
PSEUDO-MOBILE OBJECTS
ILLUMINATION
PROTAGONIST
TEST GROUND

FIGURE 10

C8

REPORT DOCUMENTATION PAGE

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14. Abstract:

Military Telerobotic Systems for complex missions will be Human-Machine-Systems for the next decades. As human performance is practically defined, system performance can only be increased by adapting technical components to the human. Research at the Research Institute for Human Engineering (FAT) includes activities in the field of telerobotics. The activities are divided into phases. The first phase is the Experimental Robot System for Human Engineering Research in Land Operated Vehicles (EROS). The EROS test facility including technical equipment and aspects of vehicle guidance is described. Also given is a systematic approach for a Human-Machine-Interface for robot control. Another project phase is the Simulation of Robot Systems (SIMROS). The experimental program includes driving tasks using monoscopic versus stereoscopic viewing systems with or without overlay computer graphics. Selected results are described.

Experimental Robot System for Human Engineering Research in Land Operated Vehicles

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1. INTRODUCTION

Military Telerobotic Systems for complex missions will be Human-Machine-Systems at least for the next decades. These "robots" will be semiautonomous and have to be coupled to the human operator (NATO, DRG, Panel 1 Study on "Robotics in the Battlefield", 1985, Study on "Robotic for the Federal Armed Forces", Research Establishment for Applied Sciences FGAN, Bonn, Germany, 1986, and Dornier Study on a "Military Robotics Programme", 1987).

Increasing overall system performance of military Human-Machine-Systems is only possible by adapting technical components to humans (Human Engineering). This basic principle must be part of the early phase of any weapon development. Human Performance is practically defined. Telepresence in military robotics systems consisting of control station, data link, and the robot vehicle is affected by the ease of interaction in a "virtual workspace". Information requested by the control station operator, his cognitive support by expert systems as well as the design of the interaction between distributed decision levels of robot/control stations are human engineering topics that are decisive to system performance. It becomes increasingly important when the data link bandwidth between robot and control station is reduced for other military reasons.

The Research Institute for Human Engineering (FAT), Bonn, Germany, is a research institute of the German MoD. It is specialised in evaluation and design of military Human-Machine-Systems and responsible for research of the methodology of human engineering evaluation of military systems. FAT has 20 years experience in the simulation of Human-Machine-Systems. Laboratory experiments in simulators using soldiers as subjects are performed under controlled experimental conditions. The conditions can be exactly reproduced and render results that are suitable for statistical treatment. Those laboratory experiments are most suitable for parametric studies at low cost. The experiments often lead to the detection of critical system elements which limit system performance. Another human engineering issue is a suitable function allocation between man and machine as well as the development of quantitative methods for evaluation of future system concepts.

2. MILITARY ROBOTIC RESEARCH PROGRAMMES IN GERMANY

The FAT research in Human-Machine-Systems includes activities in the field of telerobotics.All research activities are focussing on land robots. These robots are more complex in comparison to air/sea systems because they operate in a complex environment. Obstacles and topographics require friend/foe detection and tactical decisions in very limited time. The FAT research activities are divided into four phases (Figure 1). The first phase is the EROS phase. EROS is a laboratory test site for an Experimental Robot System. EROS is used to assess system components that limit performance in a robot system consisting of a robot vehicle in a test environment and an operator in a control station. It is designed to measure system response, compare control concepts, search for performance bottle necks, define ergonomic constraints, and serve as a test bed for a wide variety of robotic subsystems.

System simulation is a parallel and simultaneous approach to the development of the hardware system. Simulation models of both the robot and the experimental environment are developed as part of the SIMROS programme for parameter studies with a setup equivalent to the hardware. SIMROS also uses different system components than those at hand in hardware. System performance of different technical solutions can thus be studied, including an experimental situation consisting of a human operator at a control station managing both the hardware robot and a simulated robot to tackle problems of distributed decision-making in distributed systems.

Two more experimental project phases are planned. The NAVROS approach includes expert system approaches for shared decision making in a cooperative environment. Theoretical and experimental studies are planned for a system capable of semiautonomous and autonomous phases of operation under hierarchical operator management. The TAKROS phase includes tactical options influencing the robot operation in a hostile environment.

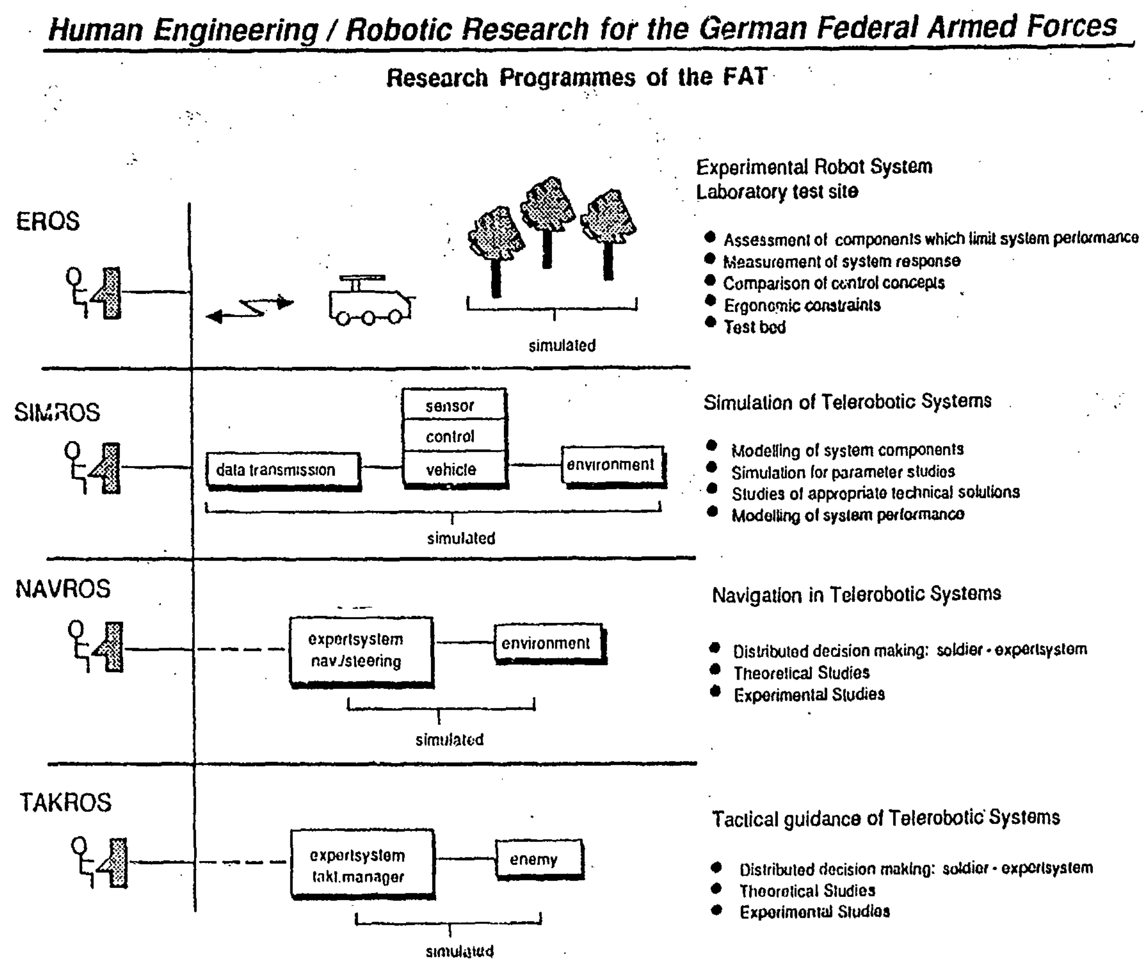

Figure 1: Research Programmes of the FAT

3. EROS TEST FACILITY

The EROS project focusses on ergonomic aspects of the Human-Machine-Interface while guiding a telerobotic vehicle in a test environment. It is based on a vehicle that operates in a factory hall. The factory hall measures approximately 18 x 14 m. It is equipped with cylindric obstacles of about 0.50 m diameter and 1.50 m height. Also included are facilities for data transmission to and from the experimental vehicle and a TV Gigahertz link. The hall is equipped with a number of safety systems to insure safe operation of the vehicle. The vehicle itself (Figure 2) is a four wheel platform of less than 2 m in length. It is 1.30 m wide and about 1.60 m high. The vehicle has two electric motors that power the two back wheels. It has a pair of front wheels which are steerable. The maximum speed is about 2.3m/s.

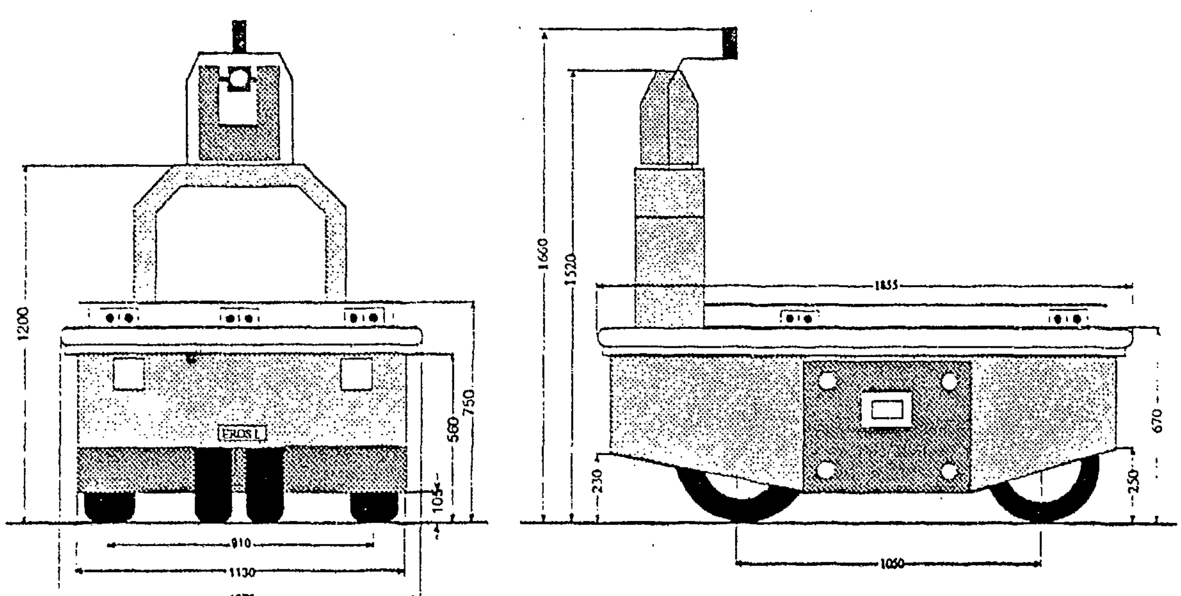

Figure 2: EROS test vehicle

The EROS-vehicle is equipped with five cameras. One of the cameras is mounted in the rear of the car on a pan and tilt head. This pan and tilt head looks mainly straight ahead on the driving path. Two cameras are mounted in the body. Through mirrors they support views of the left and right vehicle contours. These cameras are useful for manoeuvering tasks such as operating through a narrow lane. Two more cameras look backwards respectively directly in front of the car. All of the cameras can be switched to the TV link as raw videos or in a mixed version as described later.

Eight ultrasonic sensors (Figure 3) are mounted. Three of them look forward, two look left and two right. The other sensor is mounted looking backwards. The sensors have a measuring range of 0.3 to 10.7 m. The resolution is 1% over the whole range. Each of the sensors has an angular range of 40°. The ultrasonic devices are safety devices that automatically reduce vehicle speed or stop it if the distance between obstacles and the vehicle decrease beyond defined limits. An on board computer is responsible for data exchange with the control station, visual system and on board equipment.

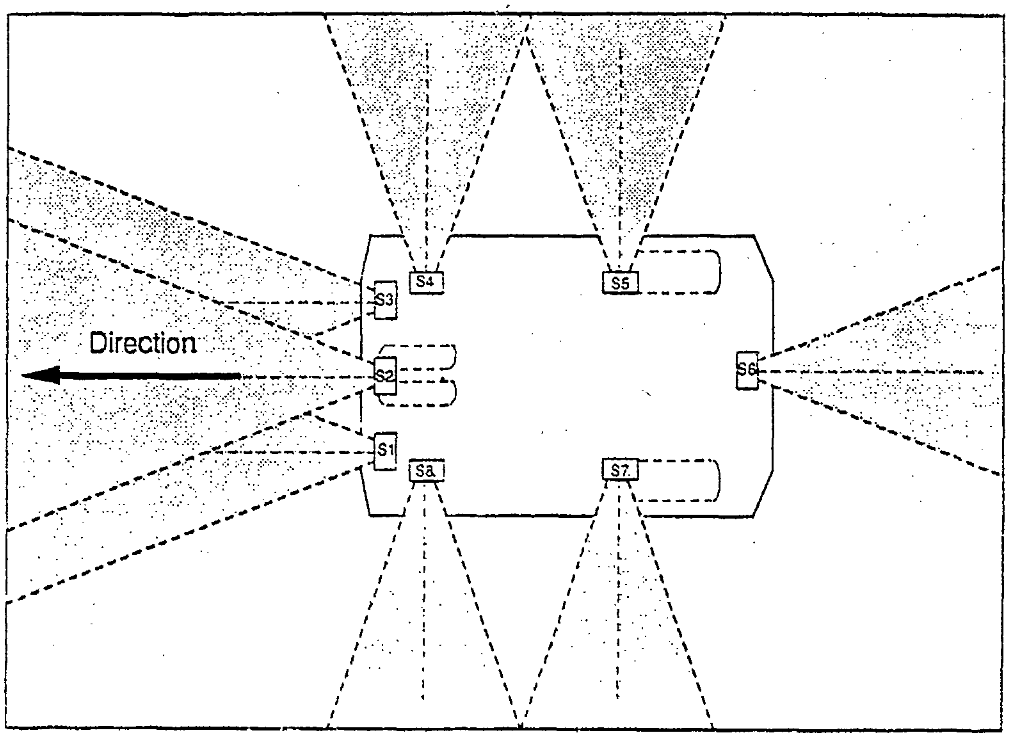

Figure 3 : Ultrasonic system on the EROS vehicle

The control console has a main TV monitor to display camera information transmitted from the vehicle. This TV picture has a number of mixing features and overlay graphics that are described later. Additional monitors display process control information in switch selectable full graphics format.

Inputs to the vehicle are through a variety of control devices which include controlsticks and an optoelectronic sensor ball. Also supplied are virtual keyboards and function keyboards. The experimenter uses TV cameras which are mounted under the ceiling and on the walls of the EROS hall for safety purposes. He also uses a multiwindow workstation to control the operation and the experiments.

4. VEHICLE GUIDANCE

The EROS vehicle is guided through a wireless link from the control station. Primary control is through one of the before mentioned control devices with visual feedback through the TV channel using the TV monitor (Figure 4). The TV picture can be presented either in color or in black and white. Standard viewing uses the main camera on the pan and tilt head. Height from the ground is 1.40 m with the camera looking forward. Camera deflection is 25° from the horizontal. Switch selectable are views through the backward looking camera and a camera which is positioned in the front of the chassis.

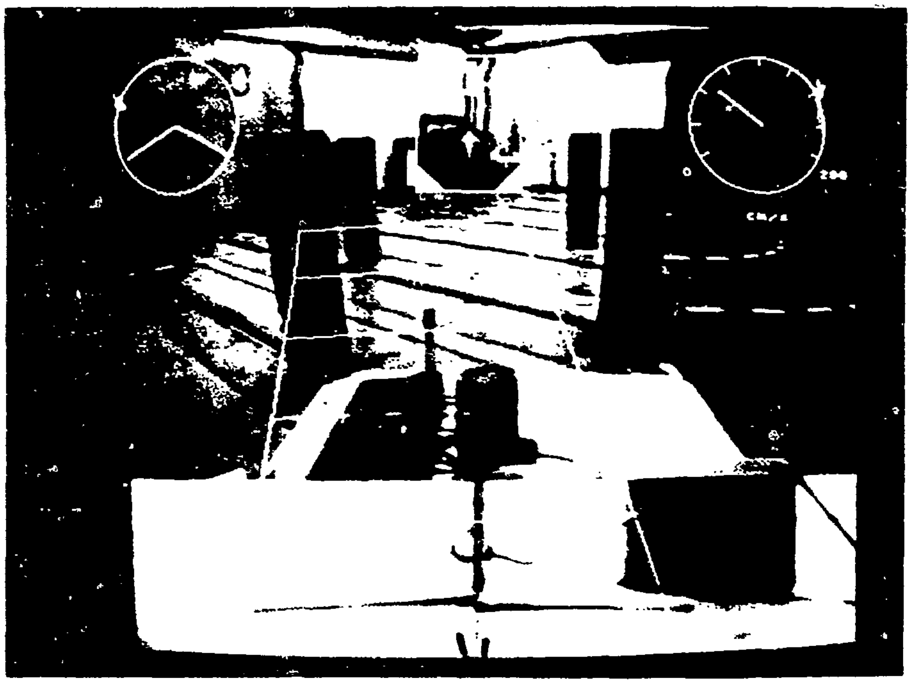

Figure 4: EROS main display

Additionally, two views along the left and right vehicle contours can be mixed into the lower third part of the TV picture. As field of view limitations showed degradation in driving performance, a wide angle lens of 6.5 mm with an angle of ~ 90° was selected. Driving while panning the camera is very difficult because drivers easily lose orientation. This state of disorientation can be alleviated by azimuthal camera movements linked with the deflections of the steered pair of wheels. Thus a "look into the curve" was realized which showed better results in precisely following a curved path.

Another increase of performance was achieved by overlaying graphical information in the video display (Figure 4). This graphical information is iconic respectively contains simple graphic features that do not overload the visual scene. In the upper third of the display three overlays were positioned. The left overlay symbolizes a steering wheel much like one in a car. This steering wheel represents the steering inputs as commanded by the controlstick x-axis deflection, transmitted and received as true steering data from the vehicle. The symbol of the steering indicator is color coded to serving the operator as an indication of safe driving and steering.

The symbol in the upper right area represents a speedometer. Its scaling is in cm/sec. The needle is displayed in green color during normal operation. Its color changes to yellow if the vehicle control processor calculates an unsafe speed regarding the curve diameter being operated upon. During backing up the vehicle and still displaying the front view the needle is switched to red thus indicating a mismatch between display and operation.

In the middle position is a symbolic top view of the vehicle. The four triangles at the vehicle corners can warn that that corner is too near an obstacle or a wall of the EROS test facility hall. The triangles are not displayed under normal conditions. They are displayed in yellow color if a distance of 2 m is reached. Below 1 m they change to red color. The distance measurement is achieved by the ultrasonic devices (Figure 3). If the operator does not command a change of directions or a full stop the vehicle is automatically stopped by a hardware security system at a preprogrammable distance from the closest obstacle.

The three rectangles at the lower left and right sides of the vehicle symbol and in the upper center (symbol for the wheels) represent the state of drives and steering system. Green color indicates normal operation of the on board systems, red is a warning due to malfunction. A malfunction in these primary driving subsystems causes the vehicle to stop. For further information the operator uses the Process Monitoring graphics System (PROMO) on the side monitor.

The arrow in the vehicle symbol symbolizes the rotation of the main TV camera to the left or right with respect to the longitudinal axis of the vehicle.

The overlay in the central part of the display is a channel display. It is calculated and projected in the visual scene showing the path being travelled for the next four seconds assuming constant speed and steering deflection. For steady cruise the channel display is static. In the case of steering into a curved path or accelerating the channel display follows in real time. It is a help during normal operating conditions but tends to overload the picture during manoeuvers in order to maintain a curved path at high speed accurately. Further experiments will be conducted with a display algorithm using a low path filter.

Overlay information of a map display was less promising because of the completely different viewpoints. "Inside out" and "outside in" views cannot be mixed due to their incompatibility. A plan view is thus presented on the side monitor upon request. It is part of the PROMO System that helps the operator to display any system parameters required in graphical forms.

This PROMO System which uses two side monitors is a very efficient tool for operator-robot interaction. Besides map information a complete set of both graphics and alphanumeric status information can be called up. Moreover results of an expert system based path planner are displayed. The system stores experimental data, retrieves, and displays processed data. Mode selections and presettings are entered via a menu oriented virtual keyboard on the screen. Figure 5 shows a PROMO display of ultrasonic data as measured by the vehicle sonar subsystem. PROMO is a multiwindow display system. For this reason the ultrasonic display can be presented together with speed and status information, a digitally generated ground map, and other selected system data.

A variety of controls is available for vehicle operation. All controls are used for driving and to input information through the Human-Computer-Interface. A steering wheel is unsuitable for computer inputs and was therefore disbanded. Standard control device is a two degree of freedom finger operated controlstick. This controlstick is built into a small console which can be positioned by the operator at his work place and which also contains function switches for vehicle and display control. The controlstick is a spring centered displacement controlstick. The x-axis deflection is used to command right or left steering wheel deflections, the y-axis deflections are for speed

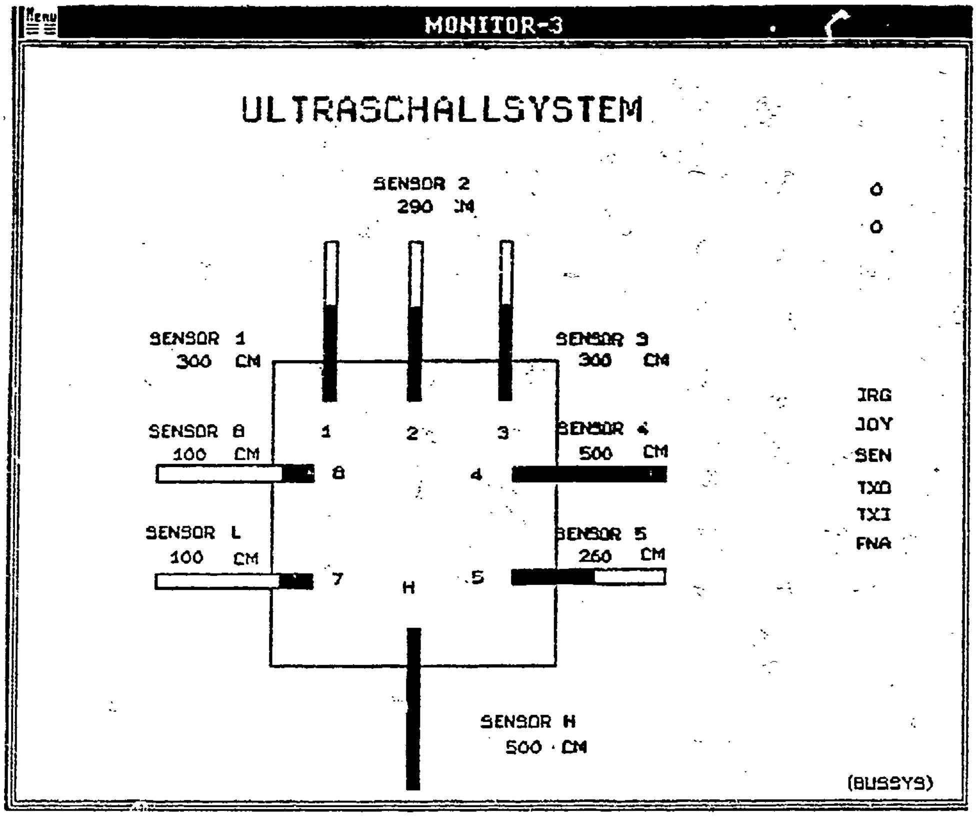

Figure 5: PROMO sensor display window

control in forward or reverse directions. Another controlstick with similar characteristics is available to control the camera pan and tilt head. Right and left deflections of that controlstick command pan movements of - 175° to + 175° to the camera positioning device. Y-axis deflections control the camera elevation. Both controlsticks function as a positioning zero-order system. As such the camera is always moved back to the normal position when the controlstick is undeflected. This method requires a precise determination of the normal position with respect to the driving task. Normal position for the experimental setup is a forward looking camera attitude with a deflection of 10°. With the optical lens used the TV picture is so adjusted that the hall floor limits are just 20% under the upper end of the TV picture.

Alternatively two controlsticks are used that are installed in the operator's aircraft type seat. Using these operating conditions the operator's forearms are placed on armrests. The controlsticks are in reach of the hands and fingers and can be deflected with hardly any forearm movement using hand and finger movements. The third control device available is a 6-degree-of freedom sensor ball which is also used in 3D manipulation of computer graphics objects in CAD systems. This device proved to be less acceptable mainly due to the fact that it was a force sensing device with practically no deflection. Driving quality with it was poor no matter which of the degrees of freedom was used for steering and acceleration.

5. SIMROS SIMULATION OF ROBOT SYSTEMS

The complexity of robot systems requires detailed analysis of system design criteria, the comparison of system concepts, and the detection of human engineering bottlenecks. This is especially true for land robots in a complex environment. The development of prototype systems with the required specifications and even a whole variety of hardware platforms is time consuming and not cost effective. The simulation of such systems is therefore required. Simulator studies in the laboratory using human subjects can be conducted under defined experimental condisions. These conditions can be exactly reproduced and evaluated using statistical methods.

In the SIMROS project phase a simulation environment is being developed which supports the experimental analysis of interaction between the operator and simulated technical components in a very early design phase. Such simulation approaches are very coarse at the present stage and support parameter studies. Further program phases will analyse task structures, function allocation between robot and control station, and define appropriate process and mission display concepts.

Parallel to the development of the EROS vehicle a real time simulation was programmed. The robot simulation covers a vehicle of similar kinematic and dynamic properties as the real car. This model can be operated using the EROS control station. The path of the simulated vehicle can be monitored on a digital map display much like the procedure using a physical vehicle. As such, critical mission phases are tested using the simulation before executing the phases using real equipment. The EROS model can also be used to investigate the system performance concentrating two missions in a single operator control station.

A simulated robot view was also developed though it is not yet in real time (Figure 6). The path of the simulated vehicle can be monitored on the map display. The path planning and navigator systems that automatically steer the vehicle on a preplanned path can also work on the simulated vehicle.

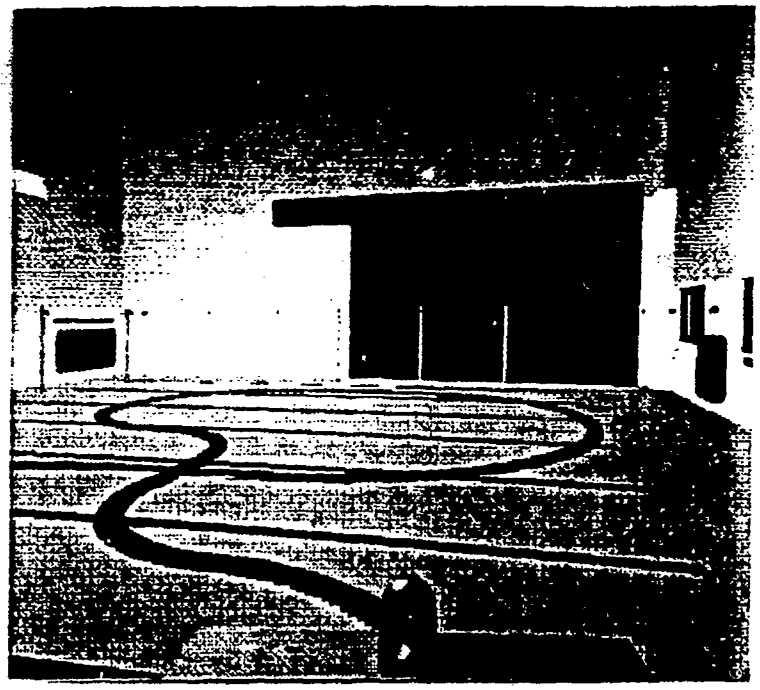

Figure 6: Simulated view from a simulated robot vehicle

6. HUMAN-MACHINE-INTERFACE FOR ROBOT CONTROL

The functions available at the robot control station and the information processing in the robot itself were structured into a systematic approach for system information input and system information output. The system input is shown in a block diagram in Figure 7. It contains blocks of functions with decreasing hierarchy from the left to the right block in the Figure. In this hierarchy the obstacle acquisition system ROSE (**R**econnaissance of **O**bstacles and **S**urveillance in unknown **E**nvironments) provides the highest degree of autonomy. The teleoperational mode is the function with the lowest autonomy. Outputs of the ROSE system is the obstacle map in a former unknown terrain. Its data are used to plan paths on a strategic level. The tactical planner finds optimal paths in the terrain as defined by the strategic planner. The navigator uses the waypoint list output by the tactical planner taking the dynamic obstacle avoidance system into account. This systematic approach supports automatic and manual operation as well as any autonomy levels in between.

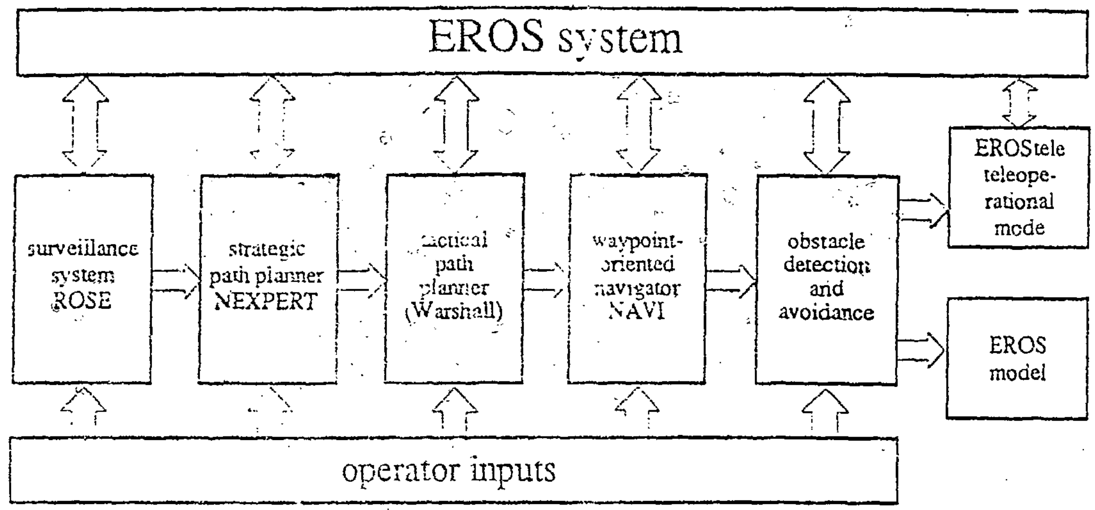

Figure 7: EROS system input

The corresponding structure for system output is shown in Figure 8.

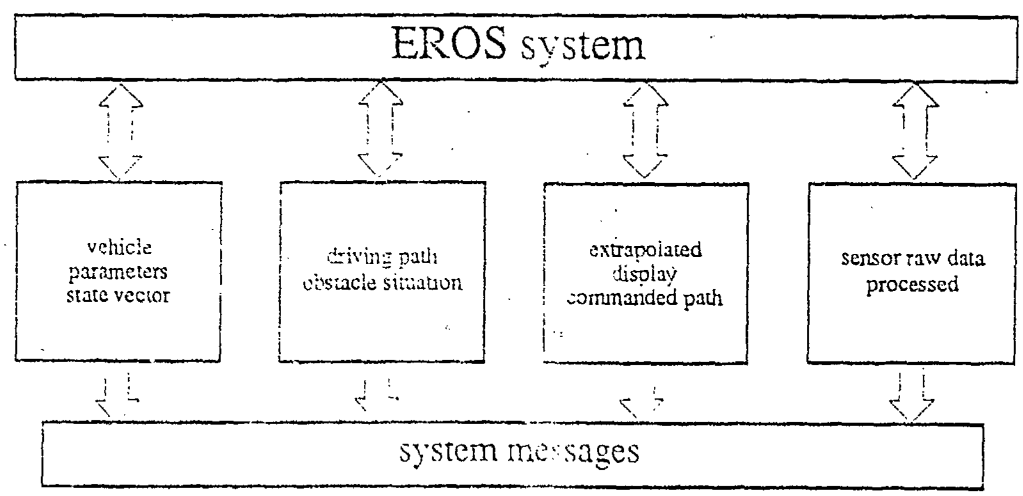

Figure 8: EROS system output

The function blocks define a modular approach of system functions that are accessible through the robot control station. Inner and outer system variables are displayed. The inner variables include vehicle parameters as well as the state vector of the vehicle. Outer variables are mission data, the obstacle overview, extrapolated path data and fused sensor informations.

The arrows indicate that the console operator can access any data in an interactive approach.

7. SELECTED EXPERIMENTS USING A STEREO VIEWING SYSTEM

Many driving experiments have already been conducted. In one experiment, the influence of a stereo TV system on driving accuracy was measured. The operators had to approach a part of the test field in the teleoperation mode that was unviable because of obstacles. They had to manoeuvre as closely as possible towards the obstacles without touching them. 50% of the subjects used a mono display first and later switched to stereo. The others started with the stereo system and switched to the mono system in the second part of the experiment. The first and second path of each of the driving tours were evaluated to form a separate result including standard deviation. Thus learning effects can be easily seen. Figure 9 shows selected results.

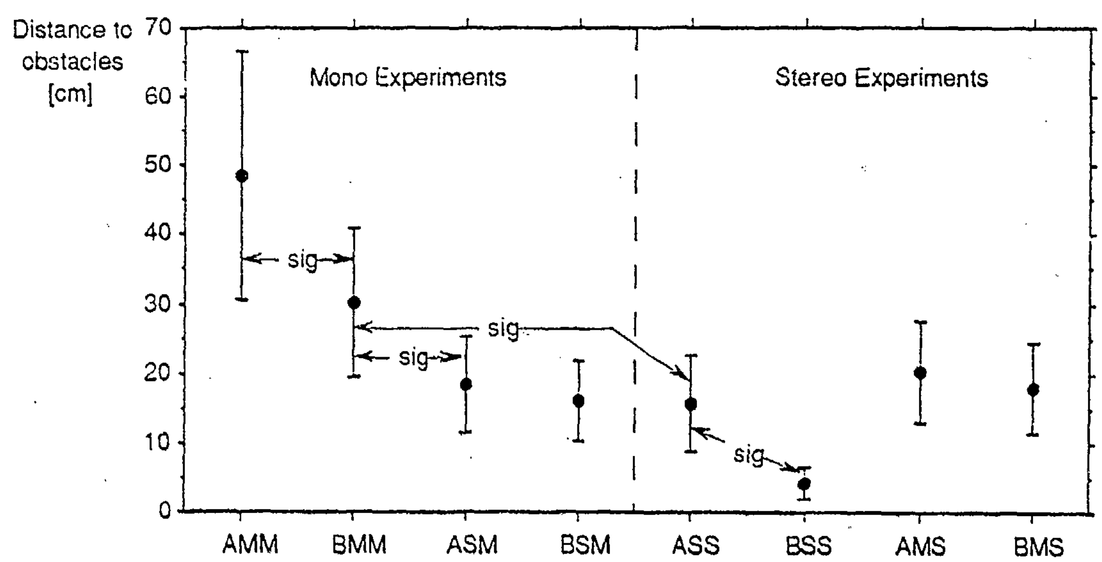

Figure 9: Experimental results for a mono/stereo driving task

A : First trial group of experimental condition
B : Second trial group of experimental condition
.M. : Group using mono display first
.S. : Group using stereo display first
..M : Mono experiments
..S : Stereo experiments

The result marked AMM shows the final distance to the obstacles, as achieved by subjects during their first trials using the mono display. These subjects were unfamiliar with the stereo system. The result BMM shows the next group of trials of the same subjects, it also shows a significantly better target approach distance compared to AMM. The significant increase in performance is due to learning. ASM and BSM relate to the trials of subjects who used the stereo system first. Their performance was significantly better but showed no learning effect.

The right part of Figure 9 shows the results of stereo experiments. Again the results are splitted into first (A) and last half of the trials (B). ASS and BSS refer to subjects who used the stereo system first. These data show a significant learning effect again. AMS and BMS indicate that subjects, who used the mono display first, performed worse compared to operators with stereo experience. They show no further learning effects.

Consequently stereo vision renders better results which is probably due to the development of a more precise mental model of the environment.

8. FUTURE PROJECT WORK

Ongoing experiments defining parameters influencing teleoperation of a vehicle will be completed. These experiments include investigation about the performance of operators using a single versus multiple controls for primary driving functions as well as mission oriented control tasks. Displays formats of overlay graphics mixed on a TV channel as transmitted from the mobile system will be evaluated in an experimental series. Ergonomic constraints of semiautonomous operation including the path planner and navigator will be studied. Problems of function allocation between the operator and the robot and how to define tasks for the robot are decisive for system acceptance and throughput and will be subject to human engineering research.

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14. Abstract:
To guide development of a mobility sensor for an unmanned ground vehicle (UGV), a field testing program was established in which alternate mobility viewing system options were objectively compared with regard to their impact on driving under controlled field testing conditions. This report describes the procedures and specific tasks used in making comparisons across the 4 viewing system options that were compared: 1) direct view, 2) direct view 40° by 30°, 3) monoscopic helmet-mounted display (HMD), and 4) stereoscopic HMD. Testing was conducted with two groups of drivers; 1) an "experienced" group who were well practiced on courses run and tested with each of four alternate viewing system options, and 2) an "inexperienced" group who were unfamiliar with courses and tested with a single mobility sensor system option on a one-time basis. Specific results in terms of relative driving efficiencies on 6 driving courses are reported and discussed with respect to their general implications for design of the man-machine interface for safe and efficient driving of UGVs in the teleoperated mode.

OBJECTIVE ASSESSMENTS OF MOBILITY WITH AN EARLY UNMANNED GROUND VEHICLE (UGV) PROTOTYPE VIEWING SYSTEM

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1.0 ABSTRACT

Over the past decade, the Naval Ocean Systems Center's Hawaii Laboratory has engaged in a program to develop unmanned ground vehicles (UGVs) that have been delivered to the United States Marine Corps for field assessments of the applicability and effectiveness of such vehicles for reconnaissance and combat in tactical environments. An essential component of these unmanned ground vehicles is a visual sensor suite and helmet-mounted display that allows an operator to view the remote scene in a familiar, natural fashion well enough to drive the UGV safely and reliably across unfamiliar off-road terrain. To guide the development of this mobility sensor system, a field testing program was established in which alternate mobility viewing system options were objectively compared with regard to their impact on driving under controlled testing conditions.

This report describes the procedures and specific tasks used in making comparisons across the various viewing system options tested. The experiment reported here was run with two groups of drivers; 1) well-practiced civilian personnel who were tested with each of four alternate viewing system options, and 2) unpracticed, enlisted Marine personnel who volunteered to be tested with a single mobility sensor system option on a one-time basis. Specific results in terms of relative driving efficiencies on six driving are reported and discussed with respect to their general implications for design of the man-machine interface for driving remotely operated ground vehicles.

2.0 BACKGROUND

The Ground-Air Telerobotics (GATERS) program was initiated in October 1985 to develop teleoperated vehicle systems for military applications. Three TeleOperated Vehicle (TOV) systems were delivered to the U.S. Marine Corps for field assessments of their operational value in tactical combat environments. Observations derived from initial field assessments of TeleOperated Vehicle (TOV) performance and their implications for future UGV developments are the topic of another paper in this volume of proceedings [1]. A TOV system consists of a remotely-operated, High Mobility Multi-purpose Wheeled Vehicle (HMMWV), a datalink, and a control interface for the human operator. Several alternative mission modules have been developed for the TOV to support a variety of observation and surveillance missions as well as forward target designation and light weapons engagement. A more detailed description of the TOV system including its control system architecture, fiber optic datalink, mobile control station, and various mission modules is available in a recent report [2]. In this paper, I describe results from a series of controlled vehicle mobility studies conducted in late1986 - early 1987 at an outdoor test course with the first operational prototype of the TOV.

2.1 Viewing Options.

In the experimentation described here, the effects of four different viewing options on driving performance were measured and compared. The four viewing options investigated were: 1) unobstructed direct view, 2) direct view with a 40° by 30° field of view, 3) monoscopic helmet-mounted display , and 4) stereoscopic helmet-mounted display Under the first two of these options, drivers viewed test courses directly; that is, they were physically present on the test courses in the vehicle and had a direct line of sight to the vehicle and courses while driving. With the remaining two viewing options, the operators' only view of the vehicle and the test courses was provided indirectly by means of a video system.

More specifically, under the "Direct View" (DV) viewing option, the vehicle operator was physically present in the driver's seat of the HMMWV with a direct, non-restricted, "natural" view of the driving course. This viewing option established a "100% telepresence" performance baseline against which the other three viewing options could be compared. Image resolution, contrast, and color sensitivity were limited only by the visual capabilities of individual drivers. Additionally, the DV option provided "perfect" head motion coupling (i.e., no position errors or motion lags), eye-head coordination, and a "natural" 1:1 spatial correspondence between perceived space and physical space.

Under the "40° by 30° Direct View" (DV 40 x 30) viewing option, the driver's view of the test site was identical in all ways to that of the DV option, except for the fact that his peripheral field of view was restricted. The central 40° by 30° of his normal binocular field was visible. Areas outside this region were occluded and not visible. Thus, the DV 40 x 30 viewing option provided all of the advantages of the DV option, but with a field of view restricted to that available under the two video viewing options described next.

Under the two video view options, the driver was also physically present in the driver's seat of the vehicle while driving it, but his only view of the test course was provided indirectly, by means of a video system. A stereoscopic pair of cameras, attached to the top of his helmet, fed a pair of small helmet-mounted CRTs, each of which was visible to only one of the driver's eyes. Opaque tape was used to prevent direct view of the driver's surroundings. The helmet-mounted display (HMD) used in this experimentation was a Honeywell Integrated Head Aimed Display Sighting System (IHADSS) modified to provide two separate video channels for stereo viewing. The HMD system itself weighed slightly less that 2.25 kg and afforded its wearer a 40° horizontal by 30° vertical, fully overlapped, stereoscopic, monochromatic field of view. A stereoscopic (stereo) pair of cameras was mounted atop the HMD with optical axes separated by 65 mm and symmetrically converged on a point approximately 8 meters ahead of the TOV front bumper. This camera pair, it's mounting plate, and attached cables added approximately 1 Kg to the overall weight burden on the operator's head.

Though resolution and contrast were greatly reduced, and color contrast was absent from the video images, it should be noted that both these video view options did provide the driver with a wealth of sensory information not readily available to an operator controlling a UGV from a remote station. Camera slewing was nearly perfectly matched to the operator's head and upper body motions with only very slight lags and distortions in the displayed imagery induced by the video scanning rate. And, except for the mismatch between visual and vestibular stimulation caused by the lack of 1:1 spatial correspondence in the display [system magnification was measured to be ~.77] ; vestibular, kinesthetic, and vibrational information was generated by the physical movement of the vehicle and driver through the courses. This non-visual sensory information provided the driver with immediate feedback regarding body orientation relative to the vehicle and vehicle dynamics with respect to the various courses run.

Under the monoscopic viewing option ("Mono - HMD"), the video signal output by the right camera was split and fed to both IHADSS displays. This provided the operator with a two-dimensional, "flat" view of the scene, though many visual cues to depth and distance were discernable within the "flat" images provided. [3]

Under the "Stereo - HMD" viewing option, images from the left and right cameras were fed to their corresponding IHADSS display units. This viewing option provided the driver with a more accurate three-dimensional view of the test course and vehicle during testing.

Under all four viewing options, drivers were instructed to maintain their upper bodies in a fixed, upright posture, making scanning motions only with movements of their heads. This was done to make scanning of the scene roughly equivalent to the scanning that would occur under teleoperation with a mechanical pan and tilt head. Since there were no external physical constraints placed on drivers other than a lap belt, slight deviations from the instructed posture were observed. However, large deviations from the instructed posture such as "leaning out" the side of the vehicle to better view obstacles in the path of the vehicle did not occur during data collection.

A true Remote View driving condition was not tested in the initial phase of the TOV mobility testing program reported here. However, more recent studies that are beyond the scope of this report have been conducted and are currently being prepared for public release as a NOSC Technical Publication [4].

2.2 Experimental Drivers

Two groups of drivers participated in the experiments. An "experienced" group, consisted of four civilian personnel (mean age = 43 years) who were licensed HMMWV operators and were well-practiced at driving all of the test courses used in the experiment. Under both Direct View and Direct Drive Video View conditions, these drivers were run through each of the courses a minimum of ten times prior to experimental data collection. A graphical analysis of measures taken during these course familiarization runs suggested that all "experienced" drivers had reached stable levels of performance on all measures taken prior to completion of the familiarization runs. Each of the "experienced" drivers was run under all viewing conditions tested (i.e., DV, DV 40° by 30°, Stereo HMD, Mono HMD).

A second, "inexperienced", group of drivers consisted of 4 detachments of 4 Marines each (mean age = 23 years). Each of these drivers was a licensed HMMWV operator and volunteered to serve as an experimental driver during a single test session. All drivers from both the "experienced" and "inexperienced" groups had normal or corrected-to-normal visual acuity as determined by a standard Armed Forces Vision Tester. Prior to experimental data collection, each of the "inexperienced" operators was driven around the entire set of courses by the data collector and instructed in the specific procedures for each of the 6 courses described in detail below. Immediately prior to testing, "inexperienced" drivers were allowed one practice run through each course under DV conditions. These instructional runs were not necessary with the "experienced" drivers due to their high degree of prior familiarity with the courses. "Inexperienced" drivers were used in order to gain an appreciation for the effects of learning and experience on driving performance under the various viewing conditions tested.

2.3 Driving Courses

Six driving courses were used in an effort to characterize low-speed mobility on a more or less ideal, paved road surface. The six courses used were originally selected on the basis of a factor analysis of 58 measures of low-speed maneuverability [4] conducted at the University of Michigan's Highway Safety Research Institute (HSRI). This battery of tests was developed to provide a cost-effective, reliable, reasonably sensitive and comprehensive metric against which vehicle control options could be systematically assessed and improved. The testing courses, described in detail below, were surveyed and marked off on a level, asphalt covered test area within 1 kilometer of NOSC-Hawaii's Teleoperator Development Center.

Though the general layout of courses used in this paper was described in the HSRI report, some slight modifications to course configurations and procedures were required for testing with TOV. Bright orange 76.2 cm [30 inch] tall traffic pylons were used to mark off all course boundaries. In certain of these traffic pylons, 1.82 meter [6 foot] long, 2.54 cm [1 inch] diameter white rods were inserted to make them visible over the high hood and rear flatbed of the TOV. Order of administration for the 6 courses was identical for all drivers on all days of testing and followed the order in which they are described below. For all courses, verbal instructions were given which emphasized the importance of accurate, error-free driving and de-emphasized the importance of speed.

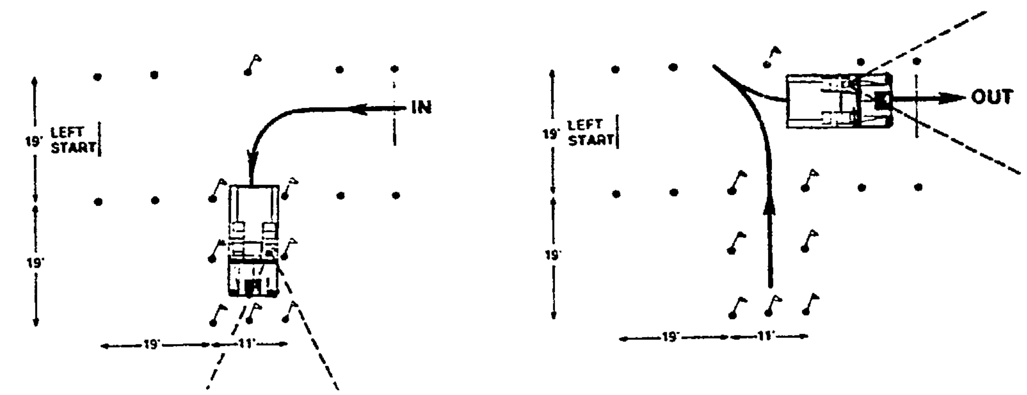
2.3.1 Course 1. Right Angle Turn- IN.

The first course run during each test session, the Right Angle Turn- IN, is diagrammed in the left panel of Figure 1. The course is configured as a 3.35 meter (11 feet) wide right angle parking space connected to a perpendicular 5.8 meter (14 feet) wide access lane. The driver's task was to start at one end of the access lane and make a controlled right-angle turn pulling as far into the parking space as possible without touching any of the cones defining the course or touching/toppling the stop cone centered at the end of the parking space with the front bumper of the vehicle. Runs were scored for elapsed time, number of cones touched or toppled during the maneuver, and accuracy of position relative to the parking space endpoint. The Right Angle Turn-IN was executed a total of 6 times per session, 3 times each from right and left START positions.

FIGURE 1. The Right Angle Turn IN/OUT Course.
Note: Distances are expressed in feet.

Phase 1. Turn IN

Phase 2. Turn OUT



2.3.2 Course 2. Right Angle Turn- OUT.

As the right panel in Figure1 illustrates, starting from the position in which the vehicle rested following the previous Right Angle Turn-IN run, the vehicle was reversed out of the parking space and across the access lane. It was then put into forward gear and driven out of the access lane in the same direction from which it had been driven in. Runs were scored for elapsed time and number of cones touched or toppled during the maneuver. As with the Right Angle Turn-IN procedure, 6 runs were measured per session; 3 from each START position.

2.3.3 Course 3. Figure-8.

The next course required an operator to negotiate a figure-8 pattern through a sparse set of cone gates (see Figure 2). Spacing between cones comprising the gates was widened from the original HSRI specification in order to accommodate the HMMWV turning radius. A single experimental run of the course consisted of three consecutive circuits through the figure-8 pattern. Runs were scored for elapsed time and number of cones touched or toppled. Two runs were measured per session.

FIGURE 2. The Figure-8 Course.

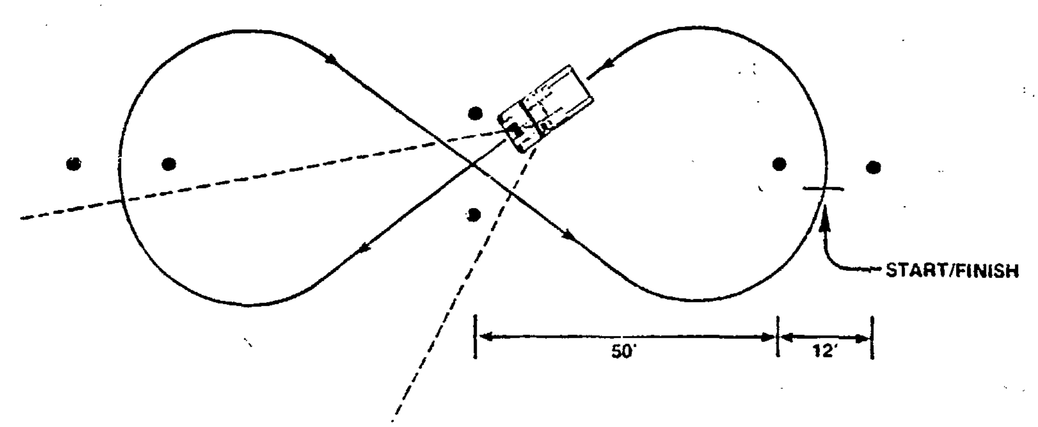
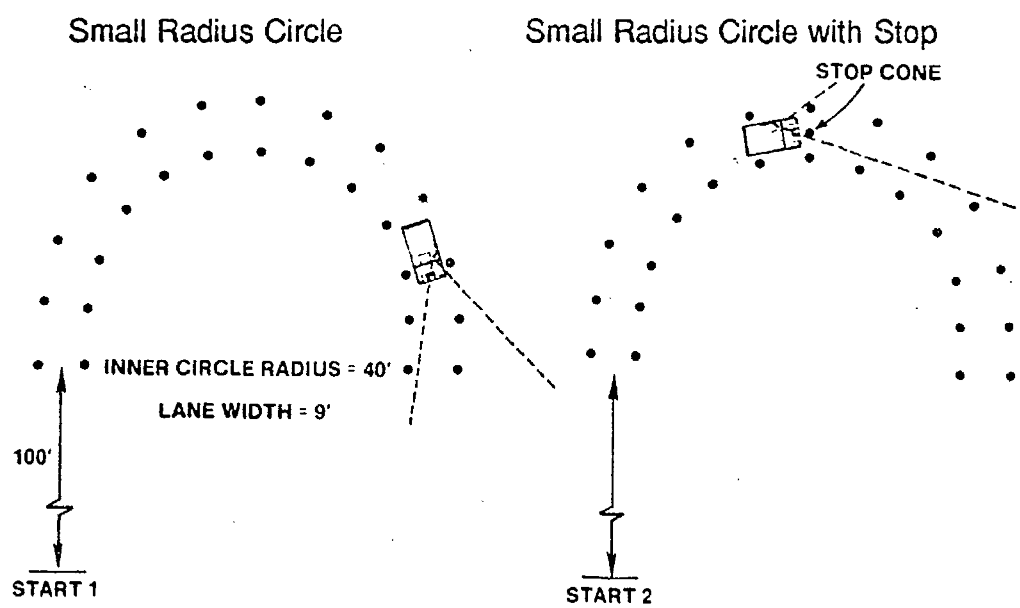


FIGURE 3. The Small Radius Circle Courses.



2.3.4 Course 4. Small Radius Circle.

The Small Radius Circle course is depicted in the left panel of Figure 3. The START position for this course was 30.48 meters [100 feet] from the first cone gate. During a testing session operators drove the course twice from each of the START positions depicted in the figure. Runs were scored for elapsed time and number of cones defining the curved alleyway touched or toppled.

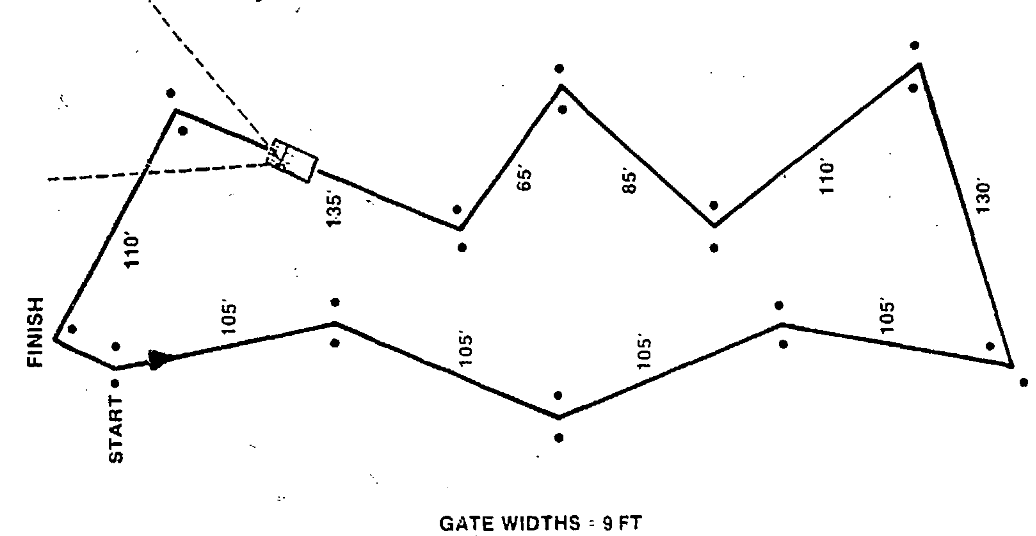
2.3.5 Course 5. Small Radius Circle with Stop.

The Small Radius Circle with Stop course is depicted in the right panel of Figure 3. The layout of this course identical to that of the Small Radius Circle with the addition of a stop cone at the apex of the arc. Drivers were instructed to position the front of the vehicle as close to the stop cone as possible without touching it. During a test session the course was run twice from each of the two START positions depicted in Figure 3. Runs were scored for elapsed time, number of cones defining the curved alleyway touched or toppled, and accuracy of position relative to the stop cone endpoint.

2.3.6 Course 6. Gymkhana.

The gymkhana course was a large, oval-shaped slalom course depicted in Figure 4. Cone separation for each of the 10 cone gates was 2.75 meters [9 feet]. Three separate runs through the course were undertaken in each session. Runs were scored for elapsed time and number of cones touched or toppled.

FIGURE 4. The Gymkhana Course.



3.0 RESULTS

3.1 Statistical Procedures Used

Performance metrics from each of the driving courses were compiled and subjected to separate analyses of variance (ANOVAs) with comparisons across the four viewing options (DV, DV 40 x 30, Stereo-HMD, and Mono-HMD) being the effect of paramount interest in each analysis. A Type-I error level of .05 for statistical significance was set prior to analysis. Repeated-measures ANOVAs were run on the results from the "experienced" drivers and between-groups ANOVAs were run on the measures from "inexperienced" drivers. Findings are presented below from all courses run across four design topic areas.

3.2 Direct Viewing Versus HMD Viewing

Not surprisingly, all statistically significant differences that were found favored the combined Direct View (i.e., DV & DV 40 x 30) conditions over the combined Video View (i.e., Mono - HMD & Stereo - HMD) conditions. The overall pattern of results that emerged from mean comparisons subsequent to the ANOVAs is presented in Table 1.

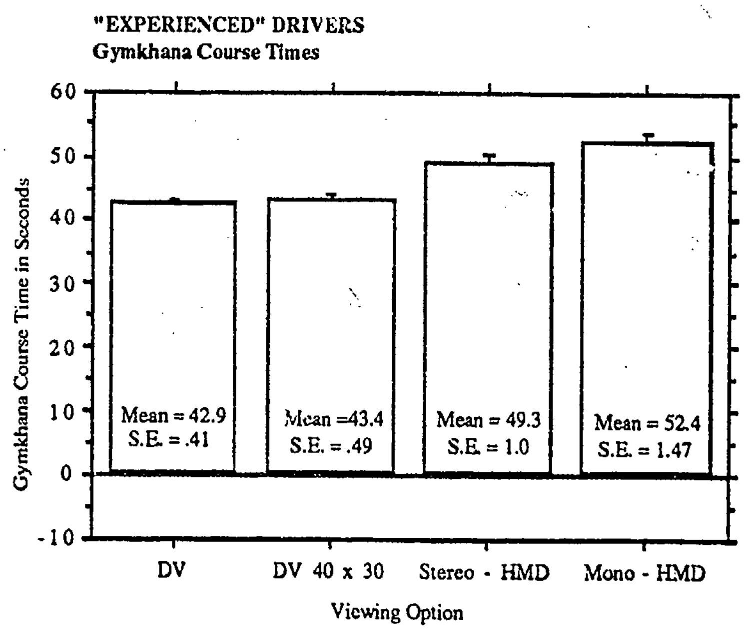
TABLE 1. Summary of Statistically Significant Advantages for Combined Direct View over Combined Video View Conditions.

	"Experienced" Drivers		"Inexperienced" Drivers	
	Time	Errors	Time	Errors
Right-Angle Turn-IN	~60% faster**	~72% fewer*	n.s.d.	n.s.d.
Right-Angle Turn - OUT	~34% faster**	n.s.d.	n.s.d.	n.s.d.
Figure -8	~31% faster*	n.s.d.	n.s.d.	~65% fewer**
Small Radius Circle	~25% faster*	n.s.d.	n.s.d.	n.s.d.
Small Radius Circle - Stop	~13% faster*	n.s.d.	n.s.d.	n.s.d.
Gymkhana	~15% faster**	n.s.d.	n.s.d.	~50% fewer*

Key:
* Type-I error probability < .05
** Type-I error probability < .01
n.s.d. = no significant difference found

In summary, statistically significant differences in driving performance measures were found for each of the six measures taken in the mobility test battery. All of these differences showed performance under the direct viewing conditions to be superior to that under the video viewing conditions tested. Differences were notably inconsistent between the two driver groups."Inexperienced" drivers produced higher rates of errors on error measures with no significant differences for the time measures. The pattern of results suggests that "inexperienced" drivers attempted to drive the vehicle at equal speeds under direct view and video view options. "Experienced" drivers drove the time-scored courses faster under direct view conditions while maintaining consistent error rates across the viewing options tested. As one example of significant performance effects revealed by the set of analyses conducted, the effect of viewing system option on Gymkhana course times for the "experienced" group of drivers is graphed in Figure 5. While maintaining essentially equivalent error rates for all conditions tested, the performance graphed in the figure is nearly identical for the two direct view conditions, whereas times are slower under the Stereo-HMD option and even slower under the Mono-HMD option. Overall, driving time under the direct view options was approximately 15% faster than driving time under video view options.

FIGURE 5. Effect of Viewing Option on Gymkhana Course Times for the Experienced Group of Drivers.



Note: the error bars graphed in this figure and subsequent figures represent standard errors defining the upper bound of the 95% confidence interval.

3.3 Unobstructed Versus Masked Video Viewing

Given the richly detailed visual information provided under both direct view options, no reliable performance difference was found between the unoccluded DV option and the peripherally occluded DV 40 x 30 option. Though error rates were consistently observed to be slightly elevated for the DV 40 x 30 option versus the DV option for both driver groups on **all** driving courses tested, none of these error rate differences were found to be statistically significant. This outcome of the analysis suggests that if sufficient image resolution, contrast, color, head motion coupling, and accurate feedback of vehicle dynamics are provided to a driver, a 40° by 30°, 1:1 field of view is sufficiently wide enough for low-speed mobility within the scope of fundamental driving tasks tested in this study. However, the consistency of the pattern of slightly elevated error rates for the DV 40 x 30 option versus the DV option does suggest that some capability is lost by restricting a driver's peripheral field of view. Whether this effect is stronger for driving over more challenging terrain remains to be determined and should be investigated.

3.4 Stereoscopic Versus Monoscopic Video Viewing

Measures were taken with the same IHADSS helmet-mounted display on identical driving courses under two viewing options; monoscopic and stereoscopic. An earlier, preliminary analysis of this data [4] revealed no significant differences between the Mono-HMD and Stereo-HMD viewing options on any of the courses tested for either operator group. The more refined analysis conducted for this paper in which the two driver groups were analyzed separately, contradicted the findings of the previous analysis by revealing statistically significant, but modest, performance advantages for use of a stereoscopic display on several of the courses tested. Table 2 summarizes these significant effects.

TABLE 2. Summary of Statistically Significant Advantages for Stereo-HMD Over Mono-HMD Viewing Options.

	"Experienced" Drivers		"Inexperienced" Drivers	
	Time	Errors	Time	Errors
Right-Angle Turn - IN	n.s.d.	n.s.d.	~36% slower*	n.s.d.
Figure-8	n.s.d.	n.s.d.	~30% slower*	n.s.d.
Small Radius Circle	~13% faster*	n.s.d.	n.s.d.	~61% fewer*
Small Radius Circle - Stop	~15% slower*	n.s.d.	n.s.d.	n.s.d.
Gymkhana	~06% faster*	n.s.d.	n.s.d.	n.s.d

Key:
* Type-I error probability < .05
n.s.d. = no significant difference found between Stereo-HMD and Mono-HMD

With regard to vehicle speeds, it appears that the Stereo-HMD option allows "experienced" drivers to maintain faster speeds than the Mono-HMD on several of the courses without a corresponding penalty in error rates. This pattern is apparent in Figure 6, a graph of the effect of viewing option on course times on the Small Radius Circle course for the "experienced" group of drivers. A possible benefit of Stereo-HMD for the "inexperienced" group may be that it imparts a more accurate sense of space, and that this, in turn, motivates them to slow down and make fewer errors when given a video view of a relatively unfamiliar driving situation. This conclusion is suggested by the patterns of performance graphed in Figures 7 and 8. The pattern of results graphed in Figure 7 shows that "inexperienced" drivers tended to drive significantly faster under the Mono-HMD versus the Stereo-HMD viewing option. A similar pattern (not graphed) was found for "inexperienced" drivers on the Figure-8 course.The "staircase" pattern of results graphed in Figure 8 was apparent in the data from a majority of courses from both driver groups, though it only reached statistical significance in one instance (i.e., Small Radius Circle course errors for the "inexperienced" group) probably owing to the small size of the sample of drivers tested.

FIGURE 6. Effect of Viewing Option on Small Radius Circle Times for the "Experienced" Group of Drivers.

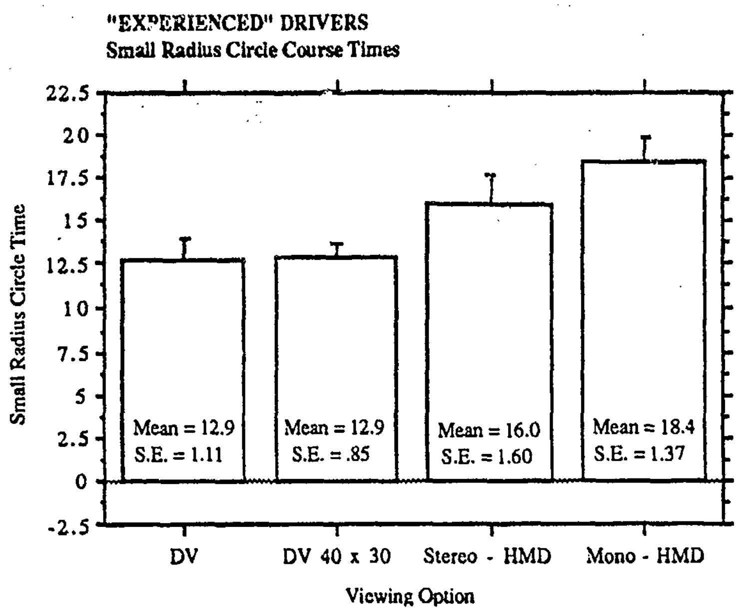


FIGURE 7. Effect of Viewing Option on Right Angle IN Course Times for the "Inexperienced" Group of Drivers.

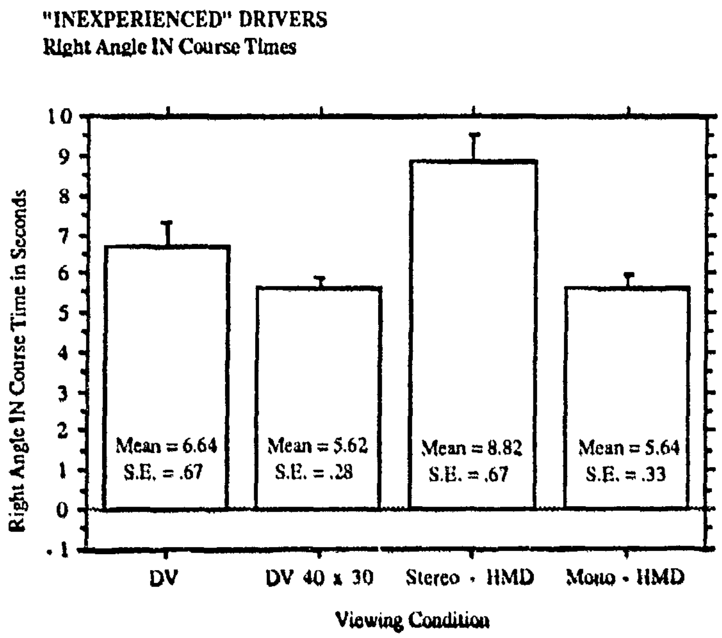
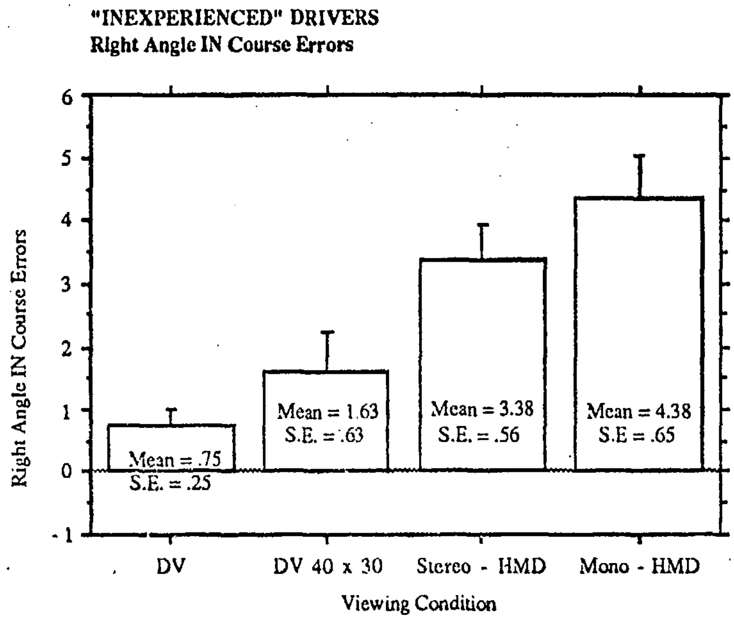


FIGURE 8. Effect of Viewing Option on Right Angle IN Course Errors for the "Inexperienced" Group of Drivers.



In attempting to generalize these findings of a stereoscopic advantage to more rigorous and challenging UGV driving conditions, one must keep in mind that past research and hands-on field experience has shown that the performance advantages which stereoscopic imagery provides are most pronounced in unfamiliar, visually cluttered, and visually degraded images. Stereo imagery is also known to be useful in judging the relative distances and orientations of objects and terrain surface features - all of which are invaluable to an operator when evaluating the composition and topography of terrain before attempting to traverse it. The results of this study are strongly suggestive of potential performance advantages to be derived by using stereoscopic imagery in UGV display systems. A more relevant, systematic, controlled comparison of UGV performance with stereoscopic and monoscopic imagery is recommended.

3.5 "Experienced" Versus "Inexperienced" Drivers

The observed effect of operator experience on driving the TOV through the test courses used in this experiment can be summarized quite simply. The "experienced" group tended to drive more conservatively than the "inexperienced" group. Under video viewing conditions, "experienced" drivers slowed down and made fewer errors on all the driving courses tested than their "inexperienced" counterparts. The "inexperienced" group tended to drive the TOV at speeds approximating those achieved under the two direct viewing conditions, but in doing so they committed many more errors than the "experienced" group. Perhaps the observed difference in performance is really just a difference in risk-taking between the two groups. The "experienced" group was considerably older and more technically astute than the "inexperienced" group. Overall, this pattern of results suggests that, given several hours of experience in driving the TOV, drivers became more cautious and lowered their driving speed to better correspond to their degraded view of the courses.

4.0 IMPLICATIONS FOR UGV DEVELOPMENT & DESIGN

Even while driving under the simplified, relatively undemanding, and benign course conditions investigated in this early study, a large performance gap was documented between direct view and video view driving. These observed differences in performance are directly attributable to parameters of the viewing systems used to view the driving situation since other aspects of the driving situation (i.e., steering controls and forces fed back through them to the driver, acoustic feedback, the dynamics of sensor aiming, and body motion senses) were generally equivalent under all viewing options tested. The findings suggest that considerable thought and effort will be required to devise UGV viewing system hardware that will overcome the technological limitations inherent in available video displays and provide a reasonable approximation to the level of performance achievable under direct drive conditions. Several obvious discrepancies between direct viewing and video viewing merit further systematic investigation. These include system magnification, spatial resolution, and image contrast. The best way to gauge the effects of these and other viewing system parameters on UGV driving is by systematic, controlled comparisons of objective performance measures.

Field of view is a fundamental parameter of any UGV viewing system. Results of this investigation suggest that a 40° horizontal by 30° vertical field of view with high fidelity head movement coupling of camera aim can provide a close approximation to the level of driving performance achievable with a full, unoccluded field of view for the type of low-speed mobility measured here. However, it should be noted that this conclusion is here only validated for a situation in which other important system parameters such as image resolution, image contrast, and system magnification are equivalent to those under direct viewing conditions. An objective study of the effects of a fixed sensor field of view on remote driving performance is currently underway at the US Army's Human Engineering Laboratory. The results of this study should hold important implications for selection of an appropriate field of view for future UGV systems.

Use of an easily implemented stereoscopic video display improved driving performance significantly, though modestly, on several of the courses tested. By providing the driver with a more accurate internal spatial representation of the driving course and his vehicle's movements within that course, the driver was perhaps able to make better decisions regarding speed and steering of the vehicle. For drivers who are highly experienced at performing a particular driving task, the additional information may allow them to drive faster while maintaining an acceptable, stable risk of erring. For drivers unpracticed at performing the particular driving task demanded by a driving course, the additional information provided by a stereoscopic display may increase their awareness of the limitations of their view and control over the vehicle and may subsequently encourage them to reduce speeds and drive more conservatively in unfamiliar situations.

The results presented in this report point very consistently to the general conclusion that providing the UGV driver with a display that more closely approximates the "full telepresence" viewing condition is a successful approach to improving driving performance as measured by systematic, objective test procedures.

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14. Résumé:

L'interaction homme-machine en robotique militaire prend place à plusieurs niveaux selon le degré d'autonomie du système commandé. Les informations échangées peuvent être de type abstrait et discontinu (ou symboliques) ou bien de type continu (ou analogique) dans le cas d'une commande en téléopération.

La qualité de l'interface hnmme-robot conditionne les performances finales du système. L'environnement militaire présente de nombreuses difficultés pour un système robotisé, et notamment la présence des menaces ennemies intelligentes. L'intervention humaine est nécessaire afin de pouvoir les surmonter.

Les difficultés de conception proviennent d'une part des limitations de performances des organes "d'entrées-sorties" de l'homme et d'autre part de la grande différence des modes de "raisonnement" entre l'homme et la machine.

La connaissance actuelle est assez empirique, un approfondissement théorique et expérimental est nécessaire.

INTERACTIONS HOMME/MACHINE POUR LES ROBOTS MOBILES MILITAIRES

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1. INTRODUCTION:

Le problème de la conception et de l'optimisation de l'interface homme-machine dans les applications militaires, n'est pas spécifique à la robotique. On le rencontre chaque fois qu'un système comporte des automatismes et lorsque un flux important d'informations est échangé avec les opérateurs. La maîtrise des avions de combat modernes par exemple exige une concentration très importante des pilotes, de nombreuses études sont effectuées afin de réduire cette charge de travail.

L'approche robotique place néanmoins le problème de l'interface homme/machine au premier plan. En effet un engin robotisé peut se définir comme l'aboutissement de la démarche conduisant au développement d'armes et de systèmes automatiques.

En première analyse une contradiction peut apparaître: plus un système est automatisé moins il est en contact avec les opérateurs humains pendant la phase opérationnelle (ce qui constitue un des objectifs de l'automatisation), aussi l'interaction homme-machine prend-elle moins d'importance dans ce cas? Cette contradiction n'est qu'apparente, en effet:

- Un système robotique entre toujours en contact avec un opérateur humain au cours de son cycle de fonctionnement, ne serait ce qu'une seule fois lors de la spécification initiale de sa mission. Une relation homme-machine s'établit donc à cette occasion.
- Les systèmes disposant d'un haut degré d'automaticité échangent des informations de contenu sémantique élevé avec les opérateurs. Or plus le niveau d'abstraction de la commande est élevé plus les conséquences d'une erreur de spécification de la tâche peuvent être graves (ce ne sont plus seulement des erreurs de trajectoire). Si l'information est plus légère quantitativement elle s'alourdit qualitativement, l'interface homme-système doit être conçu de façon à minimiser les possibilités d'erreurs.
- L'environnement du champ de bataille est complexe, très hostile et difficile à appréhender par un système autonome. En particulier il présente une composante nouvelle pour la robotique (qui est spécifique à l'application militaire), représentée par la menace qu'exerce l'ennemi sur le robot. Cette menace est agressive, elle ne peut se réduire à un obstacle classique de nature géométrique par exemple (un relief du terrain qu'il suffit de contourner). De plus cette menace est "intelligente", évolutive et imprévisible ce qui contribue à augmenter la déstructuration de l'environnement du robot qui ne pourra réagir efficacement

sans l'aide d'une "intelligence" humaine. L'assistance d'un (ou de plusieurs) opérateur(s) est donc souvent indispensable pour mener à bien une mission robotique militaire.

Les difficultés de conception de l'interface homme-système apparaissent à deux niveaux:

- Au niveau de l'**interface physique** car l'homme présente une organisation très particulière de ses "entrées-sorties" ainsi que des limitations qui sont différentes de celles de la machine.

- Au niveau **décisionnel**, les représentations internes de l'environnement et de la tâche sur lesquelles sont basées les réactions de l'homme et du robot sont très différentes. Le robot a besoin de données précises et bien structurées, toutes les ressources doivent être déclarées de façon explicite. L'homme se contente d'informations plus floues, il dispose d'une base de connaissances très développée et de capacités d'inférences incomparables (il est capable par exemple d'exploiter des images vidéo de très mauvaise qualité par reconstruction mentale du contexte, là ou le robot ne peut extraire aucune information pertinente).

2. ACTIVITE HOMME/MACHINE

On peut décomposer l'activité des opérateurs en suivant la segmentation habituelle de la commande d'un robot mobile. Les trois niveaux fonctionnels, dans l'ordre décroissant du traitement sémantique sont:

- Le niveau navigation.
- Le niveau pilotage.
- Le niveau guidage.

Le dialogue homme-machine peut intervenir a chacun de ces niveaux selon le type de système commandé. L'interaction peut aussi prendre place simultanément a plusieurs niveaux, par exemple lorsqu'un premier opérateur pilote directement l'engin pendant qu'un second opérateur surveille les menaces adverses et assiste le premier en suivant le déroulement global de la mission.

La conception de l'interface dépend directement de la nature des informations échangées et de l'activité correspondante demandée à l'opérateur, ce que l'on détaille ci-après.

2.1 NAVIGATION

Les activités prenant place au niveau navigation concernent tout d'abord la **définition de l'objectif.** Il est spécifié en termes fonctionnels et topologiques ce qui comprend:

- La définition d'un **trajet** général à suivre comme par exemple: suivre la route jusqu'au croisement, tourner à droite après l'arbre, avancer rapidement jusqu'au sommet de la colline ...

- La définition des **tâches** à réaliser sur ce trajet, ex: inspection panoramique IR pendant le parcours, relever la position des points chauds, tirer sur les objectifs détectés ...
- La précision d'**attributs** et de **contextes** comme: des informations précisant la nature des objets que le robot est susceptible de rencontrer dans son environnement (zones ennemies connues, zones interdites, zones infranchissables, amers remarquables ...). Les comportements à adopter dans différentes configurations et notamment dans les cas critiques (ex: perte de communications radio, panne ou destruction partielle d'un sous système ...).

Cette première activité prend place principalement hors ligne, pendant la phase de préparation de la mission. Elle peut être assistée par un dispositif permettant la simulation si un modèle de l'environnement suffisamment représentatif est disponible.

Le support utilisé pour effectuer cette "programmation" est généralement constitué par une cartographie plane de l'environnement sur laquelle la définition de la mission est effectuée. Cette cartographie peut rester symbolique (topologique) avec de grandes imprécisions géométriques.

Le second type d'activité des opérateurs concerne le **suivi de la mission**, il s'effectue en ligne pendant la phase opérationnelle, soit:

- La **vérification du bon enchaînement** des actions par rapport au plan prévu. Ce qui comprend les aspects topologiques (positionnement relatif du robot dans son environnement) ainsi que les retours fonctionnels (état interne du robot et de ses sous systèmes, état de réalisation des tâches spécifiées ...).
- L'**intervention corrective** de l'opérateur en temps réel en cas de besoin (assistance au robot en difficulté, réaction à un événement imprévu).
- La fourniture au robot d'**informations complémentaires** permettant d'enrichir son modèle interne (assistance au processus de reconnaissance des obstacles ou amers, ajout dans la base de données du robot d'un obstacle non détecté par les systèmes embarqués, recalage assisté du positionnement absolu dans l'environnement, ajout/modification d'une information de contexte ...).
- La **confirmation des interprétation** et la **validation des intentions** du robot comme par exemple: la levée d'ambiguïtés entre une menace réelle et un leurre, la validation du déclenchement d'un tir ...

L'interaction homme-robot peut être supportée par exemple par la même représentation symbolique cartographique sur laquelle vont se superposer à l'avancement les informations de compte rendu provenant du robot. Cependant des support différents et représentations complémentaires sont nécessaires lorsque l'opérateur doit intervenir dans le processus, la principale difficulté étant alors d'obtenir une bonne compréhension de la situation par l'opérateur.

En effet lors d'un déroulement nominal d'une mission, le rôle de l'opérateur se limite à celui d'un superviseur, se contentant de vérifier que les comptes rendus sont cohérents avec le plan de mission. Afin de suivre ce déroulement l'opérateur n'a pas formellement besoin de connaître de façon intime les détails du cheminement logique du processus décisionnel du robot, il n'a pas non plus besoin de connaître la façon dont le robot se représente l'univers qu'il rencontre.

Par contre en cas d'imprévu (par exemple une menace ennemie non modélisée, ou bien un obstacle que le robot déclare infranchissable et incontournable ...), le robot peut être bloqué dans sa progression et demander l'aide de l'opérateur. De plus la notion de l'urgence de la réaction sera souvent associée (imminence de l'agression de la menace, perte de temps dans l'exécution de la mission).

Dans ce cas l'opérateur doit être capable d'effectuer un diagnostic complet, juste et rapide de la situation ce qui est d'autant plus délicat que sa vigilance a été émoussée lors des phases se déroulant sans que son intervention dans le processus soit nécessaire. Il doit comprendre par exemple "pourquoi le robot s'est arrêté", ce qui nécessite une interprétation poussée des signaux disponibles. L'activité de l'opérateur ne peut plus se résumer à une comparaison entre la situation escomptée et la situation présente, il doit prendre une initiative et rechercher activement des "explications" complémentaires lui permettant d'appréhender l'ensemble du contexte.

2.2 PILOTAGE

A ce niveau la tâche à réaliser par le robot est décrite sous la forme de trajectoires géométriques réelles (droites, cercles ...), accompagnées d'ordres de configuration du système (valeur de gains, sélection de modes de commande ...). Les données sont toujours de nature symboliques mais elles doivent être quantifiées (une représentation topologique ne suffit plus).

Le contenu des informations échangées à ce niveau a pour objectif de spécifier l'enchaînement des instruction d'un "langage" opérationnel. Les instructions d'un tel langage sont du type suivant:

- instruction **fondamentales**: elles décrivent le comportement de base du robot en modes manuels ou automatiques (ex: mode manuel assisté, droite auto sur 100 mètres, arrêt d'urgence ...).
- instructions **harmoniques**: elles ne modifient pas le comportement de base mais permettent d'agir sur celui-ci en agissant sur les paramètres ajustables (ex: vitesse d'avance, activation/désactivation d'un procédé ...).
- instruction de **gestion des événements**: elles définissent d'une part les types d'événements à surveiller de façon asynchrone (collisions, combinaison de signaux capteurs, horloge ...) et d'autre part la réaction à adopter dans le cas ou l'événement est activé.
- instructions de **configuration**: instructions particulières orientées système.

Les échanges peuvent être effectués directement en exploitant la forme brute de description des instructions du langage (ex: *SET_SPEED (valeur), MOVE ...*). Cependant cette formulation est peu explicite, directement issue du monde informatique donc peu adaptée aux opérateurs qui ne sont pas des programmeurs; de plus elle exige des efforts de mémorisation et de contrôle importants.

L'objectif de conception de l'interface opérateur est de traduire l'expression "robocentrique" de la tâche (qui est représentée par la séquence d'instructions du langage) en une représentation plus familière pour l'opérateur de terrain.

D'autre part le système assurant l'interface doit être capable de simplifier la tâche de l'opérateur en limitant le nombre d'informations échangées (définition de paramètres par défaut, gestion de la cohérence des instructions et des séquences ...).

2.3 GUIDAGE

Ce niveau de commande reçoit en entrée la spécification d'un déplacement, il assure en sortie la génération du mouvement et son contrôle asservi en prenant en compte les limitations physiques que présente l'engin (cinématique, dynamique, saturations ...).

L'opérateur à ce niveau intervient principalement de façon **"analogique"**, c'est à dire en spécifiant de façon continue la valeur d'un ou de plusieurs vecteurs de commande (télépilotage de la vitesse et de la direction par exemple). L'interface physique est un manche de commande qui doit s'adapter aux caractéristiques physiologiques et kinesthésiques de l'homme.

3. CARACTERISATION DU SYSTEME HOMME/MACHINE

le couplage homme-machine met en oeuvre des organes physiques qui adressent les sens et les moyens d'action de l'homme. Ces éléments "d'entrées-sorties" ont des caractéristiques particulières et des limitations qui vont guider la conception de l'interface. Comme le montre la figure 1, d'après A. Bejczy, la première caractéristique est la grande dissymétrie qui conduit à une saturation à cause des limitations en nombre et en performances des canaux de sortie (envoi des informations depuis l'homme vers le système commandé) par rapport aux canaux d'entrée.

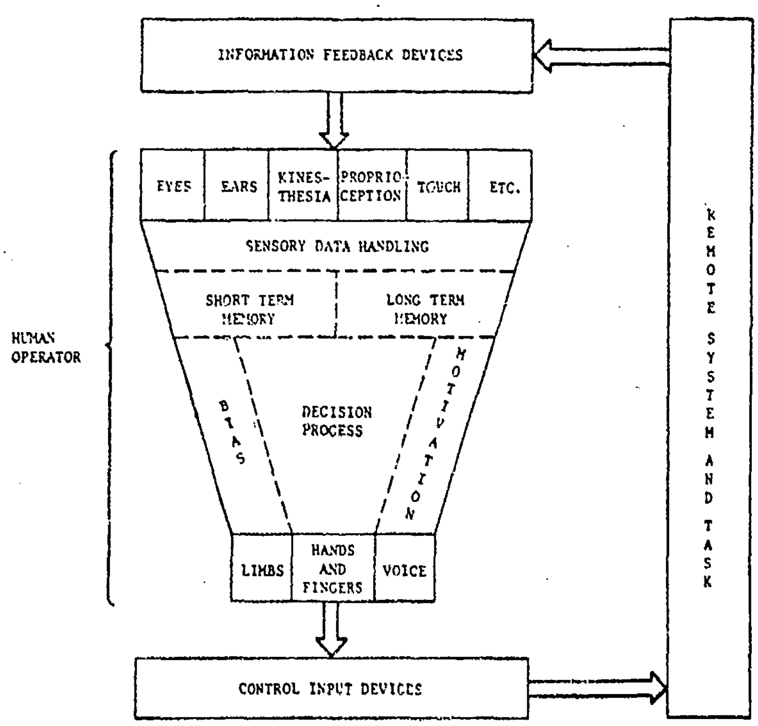

Figure 1: Canaux d'entrée-sortie de l'homme (Bejczy)

En effet en "entrée":

- La **vue** est le sens majeur de perception. Il est capable d'analyser en temps réel une grande quantité d'information brute (plusieurs mégabits par seconde) et de la traiter sur plusieurs niveaux sémantiques (symboliques et analogiques). Cependant l'homme n'est pas capable de suivre plusieurs processus simultanément, de plus les notions de fatigue visuelle et mentale sont à prendre en compte.

Les images (directe vidéo, synthétique ou symbolique) doivent être de bonne qualité et organisées de façon hiérarchique selon leur importance dans l'exécution d'une tâche et selon la nature de la tâche réalisée. La saturation du canal visuel dégrade les performances du système car ce canal sollicite beaucoup le système nerveux central.

- L'**ouïe** est un canal moins performant en capacité par contre le traitement de l'information peut être parallélisé. L'opérateur peut effectuer une tâche principale en recevant un retour sonore simultané qui ne le perturbe pas. Il peut être utilisé de façon analogique (son) ou symbolique (parole). Ce canal est exploité de façon très importante pour la communication entre opérateurs.

L'ouïe est utilisée surtout pour la transmission d'informations de surveillance (détection de bruits anormaux sur l'engin) et d'alarmes. C'est un canal efficace permettant de fournir des informations complémentaires utiles au processus de perception multisensoriel de l'homme.

- Les sens **kinesthésique** (retour d'effort) et le **toucher** sont des sens analogiques qui sont utilisés avec une classe particulière d'organes de commande actifs capables de restituer des informations tactiles ou d'effort directement dans la main de l'opérateur. Cette approche permet d'améliorer la transparence du couplage homme-machine en exploitant les automatismes humains disponibles au niveau de l'arc réflexe. Ce qui décharge le système nerveux central. La bande passante est assez importante (jusqu'à 100 hertz pour le toucher).

Les organes de "sortie" sont:

- Les **doigts** qui permettent d'atteindre quelques dizaines de bits par seconde par frappe sur clavier. La sélection d'ordres sur des menus ne dépasse pas quelques bits par seconde mais permet par contre d'accéder à des informations de contenu sémantique élevé.

- Les commandes au **pied** peuvent être utilisées en symbolique ou analogique (accélérateur) mais de façon assez limitée.

- La commande **vocale** permet de transmettre des ordres de haut niveau mais présente encore des performances trop faibles pour être opérationnelle (taux de reconnaissance et limitations du vocabulaire).

- La **main** et le **bras** peuvent imprimer des mouvements de plusieurs hertz de bande passante analogique ce qui est très utile dans le cas de commande en téléopération.

- On peut citer encore des organes de sortie inhabituels comme le suivi des mouvements de **l'oeil** et de la **tête** qui peuvent avantageusement simplifier les problèmes de pointage.

4. EXEMPLE DE CONCEPTION: LE ROBOT AMR

Le projet AMR (advanced mobile robots), mené dans le cadre du programme EUREKA a pour objectif de développer les technologies de la robotique mobile pour les applications dans le domaine de la sécurité civile.

Le système est composé de deux robots, le premier évolue en extérieur et transporte le second qui évolue à l'intérieur des bâtiments. Ils sont commandés à partir d'un poste mobile communiquant par radio avec les engins.

L'étude des missions a mis en évidence une grande déstructuration de l'environnement qui a conduit à la conception suivante de la commande:

- Le mode nominal de contrôle est le mode téléopéré, l'homme doit conserver la responsabilité directe des opération (nécessité de vigilance). L'opérateur dispose néanmoins de nombreuses assistances fournies par le système.
- Le fonctionnement automatique est envisagé pour répondre aux situations fréquentes dans lesquelles le canal de communication radio est dégradé.

La nature des activités de commande nécessite la présence de deux opérateurs. Le premier se concentre sur les tâches de téléopération de l'engin qui sont réalisées soit en télécommande directe (guidage) soit en téléopération symbolique (pilotage) par la spécification de primitives de déplacement. Le second opérateur assiste le premier en prenant à sa charge les tâches de gestion de la mission. En effet les opérations de téléopération nécessitent une concentration telle que les tâches de plus haut niveau ne peuvent être prises en compte par le pilote seul.

L'interface homme-machine, présenté sur la figure 2 est organisé de la façon suivante:

L'opérateur de téléopération dispose de leviers de commande directe analogique pour la commande du véhicule et des systèmes embarqués (cameras, bras manipulateur). Devant lui un grand écran moniteur présente plusieurs fenêtres ou sont affichées les images suivantes:

- une représentation synthétique 3D de l'environnement issue de la base de données locale donnant une vision complémentaire à celle des caméras.
- plusieurs représentations synthétiques externes du robot permettant de le situer dans son environnement (vues 2D planes de dessus).
- diverses vue de télévision directe.

L'opérateur de contrôle de mission travaille devant un écran graphique qui représente une carte topologique de l'environnement. Cette représentation est tracée par l'opérateur pendant la phase de préparation de la mission (en effet on ne dispose pas systématiquement pour les missions envisagées de cartographies précises de la zone d'intervention), le tracé topologique permet de constituer un canevas général de la mission.

L'opérateur superpose sur cette représentation un tracé symbolique en précisant les tâches à réaliser à l'avancement ("road book").

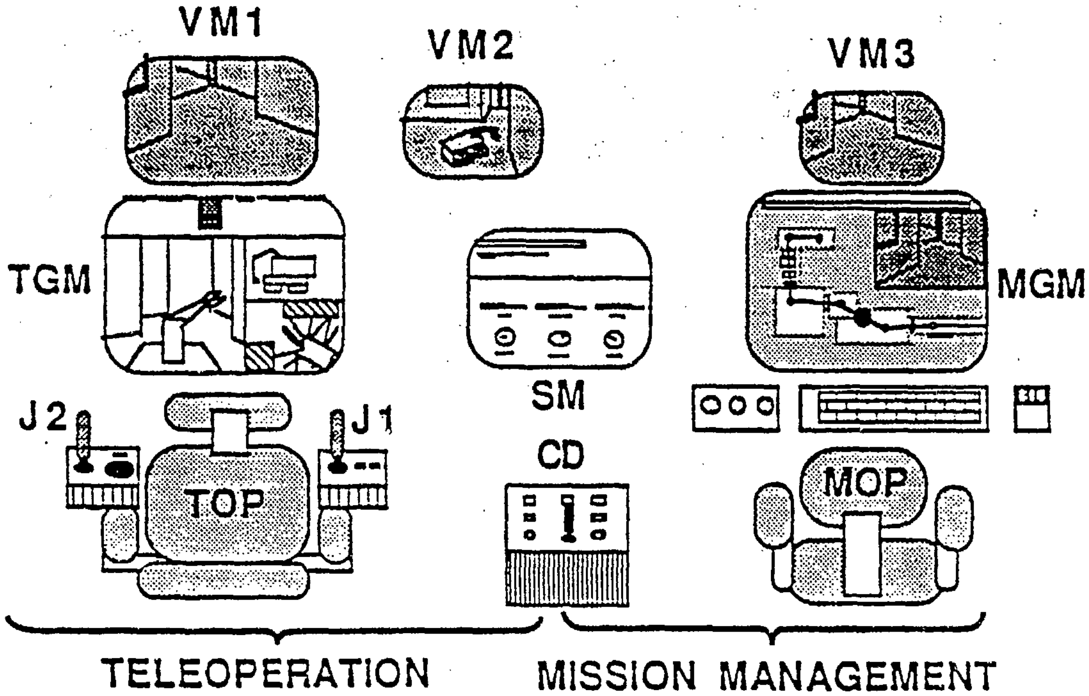

Figure 2: organisation du poste de commande du projet AMR

Lors des phases opérationnelles le robot fonctionne soit en mode téléopéré soit en mode automatique en exploitant directement la description obtenue par le "road book" (niveau navigation).

Lors du mouvement la représentation topologique est affinée et renseignée par les dimensions réelles des objets telles qu'elles sont perçues par le robot, ce qui permet de construire le modèle local de l'environnement exploité par les opérateurs (représentations synthétiques 2D et 3D). Cette construction est effectuée de façon interactive avec les opérateurs qui ne retiennent que les informations les plus pertinentes pour la mission.

Cette interface met en oeuvre des dispositifs physiques relativement standard (stations de travail graphiques) mais dont l'utilisation illustre quelques notions importantes évoquées plus haut:

- les fonctions de navigation, de pilotage et de guidage sont présentes et réparties entre les deux opérateurs.
- Les images représentées sont directement dépendantes du type d'activité exercée (2D 3D ou road book) par les opérateurs.
- L'exploitation de l'imagerie synthétique permet de ne concentrer l'attention que sur les informations pertinentes, et de compléter les retours vidéo.
- La construction interactive du modèle local qui est utilisé pour produire les images

synthétiques permet de construire un modèle d'environnement "orienté opérateur". La vision "robocentrique" est interprétée et transformée en une représentation plus directement explicite pour les opérateurs humains.

5. CONCLUSION

Les systèmes robotisés militaires doivent rester en relation plus ou moins permanente avec un poste de commande afin d'assurer leur suivi par un ou plusieurs opérateurs.

Le haut degré d'automaticité qu'il est souhaitable d'atteindre à terme - afin de diminuer l'investissement et donc l'exposition des opérateurs humains sur le champ de bataille - ne signifie pas que la problématique de l'interface homme-machine s'estompe. Les ordres de haut niveau doivent être produits de façon sûre.

Les techniques de base de conception des interfaces physiques sont disponibles, cependant elles sont encombrantes (dimensions importantes des postes de terrain conçus à partir de consoles et d'écrans standards), ce qui justifie une recherche de compacité notamment en suivant les efforts développés en aéronautique (poste virtuel intégré dans le casque).

Les techniques d'interfaçage au niveau du traitement et de la présentation de l'information sont par contre actuellement mal maîtrisées et reposent sur des approches empiriques. Il est souhaitable que cette connaissance soit approfondie au niveau théorique ainsi qu'au moyen d'expérimentations en vraie grandeur.

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14. Résumé:

A partir de l'analyse des missions de l'armée de Terre et de l'état de l'art en robotique, téléopérations, capteurs et armements, cette étude a défini des concepts de robots du champ de bataille. Une analyse de la valeur a ensuite été effectuée sur ces concepts, et des tendances à moyen/long terme ont été dégagées.

L'apprentissage du pilotage d'un véhicule fait appel à l'acquisition d'une connaissance implicite des particularités statiques et dynamiques du véhicule lui-même, autour de chacun de ses points de fonctionnement, mis en regard de l'environnement immédiat dans lequel il évolue.

Cet apprentissage étant acquis, l'opérateur exploite la richesse de ses capteurs physiologiques pour apprécier les réactions fines de son véhicule, aux ordres instantanés qu'il lui donne, mais également aux sollicitations en provenance de son environnement.

Ces informations, en retour du véhicule et de son environnement immédiat proviennent au pilote :

- par ses capteur auditifs : régime moteur, puissance fournie, roulage du véhicule,

- par ses capteurs inertiels : mouvements instantanés du véhicule, ses vitesses angulaires de tangage, roulis et lacet, ses accélérations linéaires (verticale, axiale et latérale) et son équilibre instantané (verticale locale),

- par ses capteurs visuels : environnement futur, immédiat, vitesse du véhicule (vision périphérique), position du véhicule relativement à la trajectoire à réaliser (erreur latérale, erreur de cap instantané).

Un des intérêts de la télé-opération, relativement à l'autonomie complète, d'un mobile devant évoluer dans un environnement non structuré, mal connu et potentiellement hostile, est de chercher à exploiter les capacités d'un opérateur à apprécier instantanément une situation globale complexe.

Cet objectif se heurte à la triple nécessité de disposer :

1. - de capteurs, permettant d'appréhender: l'environnement du véhicule, son comportement instantané et son état interne,

2. - d'une ligne de transmission fiable, à large bande, entre le mobile et le poste de télé-opération.

3. - de moyens physiques adéquats permettant de communiquer ces informations à l'opérateur dans le but d'exploiter les automatismes qu'il aurait acquis par apprentissage.

Le but de cet exposé va être de chercher à identifier les traitements ou modifications locales à envisager au niveau du véhicule pour en améliorer le comportement naturel, dans le but de minimiser les besoins :

- d'interfaces riches au niveau de l'opérateur,

- d'apprentissage de la complexité physique du système et des moyens d'interfaçage,

- en disponibilité de l'opérateur.

On va ainsi faire apparaître deux niveaux de traitements qu'on chercherait à réaliser localement sur le véhicule et permettant de traiter respectivement, des anomalies liées à la technologie interne du véhicule, et des effets des interactions directes entre le véhicule et son environnement immédiat.

2. - MODIFICATION DES CARACTERISTIQUES ISO-COMMANDES "INTERNES" DU VEHICULE

Dans tout véhicule on retrouve, réalisées au moyen de technologies plus ou moins complexes, les trois fonctions nominales : propulsion, freinage et direction.

Afin de simplifier la commande du véhicule on cherchera à faire disparaître la réalité technologique du système sous deux types de caractéristiques iso-commandes d'avancement et de direction, fonctions de la vitesse du véhicule, mais respectant la forme des limitations internes, externes ou ergonomiques.

2.1. - COMMANDE D'AVANCEMENT

Pratiquement, tous les véhicules à mobilité moyennement élevée disposent d'une chaîne de propulsion constituée d'un moteur thermique suivi d'un système de transmission de la puissance, commandable de façon continue ou discontinue, l'ensemble donnant accès à un domaine Force-Vitesse, borné :

a. - Au sommet du 1er quadrant par l'effort propulsif maximal disponible.

b. - Par une courbe de forme iso- puissance obtenue en combinant l'enveloppe des caractéristiques du moteur et les réglages continus ou discontinus de la transmission.

c. - A droite par la vitesse d'avancement maximale du véhicule.

NOTA :

Sur les véhicules à transmission discontinue et convertisseur de couple non commandable, la présence d'une traînée de convertisseur impose d'utiliser la commande de freinage pour contrôler le triangle de faibles vitesses et efforts propulsifs (cf. figure 2.1.1.).

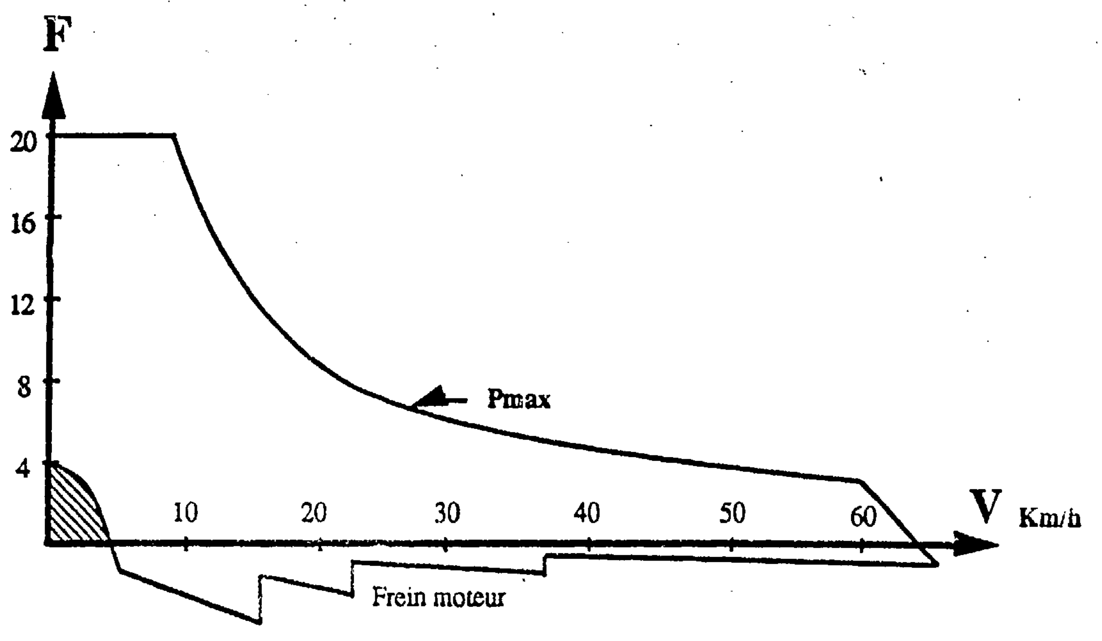

Figure 2-1-1- Domaine accessible par la commande du système propulsif

Une première partie du quadrant 4, correspondant aux forces décélératrices est fournie par le frein moteur qui peut avoir une allure fortement hachée, en particulier sur un véhicule à rapports de transmission discontinus.

Au delà, les forces moyennes et élevées de ralentissement ou de freinage sont fournies par des freins mécaniques, combinés, sur les véhicules lourds à des ralentisseurs électriques ou hydrauliques dimensionnés pour évacuer des puissances thermiques permanentes élevées.

L'effort maximal de freinage disponible est en général imposé par les caractéristiques d'adhérence maximales sur sol dur.

A l'intérieur du domaine F-V accessible, les caractéristiques iso-commandes "naturelles" du système, dépendent de la technologie et des lois de commande locales mises en place sur le moteur et sur la transmission pour minimiser les risques d'étouffement et d'emballement du moteur ou simplement pour obtenir un point de fonctionnement stable de la transmission (dans le cas de transmissions hydrostatiques).

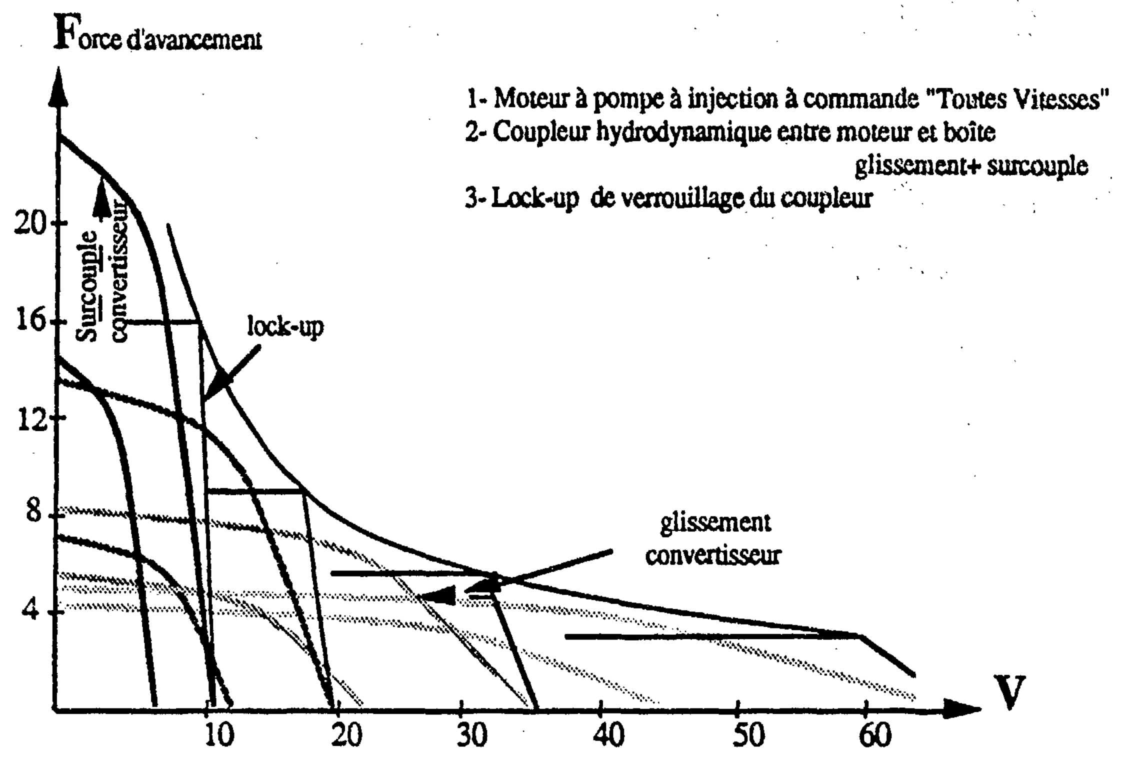

Figure 2-1-2- Caractéristiques iso-commandes naturelles d'un véhicule

Sur la figure 2.1.2. on a reproduit un ensemble de caractéristiques iso-commandes d'accélérateur représentatif d'un véhicule à rapports de boîte discontinus, et muni d'un convertisseur de couple. La force d'avancement agissant directement sur l'accélération du véhicule, la pente locale de ces caractéristiques est macroscopiquement le reflet de la constante de temps de mise en vitesse du véhicule qui varie de 0,15 s (rapports courts, force d'avancement faible) à 6 s (vitesses élevées, et convertisseur de couple en action).

Dans le but de simplifier la commande mise à la disposition de l'opérateur, et de minimiser les besoins en contre-réactions fines à lui présenter, on détruit, dans un premier temps les caractéristiques initiales du système en supprimant la contre-réaction de vitesse du moteur et en générant artificiellement des courbes iso-commandes ayant la forme générale représentée sur la figure 2.1.3.

Sur cette figure, la force d'avancement maximale correspond à une accélération du véhicule de l'ordre de 7 m/s^2. Les iso-commandes d'avancement, appliquées sur le véhicule font donc apparaître une constante de temps de mise en vitesse, de l'ordre de 2 secondes, approximativement constante dans la plus grande partie du domaine accessible. On retiendra que cet ordre de grandeur, faible pour un véhicule de compétition, est bien adapté pour une utilisation en télécommande.

Dans le système expérimental réalisé, la force propulsive, calculée à partir de la consigne de l'opérateur et de la vitesse d'avancement du véhicule, est obtenue par choix convenable de la commande d'injection, prenant en compte les caractéristiques internes du moteur, la vitesse instantanée du moteur, et l'état de la boîte de vitesse.

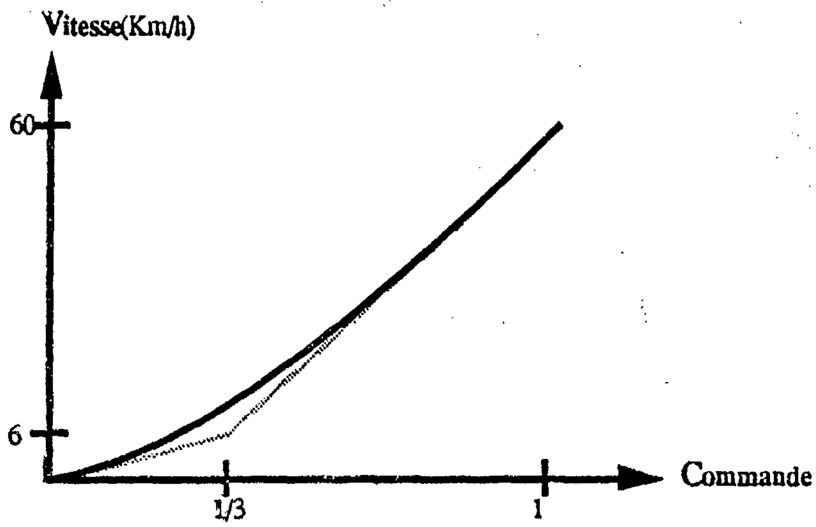

Figure 2-1-4 - Augmentation de la sensibilité de la commande aux vitesses faibles

Pour les iso-commandes correspondant aux faibles forces et vitesses d'avancement, l'automatisme ira solliciter la commande de freinage, ce qui permettra de masquer à l'opérateur l'anomalie locale dûe à la traînée du convertisseur de couple.

Autour des vitesses faibles (0-10 km/h), où une plus grande sensibilité de la commande peut être nécessaire pour mieux maîtriser les manœuvres du véhicule, on augmentera la sensibilité locale en introduisant une correspondance du type bilinéaire ou cubique entre le manipulateur et la consigne d'avancement du véhicule. Une augmentation dans un rapport de 3 à 5 du gradient local autour du zéro est bien perçue ergonomiquement (cf. figure 2.1.4.).

Au passage par zéro de la force axiale, la pente des iso-commandes d'avancement ($\approx 0{,}5$ m/s^2/m/s) est conservée dans un domaine correspondant approximativement au frein moteur moyen. Les iso-commandes d'avancement sont donc bornées, en effets négatifs, par une caractéristique iso-commande nulle.

Les iso-commandes de freinage sont obtenues par translation linéaire de l'iso-commande nulle (cf.figure 2.1.5.).

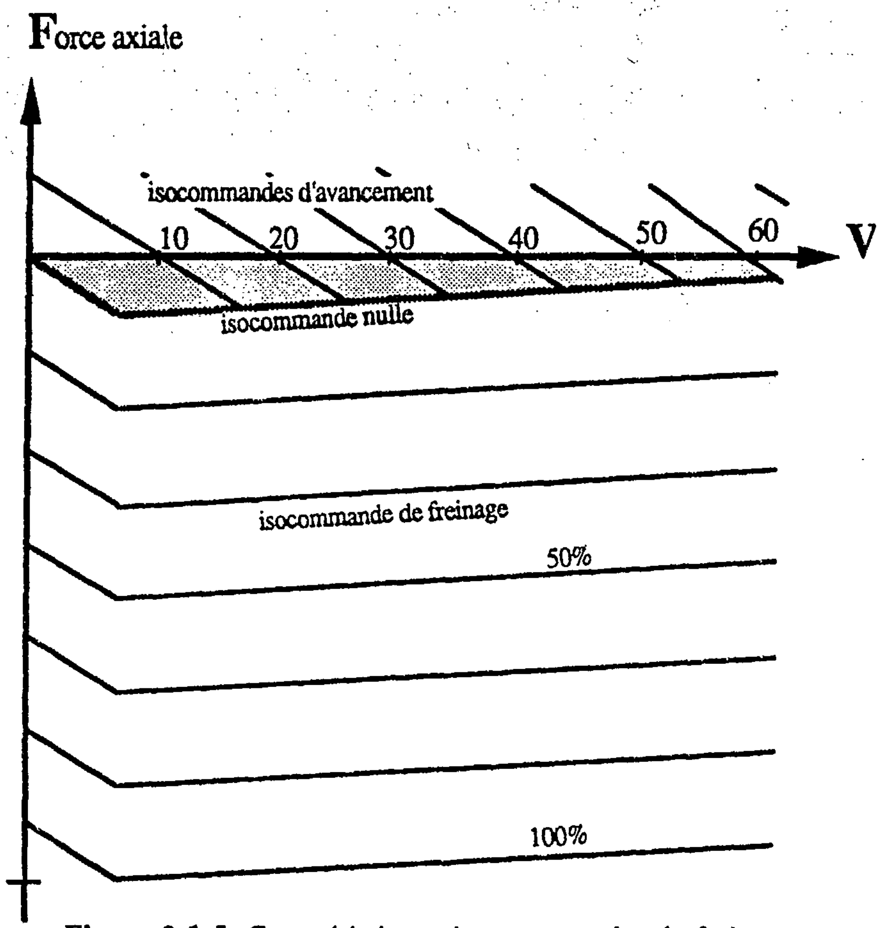

Figure 2-1-5- Caractéristiques iso-commandes de freinage

2.2. - COMMANDE DE DIRECTION

La commande de direction des véhicules à roues directrices, et d'une partie des véhicules à direction par "skid-steering" fait naturellement correspondre un rayon de virage à une consigne.

Pour les véhicules chenillés dans lesquels la commande différentielle des chenilles est réalisée par le pilotage de la cylindrée d'un groupe hydrostatique, le gradient entre la consigne de virage et le rayon réalisé varie en fonction du rapport de réduction enclenché, mais pour un rapport donné reste en première approximation constant.

Aux faibles vitesses d'avancement, le domaine des virages accessibles par la plupart des véhicules est donc borné par le rayon minimum réalisable technologiquement.

Dès que la vitesse d'avancement augmente, les possibilités réelles de virage sont limitées par des considérations ergonomiques entre 0,6 et 1 rd/s.

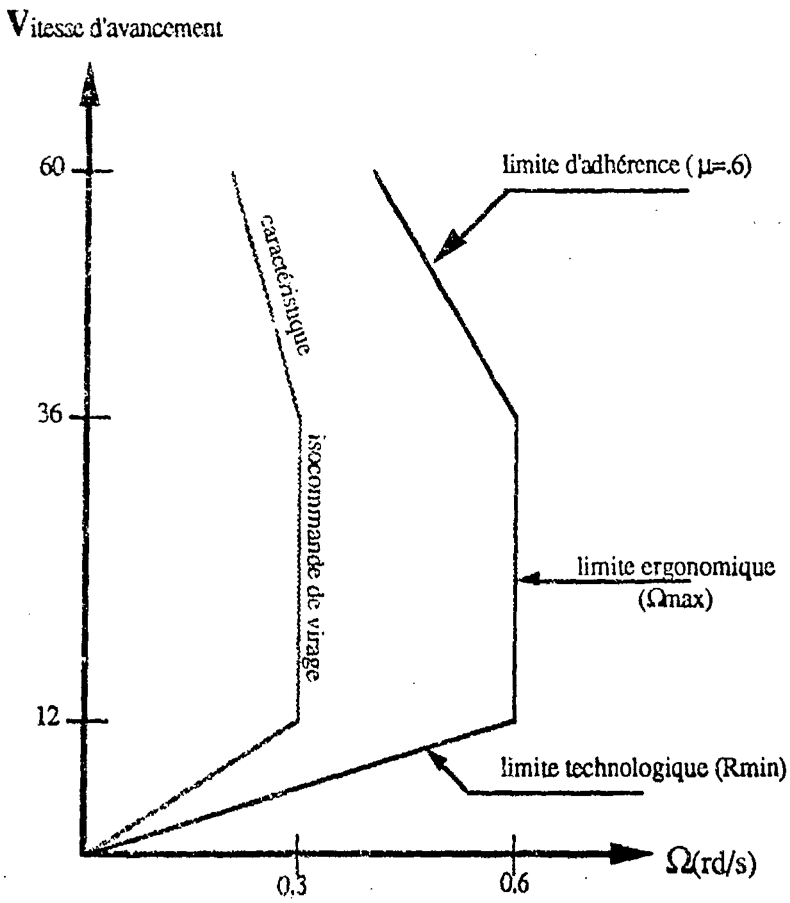

Figure 2-2-1- Iso-commandes de virage

Lorsque la vitesse d'avancement augmente encore, les possibilités de virage sont limitées par les conditions d'adhérence entre le véhicule et le sol qui bornent l'accélération centripète maximale aux alentours de 9 m/s^2 sur un véhicule à roues directrices et vers 6 m/s^2 sur un véhicule chenillé.

L'exploitation de ces considérations à la télécommande d'un véhicule débouche sur des caractéristiques iso-commandes de virage correspondant à :

- un rayon de virage constant aux faibles vitesses,

- une vitesse angulaire constante aux vitesses moyennes,

- et une accélération latérale constante aux vitesses élevées.

Ce type de caractéristique permet d'exploiter le débattement utile du manipulateur de commande dans tout le domaine des vitesses d'avancement accessibles.

3. - ACTIONS SUR LE COMPORTEMENT DU VEHICULE INFLUENCE PAR SON ENVIRONNEMENT IMMEDIAT

Un pilote, par action sur ses commandes d'avancement et de direction, agit sur son véhicule, pour contrôler sa position et sa vitesse futures, sur un horizon de quelques secondes.

Derrière cette stratégie à moyen terme, le pilote doit réagir à des réactions instantanées de son véhicule, conséquences d'une mauvaise combinaison de ses caractéristiques intrinsèques, des consignes données par le pilote, et de l'environnement immédiat.

Les réactions instantanées indésirables du véhicule sont constituées par la perte du contrôle de son lacet, et de son roulis. On admettra que la perte de contrôle du tangage du véhicule est du ressort de la stratégie à moyen terme.

3.1. - STABILITE DU LACET D'UN VEHICULE

La stabilité du lacet d'un véhicule télécommandé est une caractéristique qu'on devra rechercher, dans la mesure où l'appréciation de la qualité du terrain, aussi bien que les dosages respectifs des ordres de freinage, d'accélération et de direction ne peuvent être qu'approximatifs. On attachera donc une grande importance dans l'analyse de ces phénomènes et dans la recherche des solutions qui permettraient aussi bien de forcer le véhicule à ne pas diverger par rapport aux consignes qu'il reçoit du pilote (à l'intérieur du domaine accessible), ou d'interdire au véhicule de réaliser les consignes qui lui sont données lorsque celles-ci l'entraîneraient à l'extérieur de son domaine instantanément accessible (mise en dérapage).

3.2. - CAS PARTICULIER DES VEHICULES CHENILLES

Les véhicules chenillés ou à roues non directives constituent une famille intéressante par ses capacités d'évolution en terrain difficile.

Ces véhicules se particularisent par le fait que le synchronisme des roues ou galets d'un demi-train est assuré mécaniquement et que les seules commandes accessibles sont respectivement le mode commun et le mode différentiel.

Les véhicules à commande différentielle de la vitesse des roues ou chenilles présentent naturellement la particularité d'être instables dans une partie du domaine des virages potentiellement accessibles sur un terrain de cœfficient de glissement chenilles-sol donné.

Ce domaine est représenté schématiquement, sur la figure 3.2.1 dans un système de coordonnées lié à la trajectoire.

Dans ce domaine de virages instables, le véhicule part naturellement en survirage et referme progressivement sa trajectoire. Cette instabilité serait atténuée par une accélération violente, mais la puissance disponible est en général à peine suffisante pour entretenir le virage à vitesse élevée. L'amélioration de la stabilité du virage en présence d'une accélération est donc illusoire.

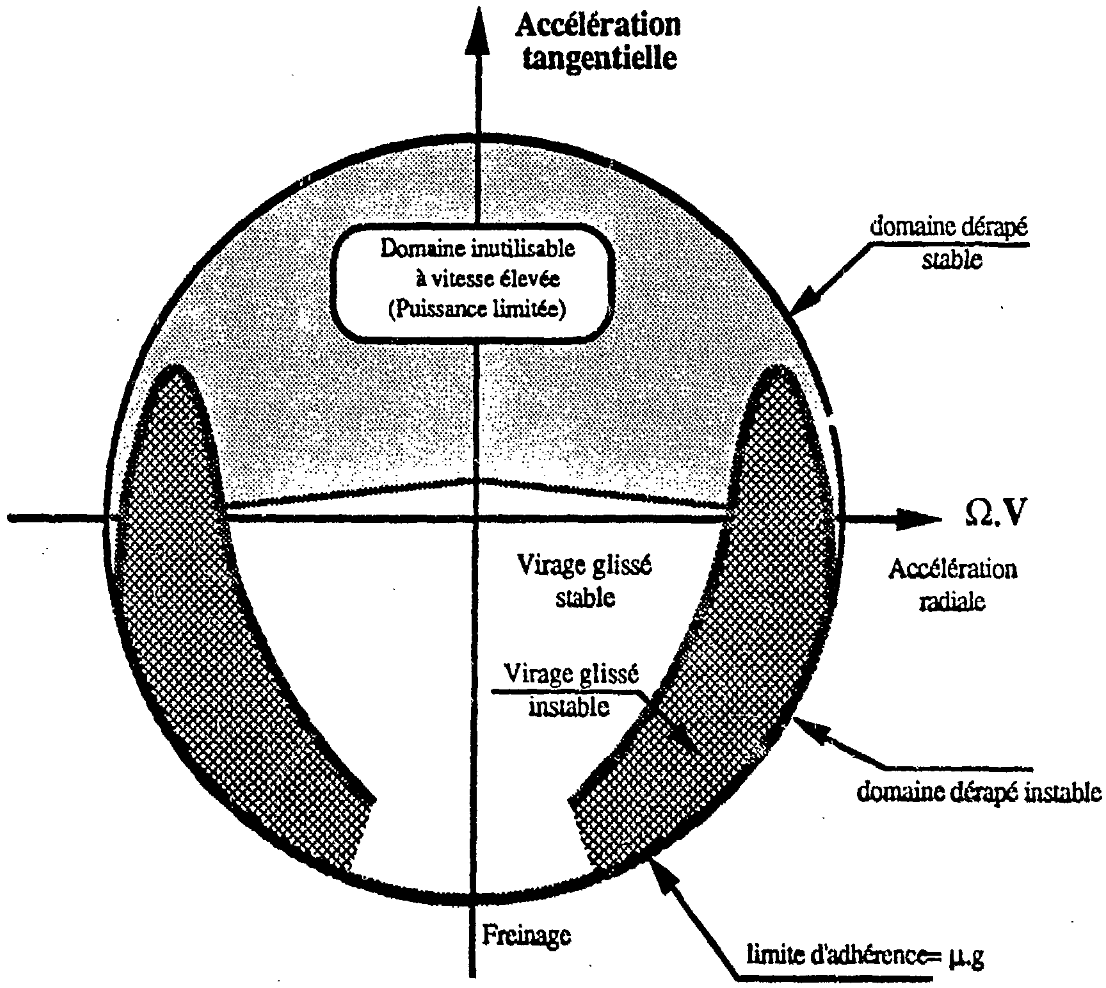

Figure 3-2-1- Domaine de stabilité naturelle d'un véhicule chenillé

Les courbes représentées sur la figure 3.2.2. donnent l'allure des caractéristiques statiques qui relient la vitesse différentielle des chenilles et la vitesse angulaire du véhicule et de sa trajectoire, sur laquelle le domaine instable correspond à la partie à pente négative.

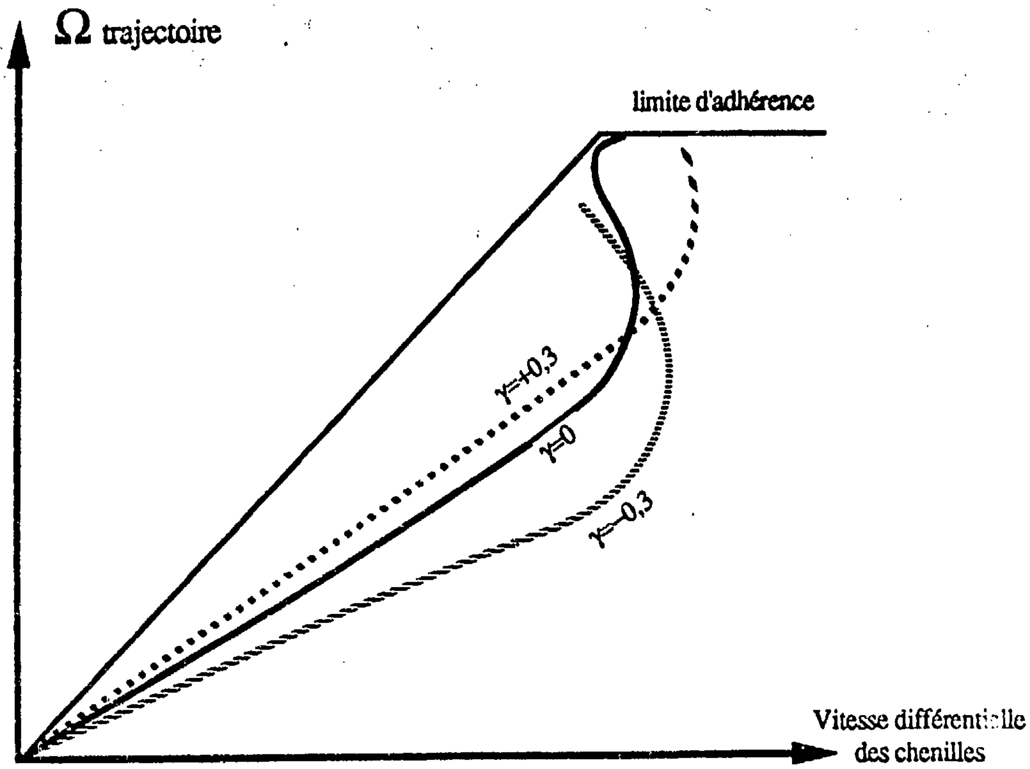

Figure 3-2-2- Virage d'un véhicule chenillé

NOTA :

Le schéma de la figure 3.2.1 laisserait supposer que tout le domaine grisé est théoriquement accessible, sous réserve d'une commande de direction adéquate. Ceci n'est que partiellement exact. En effet, on retrouve bien, sur ce type de véhicule le même genre de phénomène que sur les véhicules à roues directrices et qui concerne l'impossibilité théorique et physique d'exploiter totalement la possibilité maximale d'effort tangentiel véhicule-sol pour combiner une décélération le long de la trajectoire et une force centripète importante, en présence d'un transfert de charge axial dû à la hauteur du centre de gravité.

Sur la figure 3.2.3.on a représenté les modifications des caractéristiques obtenues par l'utilisation d'une loi de commande qui exploite la mesure des efforts latéraux sur les galets extrêmes. On notera, en particulier, que ce type de loi de commande permet de retrouver une relation biunivoque entre la commande donnée par le pilote, et la vitesse angulaire réalisée par le véhicule, et ce, en particulier en présence d'une force de décélération .On imaginera son intérêt sur un véhicule télécommandé qui, malgré les précautions prises par le pilote, peut se trouver surpris par une diminution brutale du coefficient d'adhérence qui peut momentanément placer le véhicule dans son domaine instable.

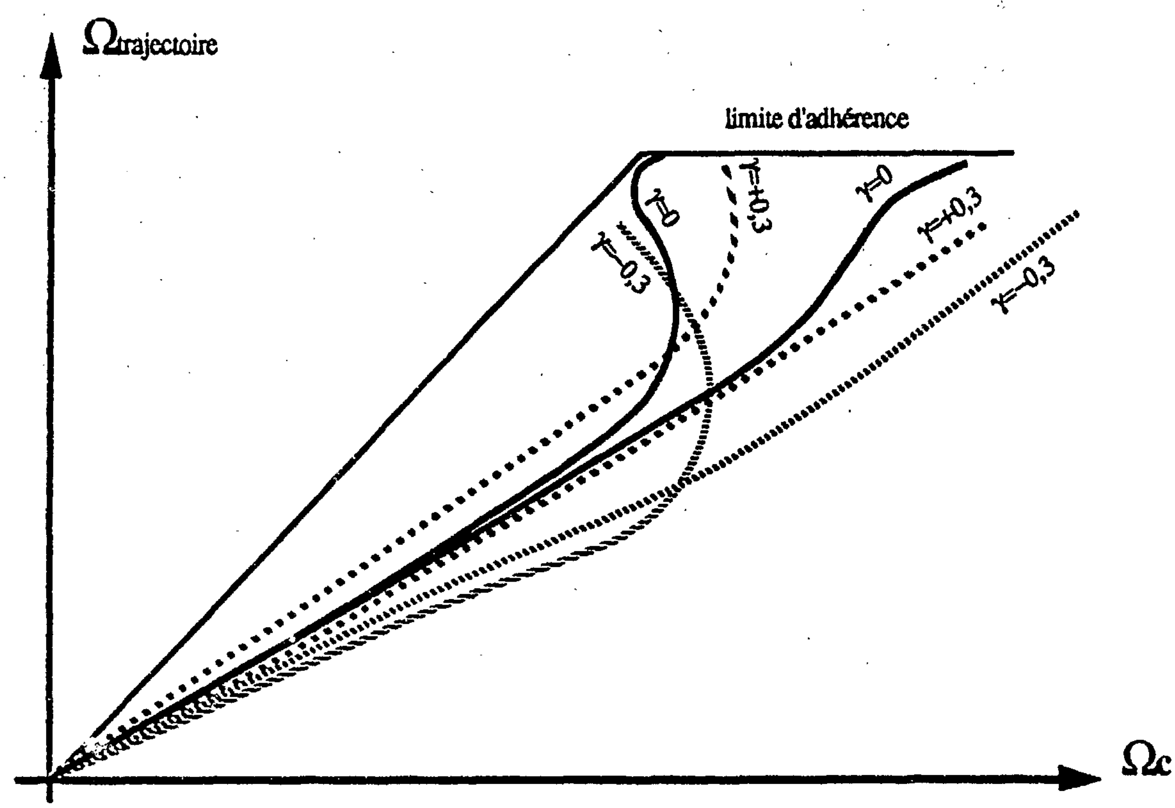

Figure 3-2-3- Stabilisation du virage d'un véhicule chenillé par contre-réaction d'efforts latéraux

En réalité, c'est surtout sur la limite du domaine que la perte du contrôle du véhicule risque d'apparaître. En effet, dès que les possibilités maximales de virage sont atteintes (limite d'adhérence), la vitesse angulaire du véhicule continue d'augmenter, alors que la vitesse angulaire de la trajectoire est bloquée à sa valeur maximale. Sur un véhicule chenillé, on montre également que la mise en place d'une très forte force propulsive aurait un effet stabilisant, dans le sens que cet effort a tendance à faire diminuer la vitesse angulaire du véhicule, mais cet intérêt n'est toujours que théorique, dans la mesure où ce type de véhicule ne dispose, en général que d'une faible force propulsive à grande vitesse.

On retiendra plutôt que tout effort de freinage appliqué sur les chenilles, alors que le véhicule a atteint sa limite d'adhérence, déclenche instantanément un départ en survitesse angulaire, amplifié par la présence d'un transfert de charge axial.

Des études sont en cours, d'une part pour compléter la connaissance théorique du comportement d'un véhicule chenillé en virage sous forte décélération, et d'autre part sur la recherche des moyens permettant de limiter automatiquement l'incidence du véhicule sur sa trajectoire lorsque des ordres supérieurs à ses possibilités lui sont donnés.

3.3. - STABILITE DYNAMIQUE DE ROULIS

Les véhicules destinés à se déplacer en terrains variés, à des vitesses moyennes (10 à 15 m/s), doivent disposer d'une garde au sol importante qui, associée à une largeur limitée les rend a priori sensibles au dévers dynamique du terrain.

Ces véhicules sont sensibles à des formes particulières du terrain qui font apparaître des vitesses angulaires de roulis importantes qui peuvent être à l'origine de décollements d'un demi-train.

Si ces variations dynamiques d'efforts sont combinés aux transferts de charge latéraux apparaissant en virage, on augmente les risques de retournement du véhicule.

Sur un véhicule piloté, ce risque est relativement limité, d'une part parce que le pilote voit l'ondulation du terrain qui va solliciter sa suspension, et d'autre part, apprécie les réactions de son véhicule, sollicité par le terrain et par les consignes de direction qu'il a pu donner pour sa propre stratégie de pilotage et pour aider le véhicule à absorber l'anomalie du terrain.

En télécommande, l'appréciation précise du terrain immédiat est délicate, et les retours instantanés du véhicule, difficiles et coûteux à mettre en œuvre.

La stabilité dynamique du roulis de certains véhicules télécommandés devrait pouvoir être artificiellement améliorée par l'exploitation de capteurs de terrain futur (à une dizaine de mètres) qui seraient exploités pour aider le véhicule à négocier l'obstacle.

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14. Résumé:

La mise au point d'un système mobile robotisé implique le développement de capteurs extéroceptifs fiables, le traitement de leurs signaux, la génération d'actions. L'ERM consacre ses recherches au guidage intelligent (ici, par l'algorithme A*) de prototypes-robots mobiles à déplacement (provisoirement) discret sur pattes (vérins), et, quand ces robots seront développés à dimension "champ de bataille" et équipés de caméras, à l'identification d'objectifs (chars) par circuits neuraux. Les résultats acquis sont présentés par cette première contribution.

(*)les des pays de l'OTAN et à leurs fournisseurs travaillant sous contrat en bonne et due forme. L'autorisation du Chef de la Section Recherches pour la Défense est requise pour la diffusion à d'autres destinataires.

1. Introduction

La robotique militaire s'intéresse à trois types de fonctions, l'information, le combat et la logistique. Chacune d'elles peut être caractérisée par différentes missions confiées à des systèmes statiques ou mobiles partiellement ou totalement robotisés. Ces fonctions et missions ont été décrites, notamment, dans (1) et résumées par le tableau 1. Les axes de recherche sousentendent une collaboration pluridisciplinaire. Nous avons souligné ceux qui nous préoccupent en priorité, et, parmi eux, l'identification d'objectifs par traitement d'images, à partir de réseaux neuronaux dans l'infrarouge thermique, le développement de prototypes-robots mobiles de laboratoire en vue de leur contrôle à partir de systèmes-experts. Cette première contribution présente ces deux aspects.

Tableau 1. Fonctions, missions et axes de recherche

Fonction	Missions	Axes de recherche
Information	Désignation des objectifs, identification, systèmes d'alerte Renseignement	Développement des capteurs Traitement d'images Systèmes statiques autonomes orientables ou télé-orientables, Systèmes mobiles autonomes Intelligence artificielle Télécommunications Traitement de la parole
Combat	Chars robotisés Artillerie automotrice,minage, déminage	Mécanique, dynamique,simulations Actuateurs hydrauliques ou autres Matériau, blindage, capteurs...
Logistique	Approvisionnement Réparations, décontamination déblaiements	Mobilité des robots Bras articulés polyvalents Cinématique et dtynamique Automates Servocommandes,etc.

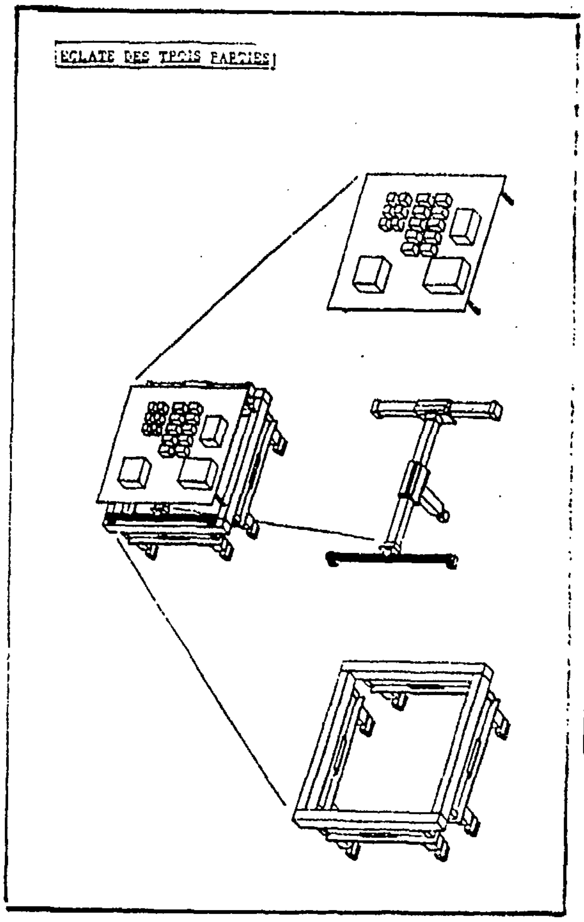
2. Développements de robots mobiles.

2.1. Architecture

Les prototypes développés,et actuellement utilisés en environnement intérieur ou en site extérieur propre, doivent permettre l'étude détaillée de leur cinématique, de leur comportement dynamique, de leurs propriétés mécaniques en vue d'une adaptation optimale à des conditions tout-terrain. Ils doivent également permettre l'étude de différents types de capteur, la mise au point de cartes électroniques d'interface vers des ordinateurs, le développement de systèmes-experts de contrôle et de commande. La démarche que nous avons adoptée est en fait voisine de celle qui préside au développement du projet Eurêka AMR (2) ou du projet PAMIR (3).

2.1.1. Robot mobile cartésien à 2 degrés de liberté.

Le premier prototype développé, dont la figure 1 ci-dessous présente une vue éclatée, présente un cadre portant de 650 mm de côté, assurant la mobilité de l'ensemble, un support mobile de sonde et un panneau de commande. Le cadre est pourvu, sous chaque côté, d'un vérin pneumatique sans tige double-effet, dont le curseur déplace une béquille horizontale elle-même pourvue à ses extrémités de deux vérins élevateurs double-effet terminés par une ventouse. Lorsque les ventouses sont activées, elles maintiennent les béquilles dans leur position courante et l'alimentation en air comprimé de deux vérins sans tige parallèles provoque le déplacement du cadre: la commande d'un tel mouvement, possible suivant deux directions orthogonales, est donc séquentielle. Elle est résumée en six étapes par la figure 2. Le terme "béquille" est choisi par analogie au mode de déplacement utilisé par un unijambiste s'aidant de deux béquilles qu'il déplace d'abord vers l'avant (étapes 1 à 4) avant de déplacer son propre corps (ici, le cadre) dans cette même direction. Les vérins élevateurs permettent d'autre part, si nécessaire, le franchissement de faibles dénivellations. Le robot peut être équipé d'un système imposé par la mission qui lui est confiée. Dans ce cas, il possède un système orthogonal tridimensionnel de balayage permettant le déplacement d'une sonde sur la surface délimitée par le cadre. Enfin, le panneau de commande supporte les distributeurs électro-pneumatique, le boîtier électrique des connexions vers ces distributeurs et vers les capteurs inductifs fin-de-course du système de balayage, vers un capteur à ultrasons monté au sommet de ce panneau et destiné au balayage extéroceptif de l'environnement du robot.
La commande du robot est assurée par un automate transitionnel programmable tandis que les impulsions nécessaires à l'activation de cet automate sont délivrés par un PC 386 où réside le système-expert décrit ultérieurement.
Le robot est actuellement pourvu d'un cordon ombilical d'alimentation en 24 V et en air comprimé. Son adaptation aux conditions extérieures impliquerait une motorisation de base électrique ou thermodynamique, le remplacement des vérins pneumatiques par leur équivalent amplificateur hydraulique, enfin le remplacement des ventouses par des roues ou par des chenillettes.
Le robot ainsi développé pèse 50 daN. Les déplacements sont, pour une séquence de 6 étapes, quantifiés à 20,08 cm et 29,98 cm en moyenne: ces valeurs liées à la course des vérins sont différentes, en X et Y, pour éviter la collision des béquilles, et mènent à une précision inférieure à 5/10.000.



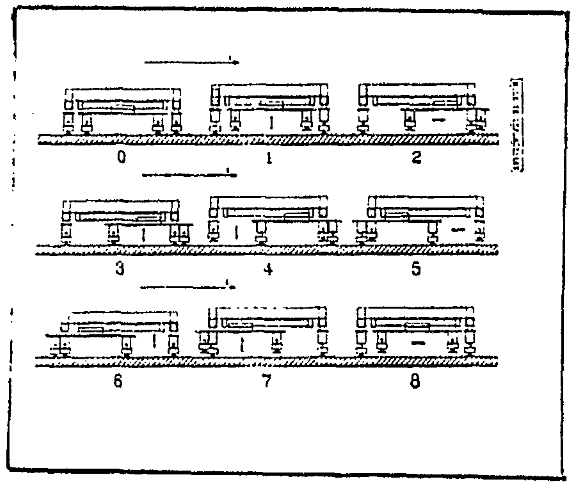


Fig 1. Vue éclatée du robot AMRUA Fig 2. Séquence d'un mouvement

En annexe, la photo 1 présente une vue "ouverte" du robot baptisé AMRUA (automate mobile piloté par une reconnaissance par ultrasons et l'algorithme A*), tandis que la photo 2 décrit le système de balayage: ce dernier permet de destiner le robot, adapté, à trois genre de mission: déminage par détection surfacique, décontamination par aspersion surfacique, inspection logistique en dotant la sonde de capteurs appropriés. D'autres types de mission peuvent aussi être imaginées. L'architecture mécanique est incontestablement avantageuse pour l'évitement d'obstacles si on la compare à celle de véhicules à roue. On a néanmoins cherché, en conservant le principe des béquilles plutôt (au stade actuel) que celui des jambes (legs), à développer une structure à trois degrés de liberté.

2.1.2. Robot mobile à 3 degrés de liberté.

Baptisé ROMOCAN (robot mobile piloté par caméra et circuit neuronique), il est schématiquement décrit par la figure 3 ci-dessous.
Son architecture est constituée de trois grandes parties:-un pied central attaché sous - un plateau intermédiaire, le tout surmonté d'- un cadre. Le robot peut reposer sur deux groupes de ventouses, trois ventouses sous le pied central ou quatre ventouses fixées au bord extérieur du cadre.

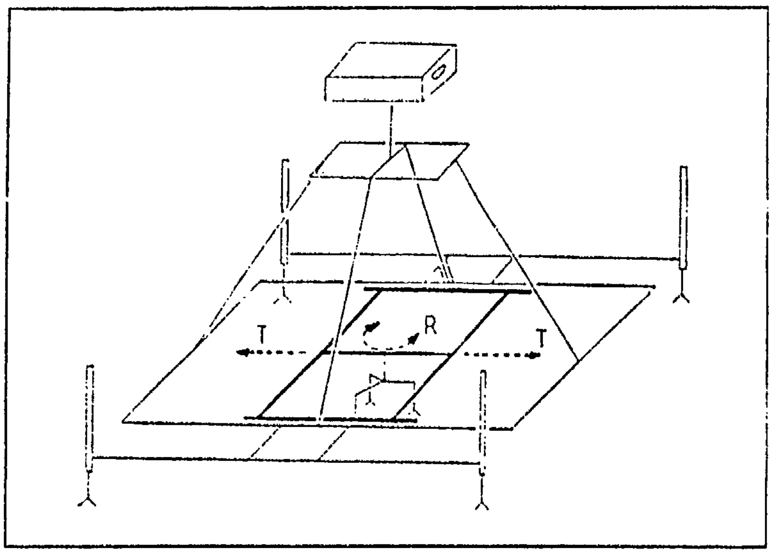


Fig 3. Le robot ROMOCAN

Les mouvements relatifs entre les différentes parties principales sont:

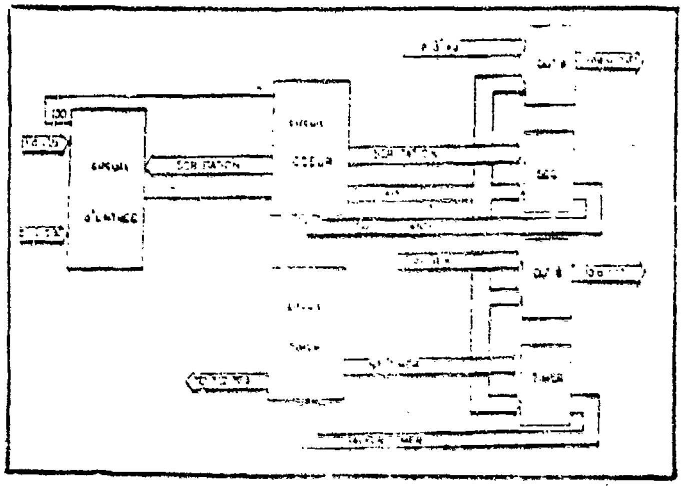
- une rotation R de l'ensemble plateau intermédiaire et cadre autour du pied central lorsque les ventouses de ce dernier sont activées, ou inversément, une rotation du pied central quand le robot est fixé par les ventouses extérieures du cadre.
- une translation T de l'ensemble plateau intermédiaire et pied central par rapport au cadre lorsque le robot est posé sur les "pattes" extérieures de celui-ci, et inversément quand le robot est appuyé sur le pied central.

Trois moteurs électriques à courant continu, équipés de réducteur, assurent les mouvements précités auxquels s'ajoute la rotation de la caméra fixée au sommet du cadre pyramidal. Les pattes extérieures sont elles des vérins élevateurs double-effet. Une rotation de ces vérins autour d'un axe horizontal, perpendiculaire à l'axe T repris sur la figure 3, permettra ultérieurement d'étudier le comportement du robot "quadrupède". La photo 3 de l'annexe donne une vue d'ensemble du robot tandis que la photo 4 présente le motoréducteur assurant la translation du cadre via crémaillère et donne également une vue du moteur de caméra et d'un vérin extérieur. Ce robot, fonctionnant sur les mêmes principes que ceux de l'ANRUA, permet cependant un déplacement dans toutes les directions, sur une surface plane ou légèrement convexe (170 mm de rayon de courbure) ou concave (274 mm). L'ensemble pèse environ 8 daN et peut être enveloppé (caméra inclue) dans un parallélipipède rectangle de 30 x 26 x 34 cm. Il est directement commandé, via cordon ombilical électrique et pneumatique, à partir d'un PC 386. Il est destiné à la reconnaissance d'objectifs (ou d'obstacles) par caméra.

2.2. Electronique et informatique.

Les deux prototypes sont électro-pneumatiques et alimentés en air comprimé et courant continu par cordon ombilical d'environ 8 m.

AMRUA : la commande des déplacements du cadre est confiée à un séquenceur logique programmable, le TRANSIMATE (4), dont les réactions se fondent, non sur l'état des entrées logiques, mais sur les transitions d'un état bas à un état haut (0 et 5 V) de ces entrées.
La carte transimate développée est reprise en figure 4: elle présente 30 lignes d'entrée, chacune d'elles pouvant être inhibée, lues successivement (1 microseconde/entrée) et comparées à leur état précédent par un circuit "coeur": en fonction de l'étape courante et de la transition observée, 16 fonctions de sortie ou 3 temporisateurs peuvent être activés. Cette carte n'utilise pas de microprocesseur mais 4 EEPROMs (out0,SEQ,out1,Timer) dont le chargement est assuré à partir d'un PC supportant un programme dont l'exécution impose simplement à l'utilisateur de remplir 4 tableaux de type "étape-action".
Le PC supporte d'autre part le programme Pascal traduisant la stratégie A✱ d'évitement d'obstacles: deux autres cartes électroniques ont donc été développées (5); l'une, montée sur le PC, assure la génération d'impulsions vers le transimate, la commande d'un moteur électrique supportant un capteur extéroceptif à ultrasons POLAROID, et la commande du capteur lui-même; l'autre, montée sur le robot, assure le traitement des signaux en adaptant leur niveau aux capteurs, moteurs et électrodistributeurs utilisés.



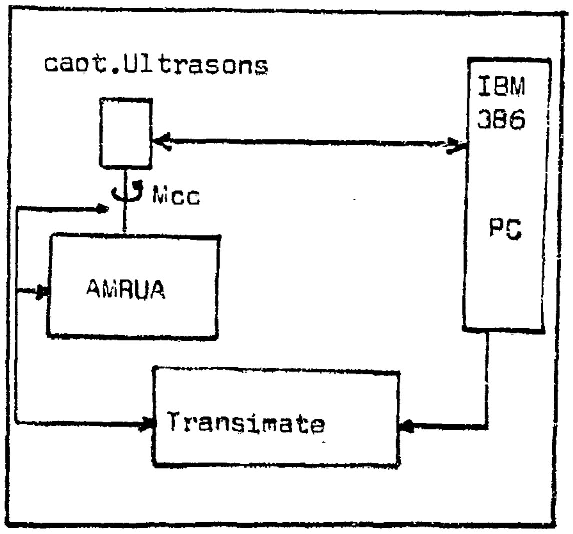


Fig.4 La carte Transimate

Fig 5. Schéma de contrôle

ROMOCAN : tandis que la figure 5 donnait le schéma général développé pour le robot précédent, la figure 6 suivante reprend l'architecture de commande de ROMOCAN. Aucun séquenceur logique n'est utilisé, la commande est directement confiée au PC (programme Pascal): une carte d'entrées/sorties FCP-024 de Flytech Technology (6) a été utilisée et montée sur le PC, tandis que deux cartes, une reprenant la partie logique des circuits capteurs, l'autre la partie puissance des moteurs et électrodistributeurs, sont montées sur le robot. Des capteurs optiques incrémentaux rotatifs d'une précision de 2° accompagnent chaque moteur, tandis que des capteurs fin de course gèrent la translation du cadre intermédiaire.

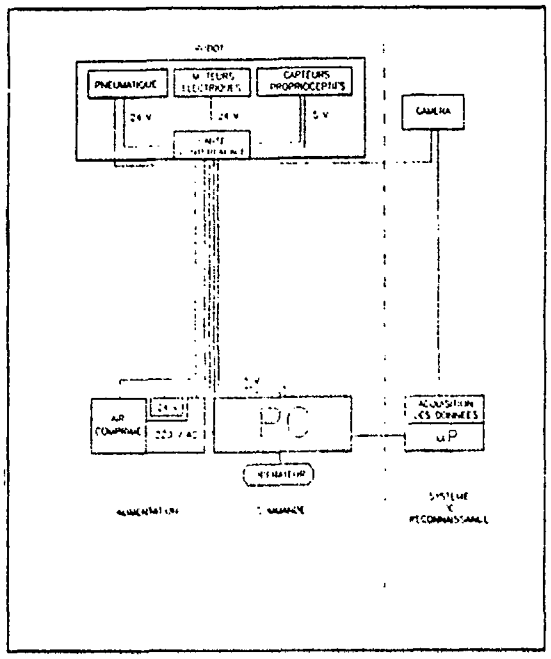


Fig 6. Schéma de contrôle Romocan

Ce dernier robot est donc un vecteur de transport d'une caméra de surveillance Ikegami ITC-410 de faible masse (1,8 kg); le premier est surmonté, lui, d'un capteur à ultrasons Polaroïd permettant la détection d'obstacles par calcul de leur distance au robot et non par identification.
Le paragraphe 3 décrira la stratégie d'évitement d'obstacles appliquée au robot AMRUA, tandis que le paragraphe 4 décrira l'identification d'objectifs. Dans le premier cas, le capteur est simple car l'accent repose d'abord sur le contrôle intelligent d'un robot mobile dont les déplacements sont imposés constants; dans le second cas, l'accent repose sur le traitement des signaux d'identification et d'images qu' un déplacement du robot ou une rotation du robot permet éventuellement d'affiner.

3. Algorithme A* appliqué à la mobilité intelligente.

3.1. Algorithme A*

L'algorithme A* est connu et, par exemple, décrit dans (7,8,9). Dès l'instant où le problème géré, en l'occurence l'évitement d'obstacles par un robot mobile, peut être modélisé par un graphe composés de noeuds n et d'arcs les reliant entre eux et associés à une fonction coût, il peut être appliqué.

3.1.1. Modélisation de l'environnement.

Le robot AMRUA est équipé d'un capteur à ultrasons monté sur un moteur à cc dont une rotation incrémentale peut être programmée. Ce capteur présente, rappelons le, trois inconvénients: l'intensité sonore décroît comme le carré de la distance et est atténuée par la viscosité provoquant des pertes dépendantes de l'humidité de l'air et de la fréquence de l'onde transmise; ses performances sont affectées par la vitesse du son, donc dépendent de la température et de la vitesse et direction du vent; la largeur du faisceau, enfin, le "beam angle" dépend du diamètre du capteur et de la fréquence: cette dernière est ennuyeuse car une fréquence élevée réduit la largeur du faisceau mais augmente l'atténuation du signal et donc réduit la portée. Enfin, deux types d'erreur doivent être traités: l'erreur de distance liée au "beam angle" dûe au fait que la distance mesurée est la distance à l'objet le plus proche (fig.7) et l'erreur de non-détection dûe à la réflexion spéculaire (fig.8)

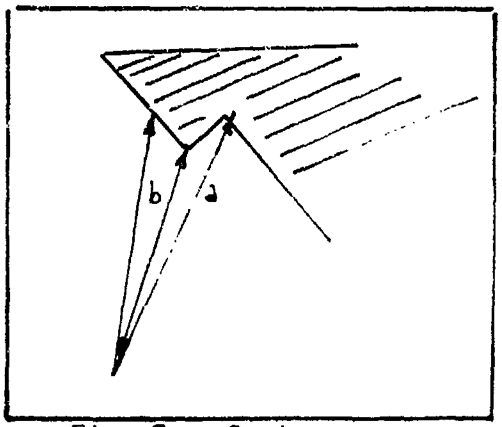


Fig. 7 a.Desired measurement
b.Actual reading

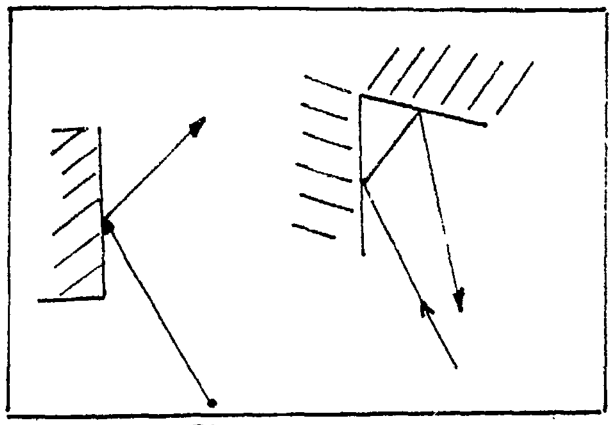


Fig. 8

Ces erreurs peuvent être minimalisées par répétition de mesures sous différents angles. Elles se traduisent néanmoins par un traitement logiciel plus lent et une commande plus sophistiquée.

Le mode de représentation de l'environnement utilisé se base sur une division de celui-ci en cellules de 10 cm de côté (voir dimensions du robot) qui sont soit vides (d'obstacles), soit occupées, soit inconnues. Lors de la rotation du capteur, chaque "vision" engendrera un triangle de précision dont l'angle au sommet(le capteur) est imposé par l'incrément (7°) et la hauteur par la distance à l'obstacle le plus proche ou par la portée maximale programmée (4 à 5 m dans notre cas).

Chaque triangle de précision est ensuite traité: les cellules intérieures aux triangles sont vides, les cellules interférant avec le polygone de visibilité construit à partir des triangles de précision successifs sont occupées ou inconnues. Pour réduire le temps de calcul un algorithme récursif simple est utilisé: partant d'un point connu intérieur au contour et d'une discrétisation du contour sous forme de pixels, l'environnement est engendré: exemple figure 9.

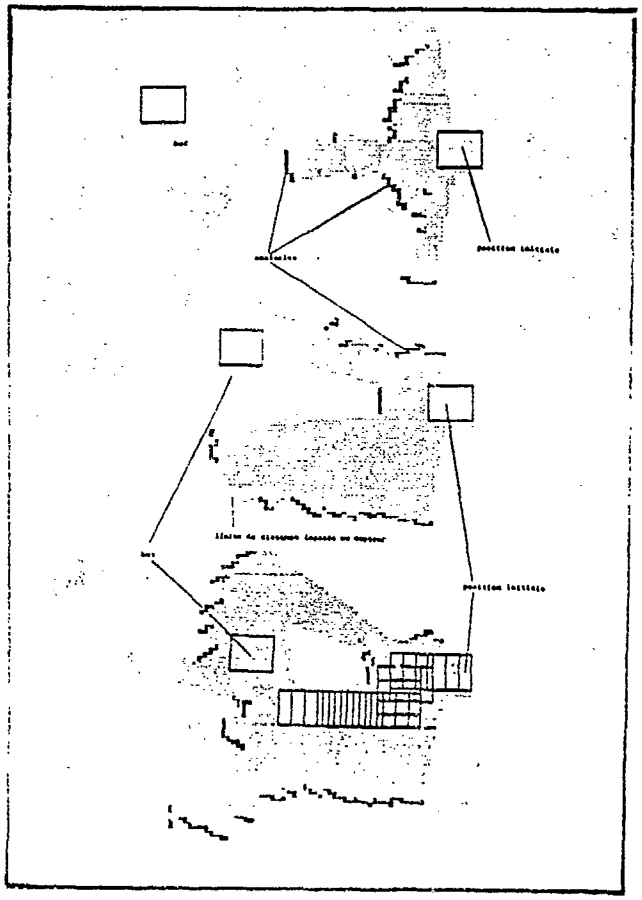


Fig 9. Carte de l'environnement

Lors des visions ultérieures (déplacements du robot), la carte de l'environnement doit être actualisée: pour chaque cellule, on garde en mémoire son état précédent, la distance qui la séparait du robot, l'étape la plus récente à laquelle elle a été traitée, le nombre de fois qu'elle a été vue pleine ou vide. Après chaque déplacement du robot (hypothèse d'obstacles mobiles), une nouvelle vision n'affectera l'état d'une cellule que si sa position actuelle est MOINS distante de celle du robot que lors de l'étape précédente.

3.1.2. Génération de trajectoires

L'espace de travail du robot est ramené à une grille bidimensionnelle de points répartis suivant les deux axes X et Y. Chaque point représente une position à laquelle le robot peut se rendre et constitue un noeud du graphe, pour autant que les cellules en contact avec le robot placé en (X,Y) soient vides ou inconnues.

La structure du robot et ses quatre déplacements possibles (X+, X-, Y+, Y-) limitent déjà le nombre de noeuds susceptibles d'être générés. La fonction heuristique de l'algorithme A* est définie par:

$$F'(n) = W_g . G'(n) + W_h . H'(n)$$

Si Xn et Yn représentent les coordonnées du noeud n et Xb, Yb celles du noeud "but" préalablement choisi, H'(n) représentera la distance

$$H'(n) = \sqrt{(Xn-Xb)^2 + (Yn-Yb)^2}$$

(en fait, cette distance est fictive dans le cas du robot AMRUA ne disposant que de deux degrés de liberté)
tandis que G'(n) sera une estimation (les incréments de déplacement sont fixes mais sujets à imprécision) de la distance parcourue du noeud actuel ou courant au noeud n. W_g et W_h sont des coefficients de pondération permettant une recherche de type "breadth-first, W_g=1; depth-first, W_h=1; ou best-first, W_g=W_h" si on minimise F'(n).

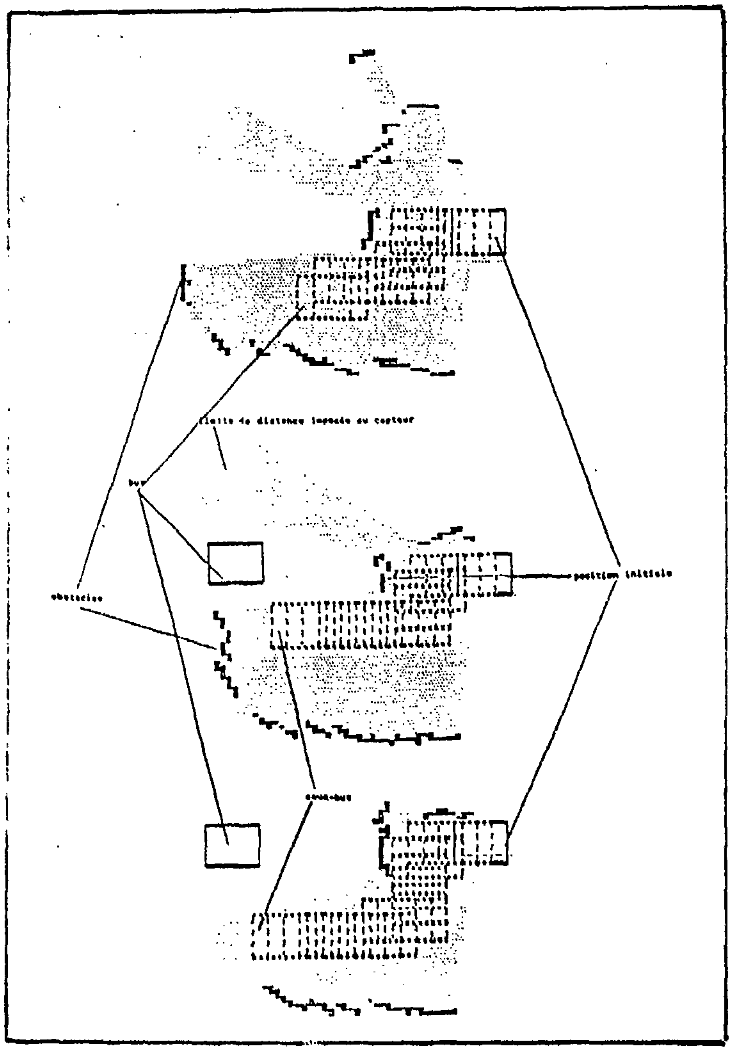


Fig 10. Exemples de trajectoires engendrées.
(Wg=0,7 ; Wh = 1,5 ; Dmax = 4 m)

3.2. Génération de sous-buts.

Lorsque l'objectif à atteindre est "invisible" ou le devient, il est nécessaire de générer un sous-but, dit prometteur s'il est proche d'une frontière avec l'inconnu d'où le capteur du robot pourra procéder à un balayage susceptible de compléter sa carte de l'environnement et de voir le but final. Au stade actuel, bien qu'on commence à pressentir l'intérêt de l'introduction des probabilités, un sous-but prometteur sera choisi dans la liste "CLOSED" (liste des noeuds déjà traités) triée sur une valeur-type définie par:

0 : un déplacement à partir de n n'entraîne aucune collision.
1 : entraîne une collision avec un obstacle seulement
2 : entraîne une collision avec un obstacle et l'inconnu
3 : entraîne une collision avec le seul inconnu.

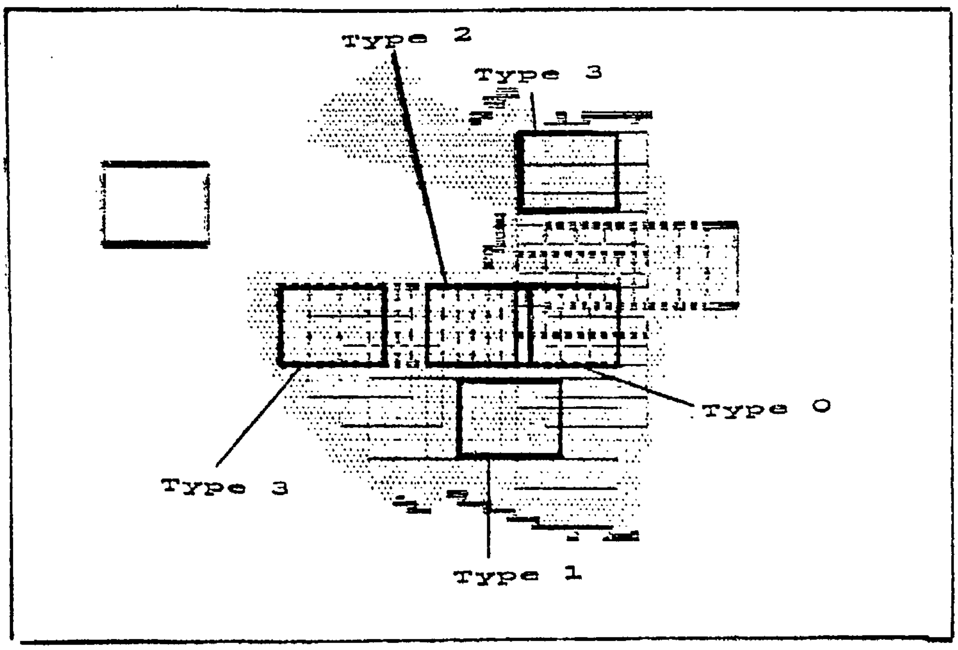


Fig 11. Valeurs-types

Un sous-but de valeur-type 3 sera préféré aux sous-buts de valeur-type inférieure.
L'algorithme décrit est particulièrement performant en site couvert et dans l'hypothèse d'obstacles fixes entre visions successives. Nous entamons à présent l'étude moins simple de la mobilité en site ouvert tandis que le programme résumé ci-dessus et entièrement décrit dans (10) est progressivement complété, empiriquement, sur base des observations de laboratoire.

4. Reconnaissance d'objectifs.

4.1. Le problème de la reconnaissance.

On développe ci-dessous une façon de concevoir la construction d'un système destiné à la reconnaissance automatique, en infrarouge thermique, d'objectifs 3-D situés dans une scène complexe et dont l'aspect est fonction de la distance. L'expertise nous apprend que le processus de reconnaissance est essentiellement fonction de la distance. On a, pour cette raison, distingué deux cas différents: le premier cas concerne les images dans lesquelles l'objectif peut être décomposé en un ensemble de primitives, le second les images pour lesquelles cette décomposition est impossible. On entend par primitive un objet, élément de l'objectif, qui possède ses propres attributs et qu'on peut décomposer en d'autres primitives, ce théoriquement jusqu'au niveau "atomique" Un char de combat peut par exemple être décomposé dans les primitives suivantes: tourelle, canon, train de roues, chassis et moteur. Le train de roues peut à son tour être considéré comme composé de roues, d'un crabotin, d'une chenille, et ainsi de suite. Le choix proprement dit de la méthode de reconnaissance est considéré comme un processus flou pour les raisons suivantes:

- la résolution de l'objectif dans l'image est essentiellement variable à cause des conditions atmosphériques et de la résolution propre au système d'imagerie utilisé.
- les méthodes de reconnaissance utilisées sont fonction de la distance du système de prise de vue à l'objectif et leurs limites d(utilisation ne sont pas figées.

Le tableau 2 ci-dessous montre un exemple de correspondance entre la notion floue de distance introduite par l'expert et les observations corespondantes.

Concept flou de DISTANCE	Description de l'objectif
très longue distance	Points chauds: pas de reconnaissance possible.
longue distance	forme globale de l'objectif
distance moyenne	composition de l'objectifs en primitives
courte distance	description atomique

Tableau 2. Exemple de correspondance entre la notion floue de distance et la description de l'objectif.

4.2. Choix de la méthode de reconnaissance.

Puisque la méthode de reconnaissance dépend de la distance, on attribue à chaque procédure k de reconnaissance une fonction d'appartenance $x_k(d)$ qui décrit en quelque sorte la fiabilité du choix k relativement à la distance d entre l'objectif et le système de prise de vues.

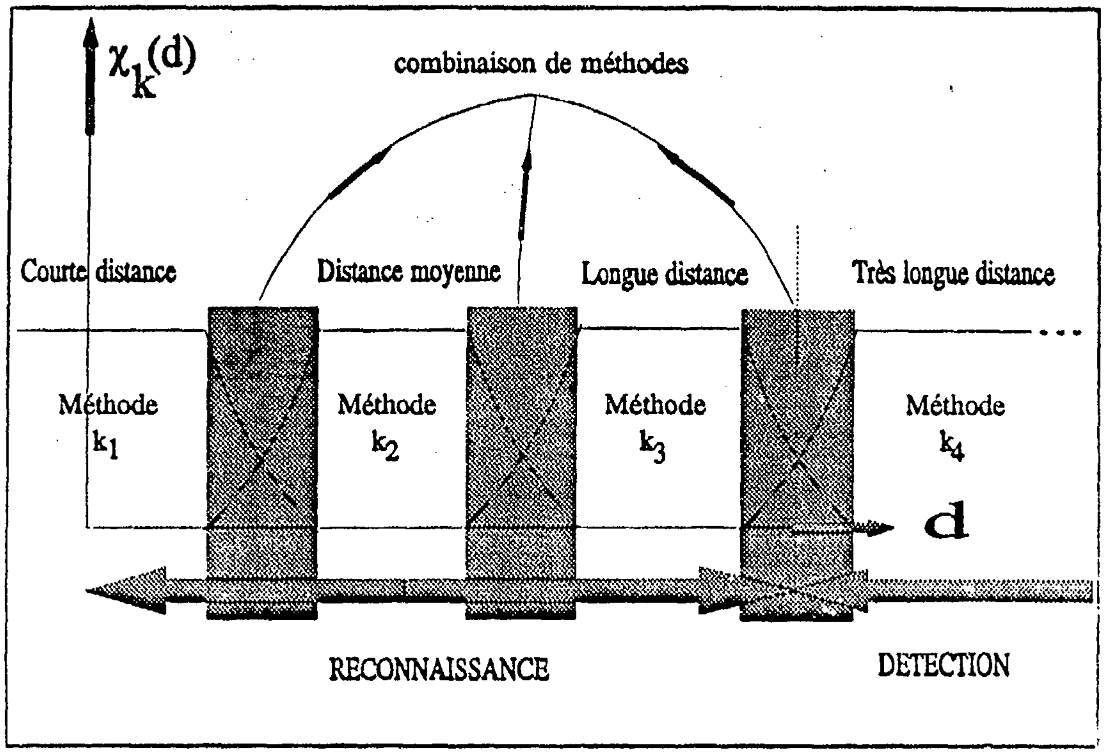


Figure 12. Exemple de fonctions d'appartenance.

La figure 12 est un exemple de subdivision de l'échelle des distances par l'intermédiaire des différentes fonctions d'appartenance et des méthodes de traitement correspondantes. Dans ce qui suit, on ne présentera que les méthodes relatives à la reconnaissance, çàd pour des distances caméra-objectif courtes, moyennes ou longues (tableau 2).

4.3. Reconnaissance à courte, moyenne et longue distance.

4.3.1. L'objectif peut être décomposé en ensemble de primitives.

Il s'agit des conditions particulières où il est possible de faire la distinction entre différentes primitives de l'objectif dans une même image. L'objectif peut être vu comme un objet tridimensionnel décrit par les primitives et leurs caractéristiques propres. Il ne faut néanmoins pas perdre de vue que le système à construire est destiné à traiter les images de sortie bidimensionnelles du système d'observation. Une solution au problème de reconnaissance peut être trouvée dans le développement d'un système expert relativement simple (11)

4.3.1.1. Construction de modèles 3-D

La première étape de la méthode consiste à construire une banque de données contenant la description des modèles 3-D des objectifs. Ces modèles sont constitués de primitives hiérarchisées en fonction de la distance, de sorte qu'à une classe de distances donnée, relative à une foction d'appartenance spécifique, (voir la notion de fonction d'appartenance décrite ci-avant) correspondent des primitives de l'objectif qu'il est possible de distinguer à la distance considérée. Les figures 13 et 14 donnent des exemples de relations entre primitives.

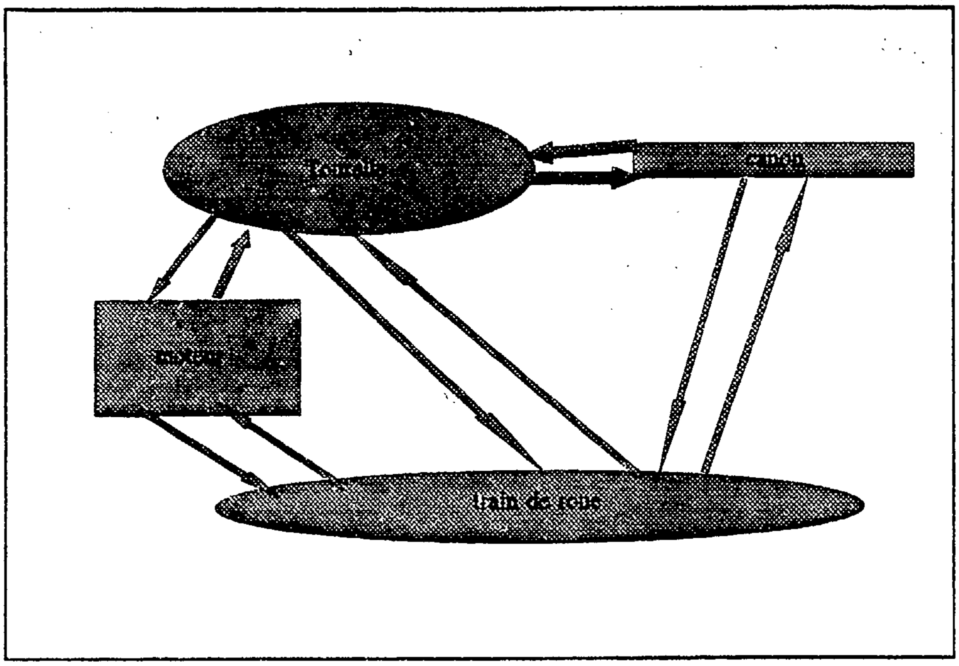


Figure 13. : exemple de graphe géométrique

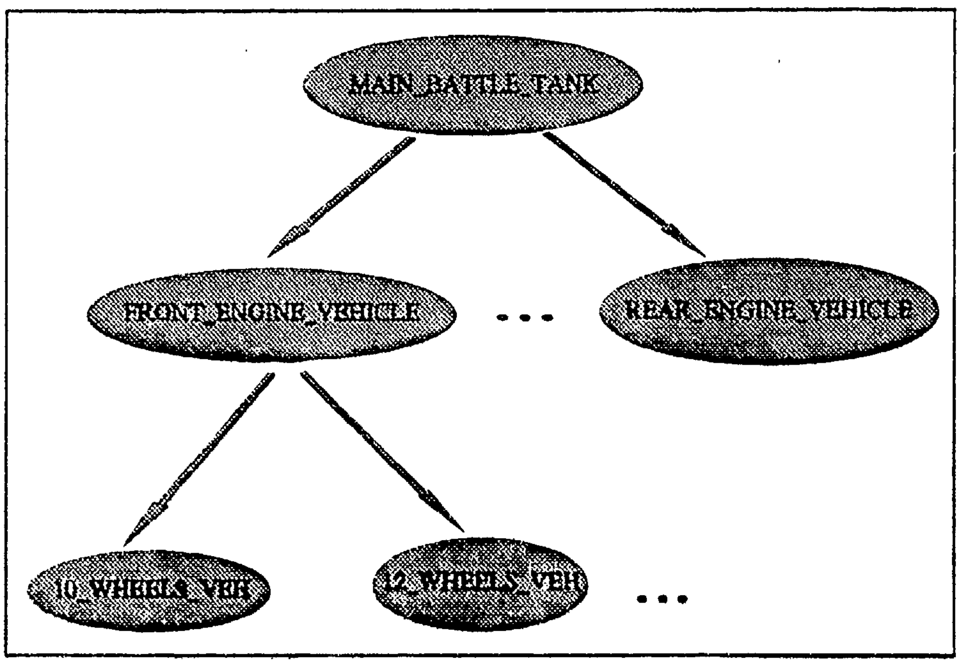


Figure 14. : exemple d'un graphe sémantique de type

4.3.1.2. Recherche de la meilleure projection 2-D

La seconde étape consiste à rechercher, parmi toutes les projections possibles des modèles dans le plan image, celle qui correspond le mieux avec l'image-sortie du système d'observation. Cette recherche peut être optimalisée en tenant compte de règles particulières tirées de la connaissance à priori que l'on a de l'objectif et de la scène.

4.3.1.3. Caractéristiques de la solution.

- Un traitement préalable des images est souvent nécessaire pour réduire le bruit (surtout en infrarouge thermique)
- Un objectif peut être reconnu à partir d'un nombre limité de primitives
- Il est indispensable de construire une base de connaissance relativement élaborée et complexe.
- La méthode permet une segmentation dynamique de l'image, à cette intention, on attribue une méthode de segmentation particulière à chaque primitive.
- La recherche d'une primitive particulière dans l'image est un processus local et est donc limitée à une petite partie de l'image.

4.3.2. L'objectif ne peut pas être décomposé en primitives.

Dans ce cas, seule une forme globale de l'objectif est disponible sur l'image, et une méthode globale de reconnaissance des formes s'impose souvent. La manière classique de procéder consiste à effectuer tout d'abord une segmentation de l'image, ensuite, à déterminer les caractéristiques propres (features) de chacune des réfions obtenues et enfin à opérer une classification optimale de ces régions au sens d'un critère particulier. Une méthode moins classique consiste à appliquer directement ou indirectement aux données des méthodes basées sur les modèles connexionnistes, appelés aussi réseaux de neurones artificiels ou encore mémoires associatives.

4.3.2.1. Méthodes classiques.

LA SEGMENTATION

Le traitement préalable à tout autre consiste dans ce cas à opérer une partition de l'image en sous-images ou régions, éventuellement disjointes qui idéalement correspondent aux différents objets qui composent l'image. On citera par exemple: la segmentation par seuillage des niveaux de gris, segmentation par croissance de régions, segmentation par regroupement de pixels (clustering), segmentation par transformée de distances, segmentation par regroupement de régions, segmentation par modèles de Markov cachés, etc.

LA RECHERCHE DES CARACTERISTIQUES DES REGIONS

Cette opération fait logiquement suite à la précédente et peut consister à rechercher des grandeurs caractéristiques et/ou descriptives d'une région dans le but de la distinguer des autres (discrimination) et ultérieurement de la reconnaître comme objet ou partie d'objet (identification). On citera, à titre indicatif, quelques caractéristiques fort utilisées, à savoir:

- les moments géométriques principaux du premier et du second ordre, qui offrent l'avantage d'être invariants en translation et en rotation.
- les grandeurs caractéristiques de la texture (12)
- la description des contours, par exemple sous forme d'une suite de couples (longueur, orientation) ou encore d'une suite de codes résultats de l'application d'une grammaire prédéfinie (13),
- etc.

LA CLASSIFICATION

Cette opération consiste à classer le plus correcetement possible les régions décrites par leurs attributs et obtenues lors des étapes précédentes (14).

4.3.2.2. Méthodes utilisant les réseaux connexionnistes.

Les réseaux connexionnistes sont composés d'éléments de calcul non-linéaires élémentaires (voir figure 15) dont l'entrée est la somme pondérée des signaux d'entrée et dont la sortie est généralement la signature (-1,+1) de la somme obtenue. Ces éléments de calcul sont organisés en couche, de sorte que chaque élément d'une couche est relié à tous les éléments de la couche précédente (voir figure 16)

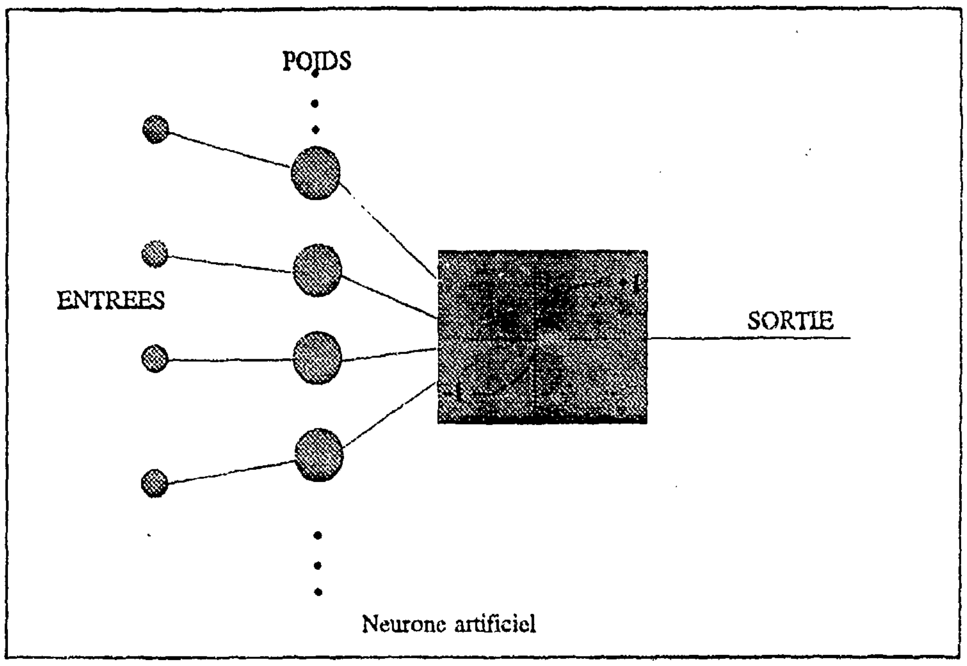


Figure 15. : élément de calcul élémentaire

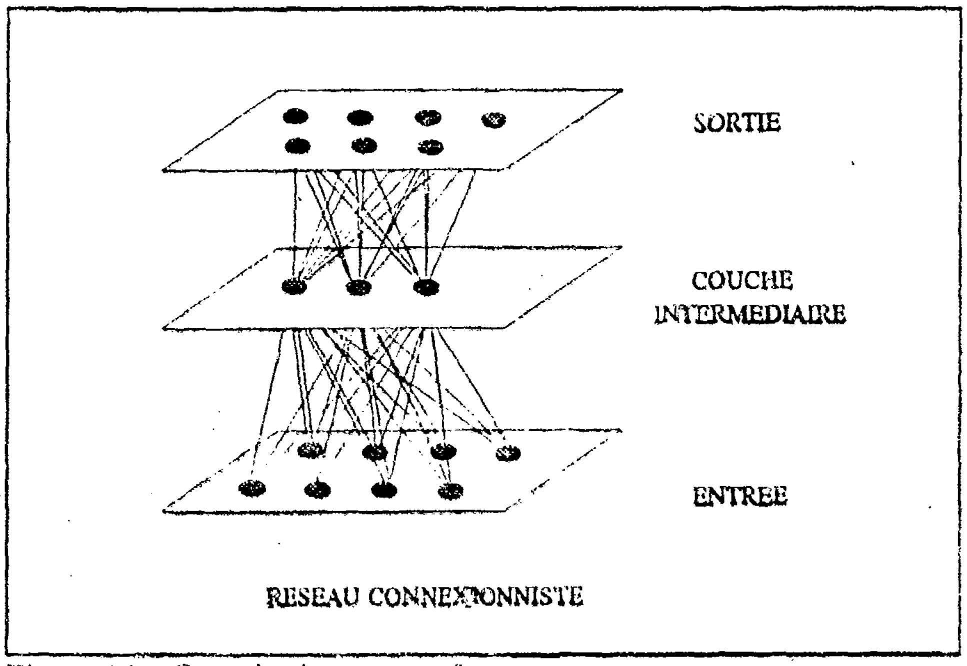


Figure 16. : Organisation en couches

On présente très brièvement ci-dessous un réseau particulier capable d'apprendre par lui-même et qui a été développé par S.Grossberg (15): il s'agit des modèles ART (Adapatative Resonance Theory) décrits à la figure 17.

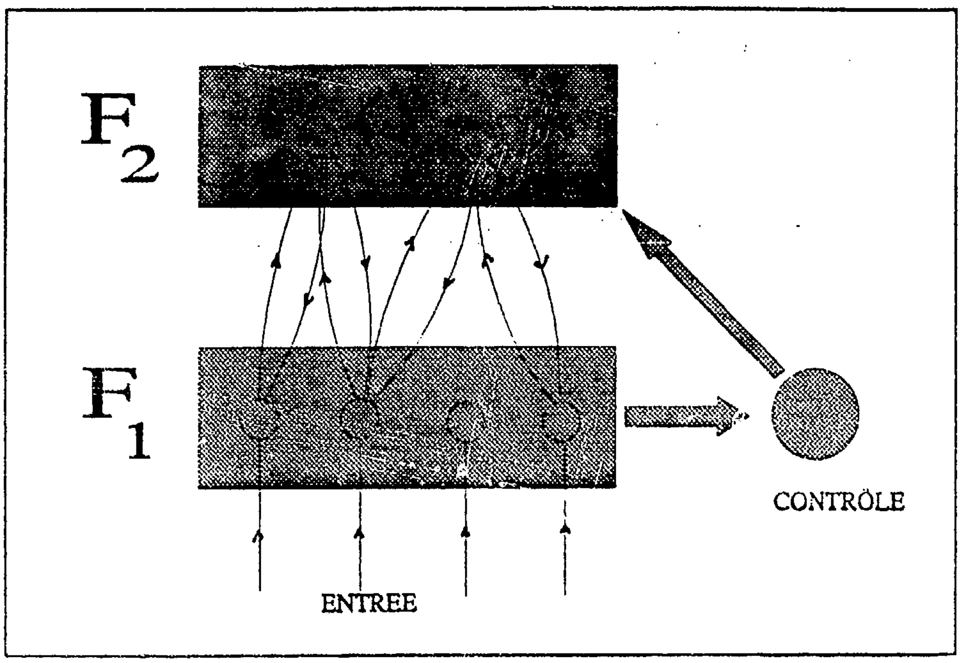


Figure 17. : réseau ART (Adaptive Resonance Theory)

L'information entrante (une image et/ou ses attributs) est transmise à la couche F1 et est comparée à l'information déjà mémorisée précédemment et représentée par un neurone de la couche F2. Si la différence entre les deux informations (à savoir celle de l'entrée et celle déjà mémorisée) est jugée négligeable par un organe de contrôle, le système admet que l'information d'entrée correspond à celle déjà mémorisée par le neurone de la couche F2 interrogé et adapte ses connaissances en adaptant le poids des connexions entre couches. Au contraire, si l'organe de contrôle juge que les deux informations ne correspondent pas, le système désactive le neurone interrogé de la couche F2 et essaie le suivant. Si d'aventure, aucun neurone de F2 ne satisfait, le système crée une nouvelle "classe d'information" en créant un nouveau neurone dans la couche F2. Lorsque les grandeurs d'entrée sont logiques, le réseau est appelé ART1, lorsque ces grandeurs sont analogiques le réseau est appelé ART2.
Dans le cas de ART1, l'entrée du système est constitué par des images binaires obtenues par seuillage des images résultats du filtrage des images originales par un filtre passe-haut destiné à faire ressortir les contours.
Dans le cas de ART2, l'entrée du système est constituée par les images originales.
Les éléments d'image de la figure 18 représentent le type d'objectifs concernés. Les résultats obtenus dans les deux cas sont très prometteurs (15)

4.3.2.3. Caractéristiques des méthodes connexionnistes ART.

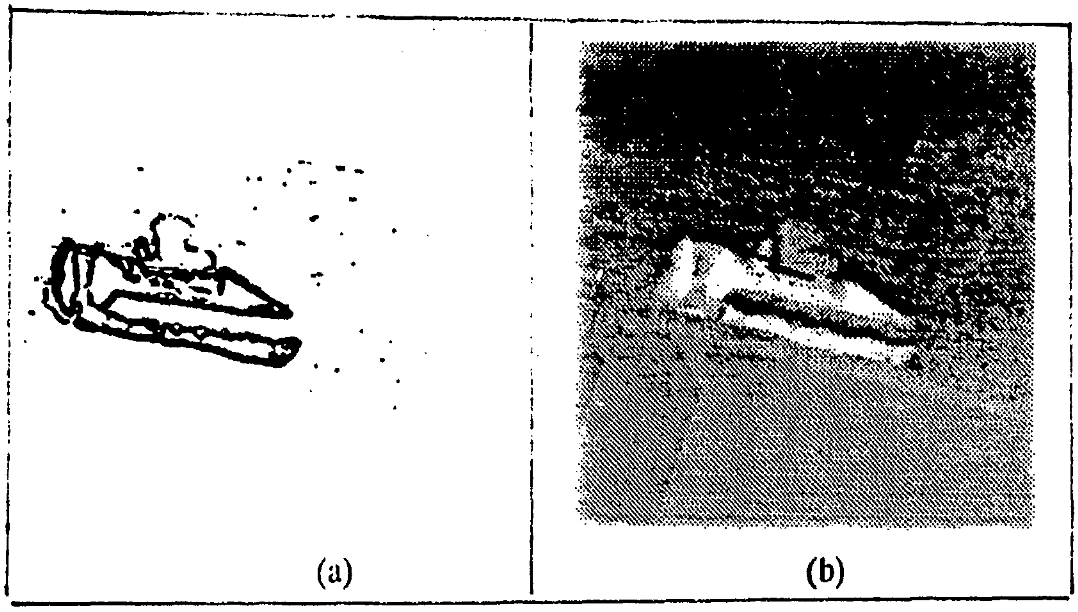


Figure 18 : (a) image binaire présentée à ART1 (b) image présentée à ART2

- un prétraitement des images d'entrée est généralement indispensable du fait que ces méthodes sont sensibles à des translations, des rotations, des changements d'échelle et des variations de brillance.
- si le prétraitement dont question ci-dessus conserve l'interprétation visuelle de l'image, il est possible de visualiser l'information mémorisée.
- l'apprentissage est adaptatif, on distingue en effet à ce stade deux sortes d'apprentissage: l'apprentissage long terme, qui concerne la création de nouveaux neurones et de nouvelles connexions entre couches et l'apprentissage court terme qui concerne l'adaptation des connexions entre couches.

5. Conclusions.

La progression de robots mobiles, type chars automatisés, sur le champ de bataille terrestre impose d'abord que soient résolus les problèmes relatifs à la mise au point de capteurs extéroceptifs performants (fonction distance, conditions atmosphériques,etc.), au traitement des signaux recueillis (impulsions, images, fonction mémorisation associative ou non), à la génération de décisions (évitement d'obstacles, tir sur objectifs reconnus, etc.). Ces études peuvent être menées, dans une mesure importante et à faible investissement, à partir de robots mobiles de dimension modeste évoluant dans un environnement progressivement plus complexe. L'architecture définitive ou semi-définitive de tels systèmes robotisés mobiles dépendra largement de la résolution des problèmes précédents (par exemple, la rapidité de déplacement ou le caractère continu ou discret des déplacements dépend de la rapidité de traitement des signaux recueillis): raison pour laquelle nous croyons qu'il faut investir de façon sélective dans la recherche "robotique" en privilégiant d'abord l'aspect système-expert.

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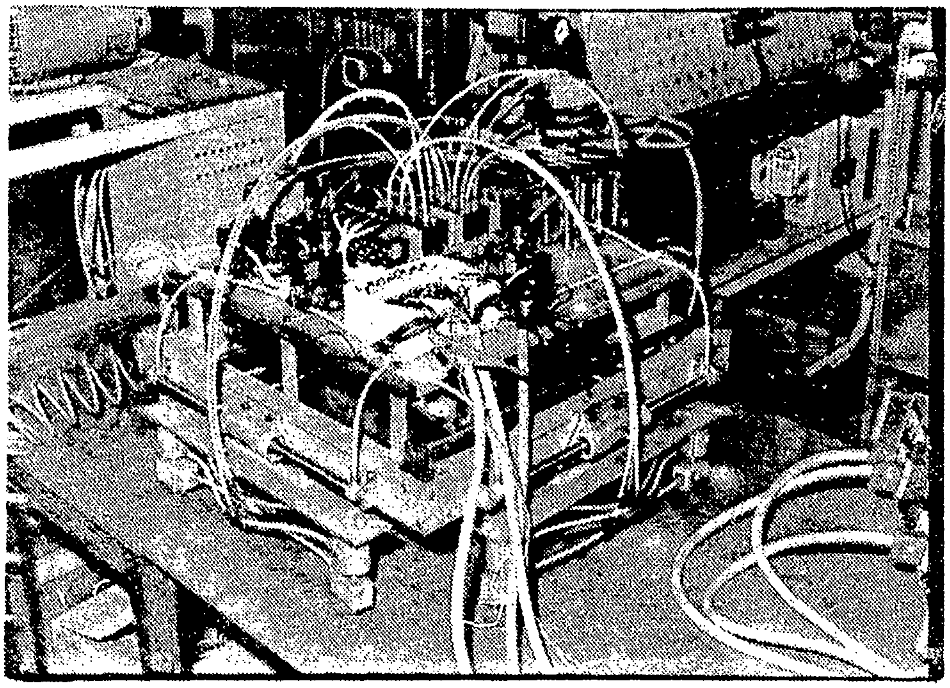

Photo 1: AMRUA (non couvert)

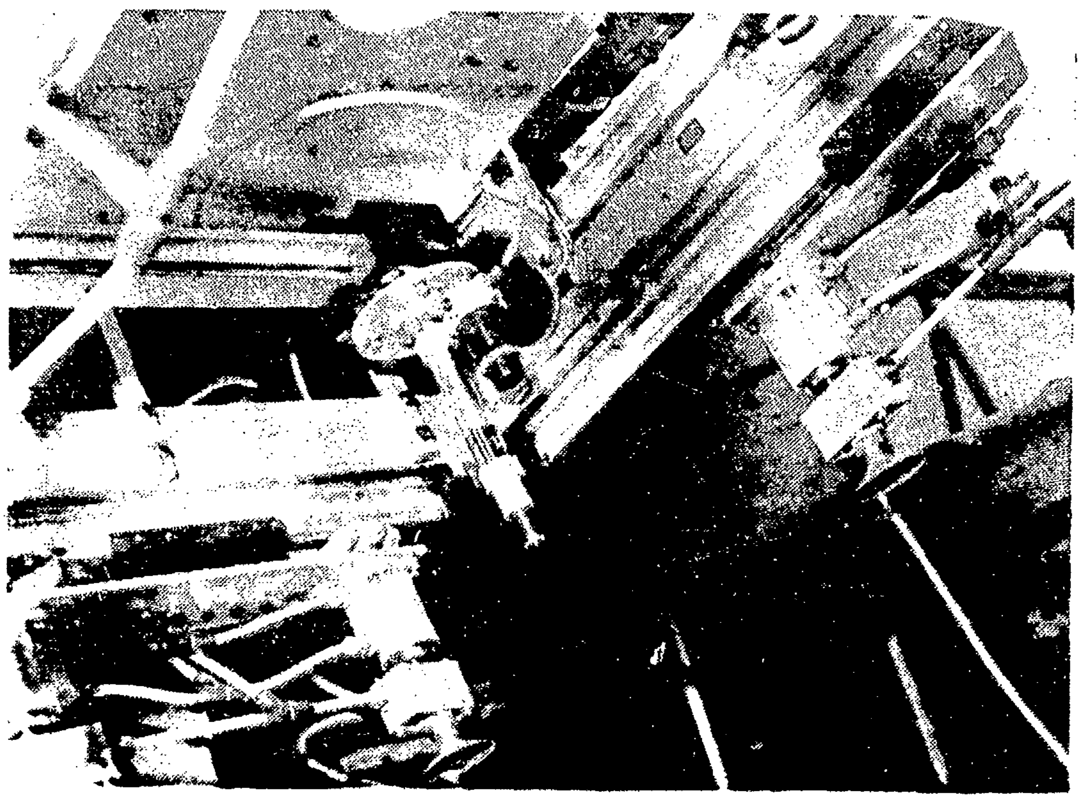

Photo 2: Système interne de balayage

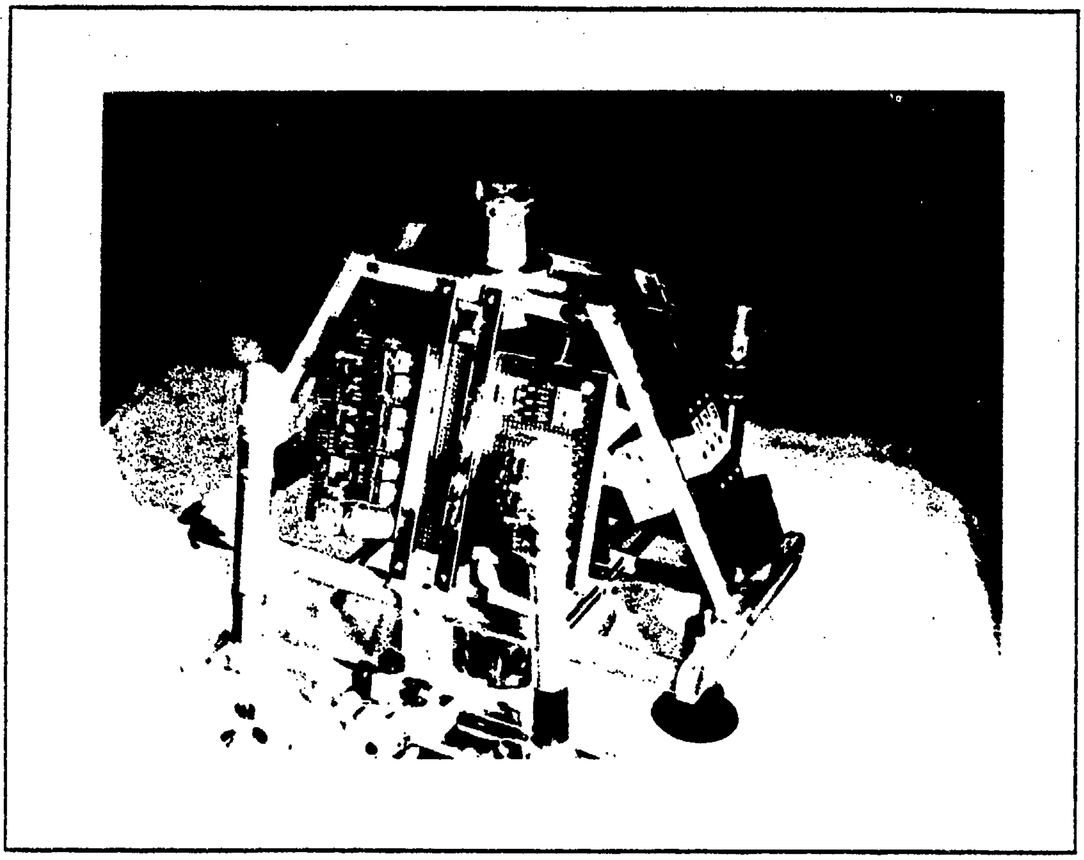

Photo 3: ROMOCAN (sans caméra, ouvert)

Photo 4: motorisation du cadre

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14. Abstract: The paper presents elegant solutions to the problems of robust execution of a robot system and provides a technique which will provide on-line autonomous trajectory generation and collision avoidance in an unstructured environment for military operations. Recently, the method of Impedance Control has emerged as a promising alternative to the conventional methods of control, to generate on-line trajectory in free motion and avoiding obstacles. In this proposed technology, a desired mechanical impedance between the robot end-effector and the target is generated by modulating the force/torque output of the actuators. A repulsive force based on the impedance between the object to be avoided and the end effector (or mobile vehicle) is used to modify and avoid obstacles on-line during the gross-motion. Implementation issues are discussed and the computer simulations results are also included.

IMPEDANCE CONTROL FOR MILITARY OPERATIONS

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1.0 INTRODUCTION

1. The main characteristic of military operations are totally different than the tasks carried out by industrial robot in a factory environment. The reason for this is the nature of environment in both operations. Military operations take place in an unstructured and uncertain environment which can not be controlled. Therefore, all sophisticated techniques of programming robots to carry out task repetitively in a structured environment will not simply work for military operations. Consequently, the only solution for this problem is some form of autonomy under the supervision of an operator. To begin with, teleoperation has been used extensively in a range of applications to understand the remote manipulation concept and human-system interactions. It also provided a basis for a smooth transition towards a higher autonomy in a robotic system.

2. A robotic system which must cope with an unstructured environment should deal with the problems provided in Figure 1. A fully autonomous robot will be responsible to deal all of these problems [1]. However, the ability of robots to perform tasks autonomously under sensor-based control is rather limited and human intelligence can be quite useful to provide a complete system solution for military operations. Considering the state of the art of robotics technology, the robot's best abilities are essentially at the execution level such robot manipulation, while the least capabilities are at the decision level of the task hierarchy where the operator excels.

3. Among the desired features for robot manipulation for extending the field of future applications, are autonomous trajectory generation and automatic collision avoidance with known or unexpected objects in the work volume. The artificial mechanical impedance method analyzed in this paper is based on the modulation of the torques in such a way as to produce, between the target and the manipulator endpoint, the dynamic effect of a desired linear or nonlinear mechanical impedance.

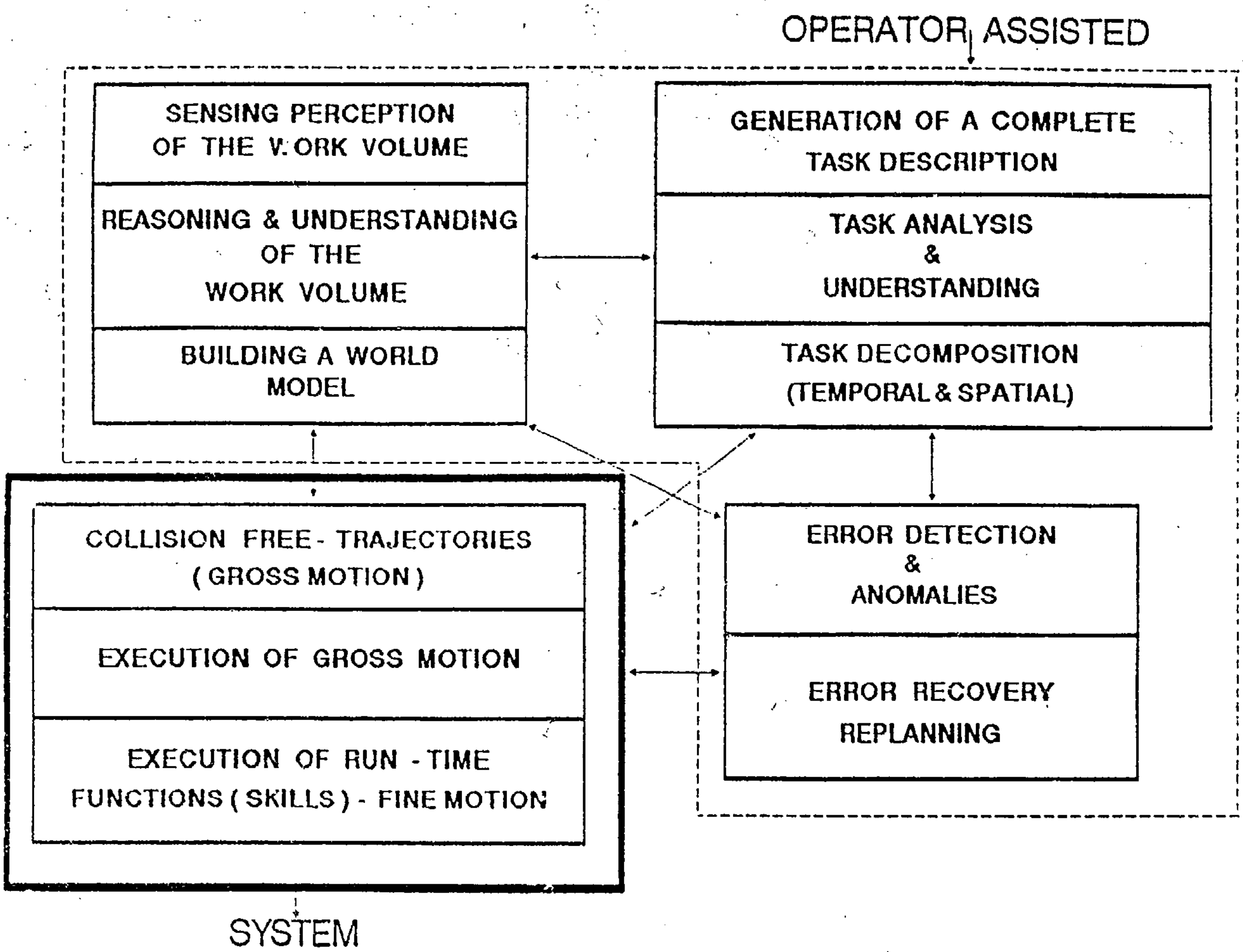

Figure 1: Robotic Activities and Functional Distribution

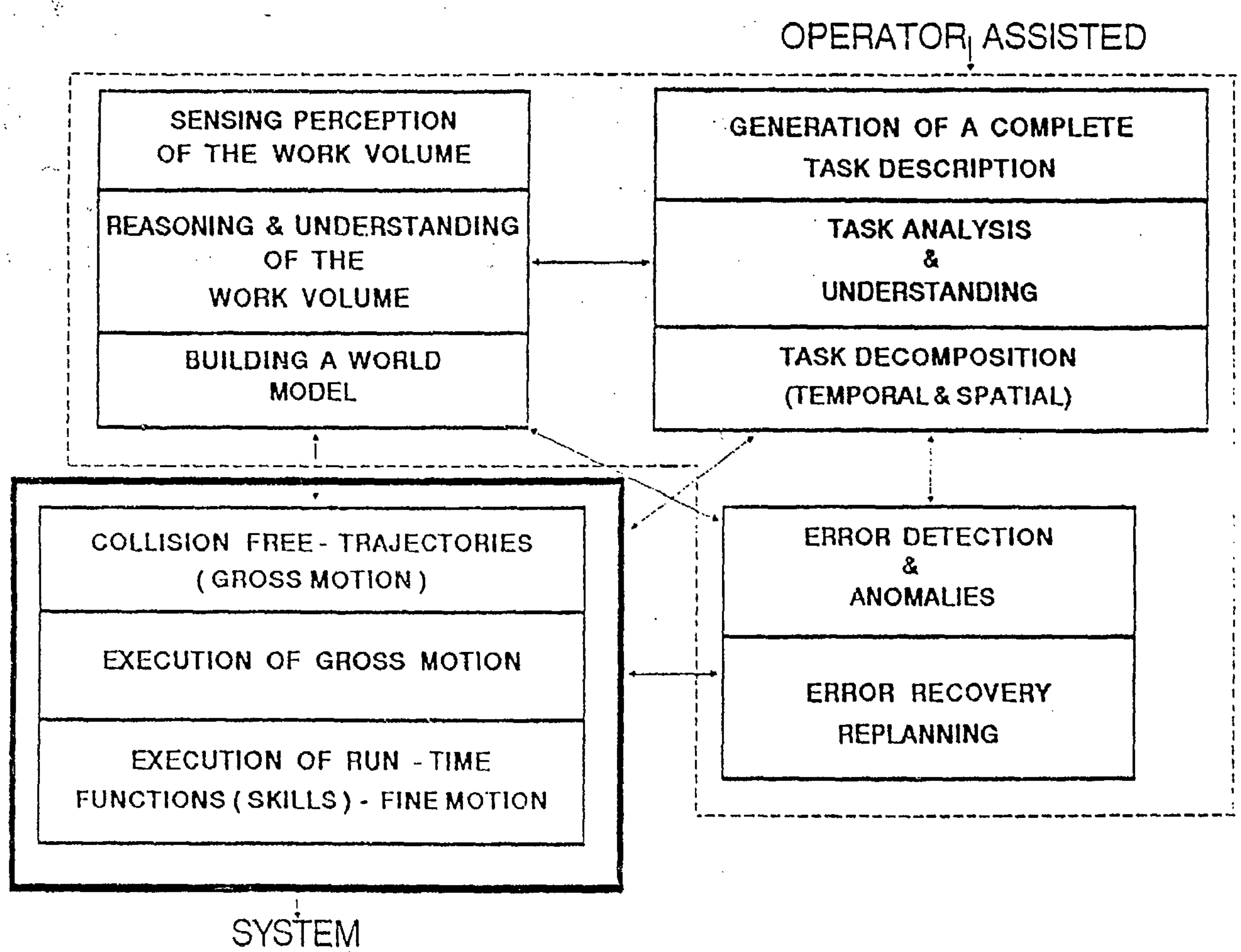

Figure 1: Robotic Activities and Functional Distribution

The result of using this method is the integration of the controller model with the nonlinear dynamics model of the robot into a single mechanical model which is used to obtain the desired mechanical properties. A particular feature of the method is that the generation of a trajectory results 'naturally' from certain Cartesian space specifications.

4. In this paper, the artificial impedance method is used for the trajectory generation of a jointed manipulator in free motion and for the trajectory correction in order to avoid collisions with obstacles. Simulation results for a two degree-of-freedom manipulator are compared with those of a PD position controller. For obstacle avoidance the artificial impedance approach is used in conjunction with a 'coastal navigation' scheme which provides a means of generating trajectories in non-convex spaces utilizing proximity-sensor data. The technique has the potential of permitting operation within an unknown workspace and of providing trajectory correction to avoid collisions with unexpected or moving objects. Simulation results illustrate this technique.

5. Artificial impedance approach of a single arm motion control has been intensively analyzed in the last decade. The results of the first part of the paper show that the trajectory of a single arm robot can be generated in real time by assuming artificial impedances in the robot workvolume. In the second part of the paper, artificial impedance approach is applied to dual arm robots.

6. Dual arm robot motion is analyzed for two distinct phases, the approaching phase, when each arm is moving independently toward the desired positions, and the coordination phase, when the two arms are transporting together an object to a desired position. The motion in the approaching phase will be coordinated by introducing artificial attractive impedances between each arm and the desired positions (to generate attractive forces between the arms end points and the targets) and artificial repulsive impedances between the arms and obstacles (to generate artificial repulsive forces and avoid the collisions of the moving arms) in the case of the detection of obstacles on the arms trajectories.

7. The motion in the second phase, when the two arms are holding a rigid object, represents the motion of a closed loop mechanism. Artificial impedance approach to motion coordination, in this case, is based on designating one arm as a leader arm and the other as a follower arm. In order to move the piece safely, materials and holding requirements impose kinematics and dynamics constraints at the contact points of the piece and the two arms. When using artificial impedance approach, these constraints are transformed into virtual impedances between the two arms which simulate maximum elastic forces and torques applied on the piece and maximum/minimum holding forces. This approach permits coordination of the motion of the two arms in the same fashion as in the case of free motion by introducing suitable artificial impedances between the arms and the desired positions and the obstacles.

8. The paper presents the analytical model of the impedance based control of a dual arm robot, as well as simulations of the operation of the impedance based controller in the approaching and coordination phases of the motion of the two arms. The objects will be assumed in simulations as rigid bodies, elastic bodies and as strings.

9. In the last part of the paper, implementation aspects of the artificial impedance approach are analyzed. In particular, various nonlinear compensation methods of linearization-decoupling of the robot are reviewed. The state-feedback compensation method is compared to the perturbation observer method. Robustness aspects are discussed and a Three-part control scheme is presented.

2.0 MILITARY REQUIREMENTS FOR MANIPULATOR CONTROL

10. Various military organization are investigating the roles of robotics in military operations. It is commonly accepted that the robotics technologies will significantly affect the issues such as manpower requirements (i.e. reducing the number of personnel, increase individual effectiveness), and soldier risk exposure (i.e survivability) in all types of warfare including nuclear, biological, chemical weapons and as well as in peace keeping operations.

11. In future, military robots will be capable of operating autonomously on the battlefield. Such an advanced, intelligent robot would be able to take place of a soldier, to move in difficult terrain, to recognize dangers, distinguish between friend and enemy, and fight very efficiently with minimum human interaction. However, the state of the art of robotics technologies show that it is currently not possible to have fully autonomous robots to meet military requirements. Therefore, an effective solution for military operations is the limited autonomy or supervised autonomy where the responsibilities are distributed according to capabilities between the operator and the robotic system. The general activities and functional distribution are shown in Figure 1.

12. In order to use robots effectively in military operations (considering the risk associated with the sensitivity of the tasks in military operations dealing with explosive materials, etc.), the robot controller system should have extremely robust, reliable and accurate manipulation capabilities. Among the desired features for robot manipulators capabilities in future applications are autonomous trajectory generation and automatic collision avoidance.

3.0 FORECAST OF VARIOUS APPROACHES TO ROBUST MANIPULATION CONTROL

13. Cartesian space control formulation of robot manipulators led to the development of artificial potential field and artificial impedance approaches. Continuum mechanics formulation of the artificial potential field consists in choosing an attractive potential field to correspond to the potential field of linear elastic springs while the repulsive potential fields are chosen to correspond to potential fields of nonlinear force functions dependent on the shortest distances between the manipulator parts and each obstacle.

14. Khatib extends the Lagrangian formalism of robot dynamics to include artificial potential fields (APF) involving an attractive force field associated with the end effector and the position to be reached, and fields of repulsive forces associated with obstacles and the manipulator parts [2].

15. The continuum mechanics formulation requires equations which provide a continuum geometric modelling of the obstacles using primitives such as points, lines, planes, ellipsoids, parallelipipeds, cones and cylinders. Also, as in all artificial potential field and impedance approaches to Cartesian control of the robot motion, the robot arm dynamics as seen by the robot controller is decoupled by compensation of the inertial, centrifugal, Coriolis, gravitational and other nonlinear components of the dynamic equations. In addition, the APF-based controller needs a dissipative force term in Cartesian space added to obtain asymptotic stability.

16. Takegaki and Arimoto [3] develop a joint-space attractive potential field in the Hamiltonian formalism for conservative forces. The Hamiltonian in this case represents the total energy of the system, which is used as a Lyapunov function for proving asymptotic stability. Any desirable potential function which is positive-definite may be chosen. A linear feedback of joint velocity is added to the joint-torque control law for asymptotic stability.

17. Andrews and Hogan [4] simulate the avoidance of a moving target using the APF approach. They show also that the attractive artificial potential field is equivalent to artificial mechanical impedances in Cartesian space between the manipulator end-effector and the target for the case of conservative fields. A dissipative term in the control law is added for stability.

18. Slotine [5] continues the joint-space stability analysis of Takegaki and Arimoto including directly the damping part of the joint control law in the power balance equations of the manipulator dynamics and joint actuators. In the Hamiltonian formalism, for conservative forces the derivative of the total energy (the actual manipulator and the virtual energy associated with the proportional part of the joint controllers) is known to equal the power dissipated by nonconservative forces, namely, the artificial joint dampers correspond to the damping component of the joint control law. The overall approach to control, while not formulated for Cartesian space, provides an interesting background for interpreting APF and Artificial Impedance approaches.

19. Krogh [6] introduces discontinuous generalized potential fields which surround an obstacle up to a chosen distance from the obstacle and are defined as position and velocity dependent potentials. The resulting generalized potential fields cannot be interpreted in terms of artificial mechanical impedances.

20. A time-optimal approach to a robot controller based on generalized potential fields is simulated by Newman and Hogan [7]. The resulting bang-bang control might be undesirable for robot control, particularly in structurally flexible systems, because of the possibility of exciting high order (probably unmodelled) dynamics. Cartesian decoupling is a prerequisite for the success of this scheme.

21. The APF control schemes discussed above, [2] to [7], are formulated as continuum mechanical problems and so require equations describing the geometric shapes of objects in the robot workvolume in continuum mechanical form. The actual application of these schemes is based on

lumped parameter control laws which suggest that it is perhaps more appropriate to consider a lumped parameters formulation of the dynamics in robot Cartesian space and artificial mechanical impedances.

22. Hogan [8],[9], presents a rigorous formulation of the Artificial Impedance approach in robot Cartesian space. He applies it to free motion and to object-contact motion of a robot arm. Joint torque control laws are derived for realizing a desired diagonal artificial mechanical impedance between the end effector and the target. This scheme does not use inverse kinematics, but requires nonlinear decoupling in Cartesian space using position and speed measurements in the joints as well as object-contact force measurement. A stable motion results in the experiments presented with a two degree of freedom direct drive horizontal robot. No collision avoidance experiments are included.

23. None of the foregoing schemes include representation of the contacted object dynamics. Kazerooni [10] develops an artificial mechanical impedance approach in which the desired position command is modified by an artificial admittance which compensates the robot compliance for the contact force. Anderson and Spong [14], present a hybrid admittance/impedance control combining hybrid position/force control and artificial impedance approach.

24. Lawrence [11] analyzes the Artificial Impedance approach as a torque-command scheme and as a position-command scheme (when computation/communication delays affect the impedance controller) and finds the two schemes complimentary.

25. Necsulescu et al [12] simulate collision avoidance of multiple and moving obstacles for a two degree of freedom, planar robot equipped with a controller using Artificial Impedance approach. The results show that trajectory control and collision avoidance can be realized using the Artificial Impedance approach and provide evidence that this technique is a promising alternative to the preplanning schemes, as is proposed in numerous other papers, for example [13].

26. Dual-arm robot motion control requires a higher level of controller complexity compared to the single-arm robot motion control because of the need to continuously coordinate the motion of the two arms.

27. Various combinations of position and/or force control of the two-arm motion have been reported in the literature. Luh and Zheng propose a leader/follower coordination strategy with no force feedback [22],[23]. Kinematics constraints for the closed kinematic chain are used for the determination of the follower motion given the leader motion in terms of positions, velocities and accelerations. One rigid body and two articulated rigid bodies are used as loads. The dynamic dependence of the leader and follower input generalized forces are also derived. The major difficulty in using these results to coordinate the motion comes from the lack of contact/force feedback. Consequently, such a coordination scheme would be successful only in the case of no servoing and modelling errors.

28. Ozguner et al develop an approach for cancelling the cross coupling terms of the dual-arm dynamics which reduces the control problem to controlling independent joint servomotors [24]. This is achieved by a sliding mode, discontinuous controller with gains obtained for a given bound on the norm of cross-coupling interactions. Simulations are performed for free and contact motion of the two arms with no load. No comments are made concerning the evaluation of the norm of cross-coupling interactions and on the operation for various loads.

29. Swern and Tricamo propose a modification of the position controllers of the two arms intended to compensate the constraint forces applied by the arms on the load [25]. This is achieved by correcting the reference positions based on the end-effector's measured forces/torques and the load stiffness matrix. A flexible rod and a beam are used as loads in simulations and a recursive identification scheme is used for the load stiffness matrix. While this approach uses the actual load stiffness matrix, Kazerooni and Tsay propose an artificial compliance for a similar control scheme [26]. The effect of joint flexibility on the steady-state error in the object position is analyzed by Ahmad and Guo for arms with position/force controllers [27].

30. Some dual-arm motion hybrid coordination schemes are developed based on the workspace force, velocity and position vectors defined as symmetric functions on their joint-space counterparts for the two arms. Uchiyama and Dauchez propose a hybrid control scheme for a chosen set of relative and absolute force and velocity in the workspace [28]. Kopf and Yabuta compare, experimentally, the leader/follower and hybrid control schemes [29]. In the former control scheme, the leader is position controlled and the follower is force controlled while in the latter control scheme, absolute position of the centre of the object and the relative (internal) force applied on the object are controlled symmetrically for the two arms. The leader/follower scheme has performed poorly. This can be explained by the lag in the reaction of the follower. The hybrid scheme has had restricted use because of the requirement of the symmetric functions mentioned above.

31. Suh and Shin generalized the leader/follower scheme by allowing the follower grasping position to change when reaching a configuration singularity, or for obstacle avoidance [30].

32. The literature review has shown that the dual-arm motion coordination results to-date cover only a limited variety of types of payloads and do not include such payloads as a string/blanket or a vibrating structure (with the exception mentioned above).

33. Also, collision avoidance for dual-arm robots has not been analyzed in detail, but only the use of the spatial planning approach from single to dual arms [31].

34. Several solutions were proposed for robust robot control. Some Solutions are applicable to the Artificial Impedance approach as for example Model Reference Adaptive Control [38,39,40] and Second Method of Lyapunov-based designs. Model Reference Adaptive Control can be formulated for a reference model which represents a set of three independent translational mechanical impedances and three independent rotational mechanical impedances i.e six second order linear, constant parameter differential equations. The error between the reference model positions

and Cartesian end-effector positions would be used, in this case, for the adaptation mechanism. This approach benefits from the robustness of MRAC approach, but only asymptotically the robot arm would behave like the desired Cartesian space impedances.

35. Second Method of Lyapnuov-based design has been used for obtaining sliding mode controllers for single [41] and dual arm robots [23]. The application of a sliding controller for implementing an Artificial Impedance approach has been explicitly formulated by J.J. Slotine [42, pp. 214-215]. In this case, sliding surfaces are chosen as linear functions of the errors, for the Cartesian state variables, and of the environment contact forces. In sliding mode, the controller would make the robot behave like the desired impedance. The resulting discontinuous control law, inherent to the application of the second method of Lyapunov, can be approximated by a boundary layer-based continuous control law. Maintaining sliding mode required sufficient torque output, large actuator bandwidths and fast closed loop components other than the robot arm.

36. Second Method of Lyapunov can be applied directly for obtaining a corrective term added to a linear control law in order to compensate for the errors resulting from inexact cancellation of the nonlinear dynamic terms by nonlinear state feedback compensator. Again, a discontinuous corrective term would result and a continuous approximation solution is proposed for joint decoupling case [19, pp. 227-236]. A similar formulation can be developed for Cartesian decoupling case and Artificial Impedance approach case. An interesting alternative in this case, to the use of Lyapunov functions, is the use of Hamiltonian functions. This has the advantage of interpreting the time derivative of the Hamiltonian of the conservative part of the system as describing the power transfer from the conservative part to the dissipative part of the system [17]. An application of a nonlinear version of MRAC to a two DOF robot arm modelled by Hamiltonian dynamics using a single rigid link reference model led to a nonlinear-discontinuous control law [45]. The Cartesian space control and Artificial Impedance approach for the Hamiltonian systems were not formulated in [45]. An interesting alternative to the joint torque computation using the inverse dynamics (contained in the nonlinear state feedback compensator) is the use of a disturbance observer for estimating the same torque, but using measurements of the actuator currents and joint accelerations (or computations of the derivatives of joint speeds) [43]. This results in a suitable joint decoupling if sensors bandwidths are sufficient and the computation time for the disturbance observer is sufficiently short. Later formulation of the Cartesian control of a joint decoupled robot arm was based on a resolved acceleration control scheme and can also be used for the Artificial Impedance approach [44].

4.0 THE CONCEPT OF IMPEDANCE CONTROL

4.1 The Basic Model

37. The Artificial Impedance approach can be conceptually illustrated for a simple position control problem. We assume a mass m, (positioned at x) separated from a moving target (positioned at x_d) by an artificial elastic spring with stiffness K in parallel with an artificial damper with coefficient B. A term

$M\ddot{x}$, where M is a virtual mass, is also included.

The equation of contact motion of the mass is given by

$$f = m\ddot{x} + f_{ext} \tag{1}$$

where f_{ext} is the contact force.

An artificial impedance between x and x_d would be described in this case by

$$-f_{ext} = M\ddot{x} + B(\dot{x}-\dot{x}_d) + K(x-x_d) \tag{2}$$

38. The inclusion of a term proportional to $\ddot{x}_d$ in this equation, as in [11,20], requires assumptions concerning the target inertial properties (unit mass in [20] or virtual mass M in [11]). In this paper we chose an artificial impedance structure which can be physically reproduced by adding a M-m mass to the mass m and a parallel link of a spring K and damper B between the mass and a massless target.

39. There are two situations considered here in the design of the impedance control scheme: free motion of the mass, and contact with an object. In the case of free motion, only $x(t)$ and $\dot{x}(t)$ may be measured.

4.2 Free Motion Control of a Frictionless Rigid Body

In the case of free motion

$$f_{ext} = 0 \tag{3}$$

which transform (1) and (2) into

$$f = m\ddot{x} \tag{4}$$

and

$$M\ddot{x} + B(\dot{x}-\dot{x}_d) + K(x-x_d) = 0 \tag{5}$$

Eq. (5) gives the computed acceleration

$$\ddot{x}(c) = M^{-1}B(\dot{x}_d-\dot{x}) + M^{-1}K(x_d-x) \tag{6}$$

Substituting x in eq. (4) by x(c) we obtain

$$f = m[M^{-1}B(\dot{x}_d-\dot{x}) + M^{-1}K(x_d-x)] \tag{7}$$

40. The control law (7) and the system equation (4) are represented in Figure 2. The desired artificial impedance in eq. (5) contains three parameters, M, B and K, but in the case of free motion, only two controller parameters, $M^{-1}B$ and $M^{-1}K$, can be independently chosen for a required error dynamics in eq. (7).

41. The control scheme of Figure 2 is identical to a PD position control scheme. The artificial impedance approach provides, however, physically meaningful interpretation of the controller gains of eq. (7).

4.3 Contact Motion of A Frictionless Rigid Body.

42. We assume that the motion of the mass m is impeded by an obstacle continuously in contact with the mass; consequently, the motion of the obstacle is imposed on the motion of the mass, $x(t)=x_1(t)$ where $x_1(t)$ is the coordinate of the obstacle. Further, we assume that the motion of the obstacle is faster than the motion of the target so that eventual interception is possible. The contact of the mass with the obstacle produces a force f_{ext} which can be measured. The states x(t) and x(t) are measured also.

We obtain from Eq. (2), the computed acceleration

$$\ddot{x}(c) = M^{-1}B(\dot{x}_d-\dot{x}) + M^{-1}K(x_d-x) - M^{-1} f_{ext} \tag{8}$$

Substituting x in (1) by x (c) we obtain

$$f = m\{[M^{-1}B(\dot{x}_d-\dot{x}) + M^{-1}K(x_d-x)]-M^{-1} f_{ext}\} + f_{ext} \tag{9}$$

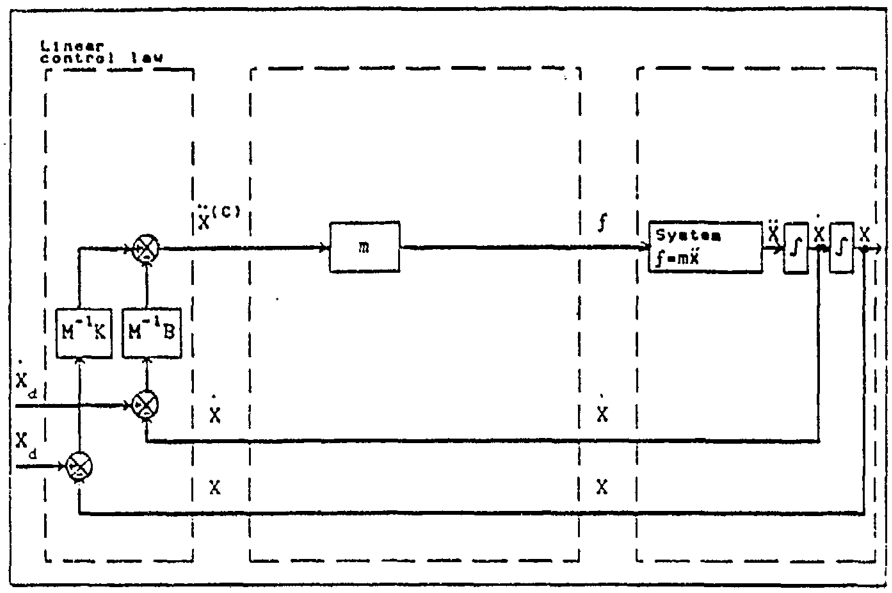

Figure 2. Artificial Impedance Approach scheme for a m in free motion

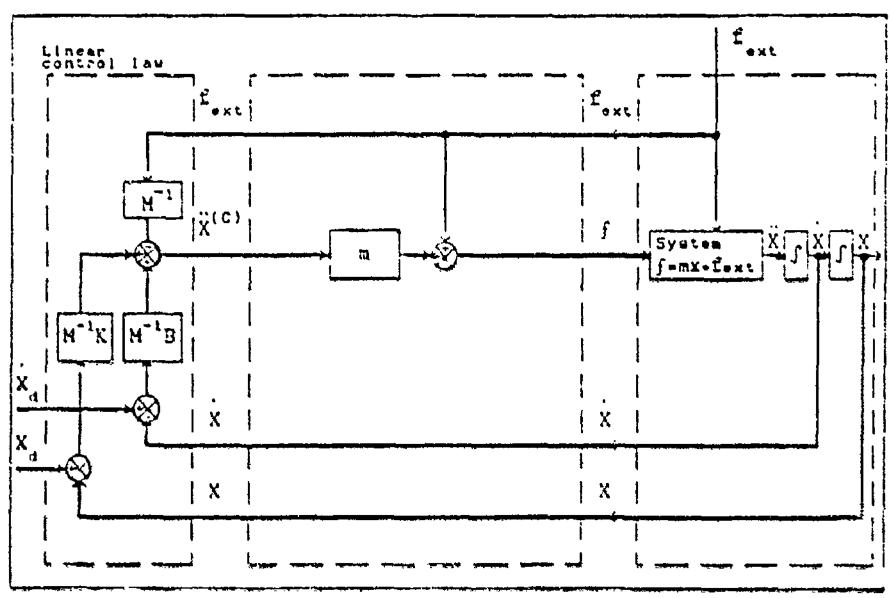

Figure 3. Artificial Impedance Approach scheme for a mass m in contact motion

43. The control law (9) permits the calculation of the force command f for given measurements of x, x and f_{ext} and known values for x_d and $\dot{x}_d$. The block diagram in Figure 3 shows a modulation of the active force f applied to the mass m which, besides the linear control low output $\ddot{x}$ (c) contains also a feed-back term of the measurement of the contact force, which is not present in PD position control law. For M=m, the coefficient of f_{ext}, $1-mM^{-1}=0$, and the contact force does not influence position control command any more.

5.0 AUTONOMOUS TRAJECTORY GENERATION AND COLLISION AVOIDANCE FOR SINGLE ARM ROBOTS USING IMPEDANCE CONTROLLERS

5.1 The Model

44. Assuming that the measurement of Cartesian contact forces 6x1 vector F_{ext} between the end point of a 6DOF jointed robot and the environment is available, the dynamic equation in terms of 6x1 vector Θ of joint angles gives the following 6x1 vector τ of joint torques

$$\tau = M(\Theta)\ddot{\Theta} + V(\Theta,\dot{\Theta}) + J^T(\Theta)F_{ext}. \qquad (10)$$

45. The term $M(\Theta)$ is the configuration-dependent matrix of inertias. Here $V(\Theta,\dot{\Theta})$ includes Coriolis, centrifugal, gravitational and frictional terms and $J(\Theta)$ is the robot Jacobian matrix. Specific to the Artificial Impedance approach is the choice of a desired artificial impedance between the end point, positioned at X(a 6x1 vector) and the target positioned at X_d (a 6x1 vector), producing the following desired dynamics

$$-F_{ext} = M\ddot{X} + B(\dot{X}-\dot{X}_d) + K(X-X_d) \qquad (11)$$

M, B and K are 6x6 diagonal matrices of the desired artificial impedance in Cartesian space. From robot kinematics, the following relationships between state variables in joint space and in Cartesian endpoint space can be written [14]

$$X = KIN(\Theta) \qquad (12)$$

$$\dot{X} = J(\Theta)\dot{\Theta} \qquad (13)$$

$$\ddot{X} = J(\Theta)\ddot{\Theta} + \dot{J}(\Theta)\dot{\Theta} \qquad (14)$$

where the Jacobian 6x6 matrice $J(\Theta)$ relates joint velocities $\dot{\Theta}$ to base frame defined endpoint velocities $\dot{X}$. Using Eqs. (12) to (14) in Eq. (11), F_{ext} can be written as a function of Θ, $\dot{\Theta}$, $\ddot{\Theta}$

$$-F_{ext} = MJ(\Theta)\ddot{\Theta} + M\dot{J}(\Theta)\dot{\Theta} - B[\dot{X}_d - J(\Theta)\dot{\Theta}] - K[X_d - KIN(\Theta)] \tag{15}$$

Based on measured $\Theta, \dot{\Theta}$ and F_{ext}, eq. (15) gives the computed acceleration

$$\ddot{\Theta}(c) = -J^{-1}(\Theta)M^{-1}F_{ext} - J^{-1}(\Theta)\dot{J}(\Theta)\dot{\Theta} + J^{-1}(\Theta)M^{-1}B[\dot{X}_d - J(\Theta)\dot{\Theta}]$$
$$+ J^{-1}(\Theta)M^{-1}K[X_d - KIN(\Theta)] \tag{16}$$

Substituting $\ddot{\Theta}$ in eq. (10) by $\ddot{\Theta}(c)$ we obtain

$$\tau = -M(\Theta)J^{-1}(\Theta)M^{-1}F_{ext} - M(\Theta)J^{-1}(\Theta)\dot{J}(\Theta)\dot{\Theta} + M(\Theta)J^{-1}(\Theta)M^{-1}B[\dot{X}_d - J(\Theta)\dot{\Theta}]$$

$$+ M(\Theta)J^{-1}(\Theta)M^{-1}K[X_d - KIN(\Theta)] + V(\Theta,\dot{\Theta}) + J^T(\Theta)F_{ext}. \tag{17}$$

or

$$\tau = M(\Theta)J^{-1}(\Theta)\{M^{-1}K[X_d - KIN(\Theta)] + M^{-1}B[\dot{X}_d - J(\Theta)\dot{\Theta}] - \dot{J}(\Theta)\dot{\Theta} - M^{-1}F_{ext}\}$$

$$+ V(\Theta,\dot{\Theta}) + J^T(\Theta)F_{ext} \tag{18}$$

Using the notations M_x for the Cartesian mass matrix and V_x for the velocity dependent and gravitational terms, we obtain [14]

$$M_x(\Theta) = J^{-T}(\Theta)M(\Theta)J^{-1}(\Theta) \tag{19}$$

and

$$V_x(\Theta,\dot{\Theta}) = J^{-T}(\Theta)[V(\Theta,\dot{\Theta}) - M(\Theta)J^{-1}(\Theta)\dot{J}(\Theta)\dot{\Theta}] \tag{20}$$

Using the notations (19) and (20) in (18) we obtain

$$\tau = J^T(\Theta)\{M_x(\Theta)\ \{M^{-1}K[X_d\text{-}KIN(\Theta)]+M^{-1}B[\dot{X}_d\text{-}J(\Theta)\dot{\Theta}]\text{-}M^{-1}F_{ext}\}$$

$$+ V_x(\Theta,\dot{\Theta})+F_{ext}\} \tag{21}$$

For $M=M_x(\Theta)$, the coefficient of F_{ext} is $I\text{-}M_xM^{-1}=0$ and F_{ext} does not influence the position control commands.

We can denote the computed Cartesian acceleration by

$$\ddot{X}\ (c) = M^{-1}K[X_d\text{-}KIN(\Theta)]+M^{-1}B[\dot{X}_d\text{-}J(\Theta)\dot{\Theta}]\text{-}M^{-1}F_{ext} \tag{22}$$

Using the relationship between the Cartesian force 6x1 vector F and τ [14], $F=J^{-T}(\Theta)\tau$, we obtain the Cartesian space dynamics equation

$$F' = M_x(\Theta)\ \ddot{X}\ (c)+V_x(\Theta,\dot{\Theta})+F_{ext} \tag{23}$$

For F and $\ddot{X}$ (c) defined with regard to the robot base frame, $M_x(\Theta)$ results a diagonal matrix.

46. Equation (22) gives the output of a linear Cartesian controller and equation (23) contains the Cartesian decoupling scheme terms $M_x(\Theta)X$ (c), $V_x(\Theta,\dot{\Theta})$ and F_{ext} (see Figure 4). The Cartesian decoupling scheme has not been in this derivation assumed, but rather is a result of imposing the desired artificial impedance in equation (11) between the robot endpoint and the target as a reference model.

47. Collision avoidance features can be incorporated in this scheme by posing artificial repulsive impedances between the robot arm and the obstacles [11].

5.2 Difficulties Associated With The Application Of The Artificial Impedance Approach To Robot Trajectory Generation.

48. The resultant of the action of the attractive and repulsive impedances is zero for $x=x_d$ whenever the artificial impedances are defined to simulate the effect of physical impedances applied to the same Cartesian decoupled robot arm [9]. The repulsive artificial impedances were previously reduced to virtual springs [9,20]. This choice results in a large reflection on the resulting repulsive potential field when a simple obstacle is encountered. Multiple obstacles, in particular configurations, can lead to poorly damped or unstable robot arms motion as a result of continuous reflections on the resulting artificial repulsive potential fields surrounding the obstacles. This is also shown in the simulation results described in this paper. The choice of spring-damper type of artificial repulsive

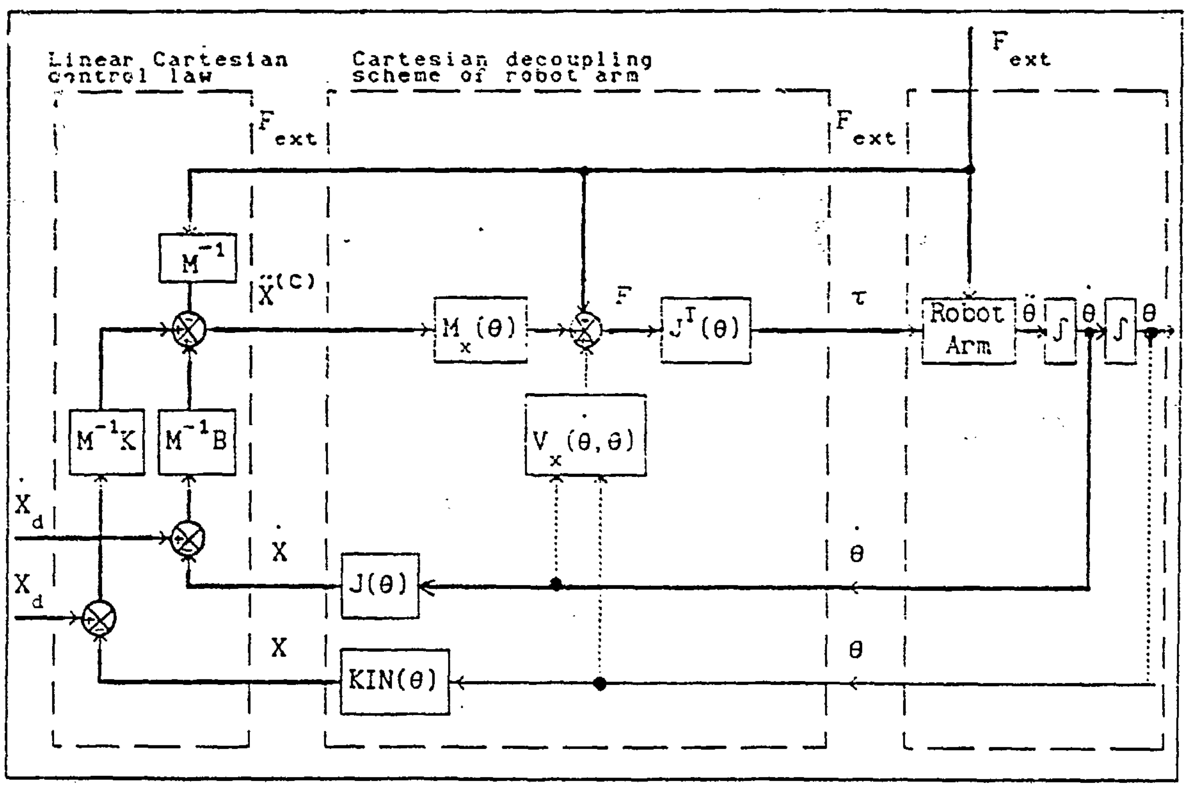

Figure 4. Artificial Impedance Approach in a Two part Control Scheme

impedances creates the necessary damping associated with each artificial impedance. This solution produces the same performance for multiple obstacle case when compared to the solution of adding a speed dependent term added to a conservative artificial impedance or potential field, as in [2,3], only if the velocity dependent term is applied along the resultant force produced by the combined effect of all conservative terms.

49. Another important difficulty in this case is the possibility of local static equilibrium points in the robot Cartesian space. This possibility is obvious in case of obstacles which create potential field concavities in the path of the end effector toward the desired position, i.e. when the resultant of the repulsive and attractive potential fields is zero for $X \neq X_d$. In this paper artificial impedance approach is used for trajectory generation and correction in case of obstacles by posing artificial impedances in the Cartesian space. Further modifications of the choice of Cartesian space artificial impedances can lead to solutions for escaping the local potential traps by using a coastal/surface navigation scheme. The schemes consist of Cartesian tracking of virtual attractive points moving along a safe path. In the case of a planar manipulator, coastal navigation scheme consists in creating a virtual attractive point X_v which will move continuously on a path orthogonal to the vector starting at end effector position and ending in the point X_0 detected by proximity sensors on the obstacle as the closest to the end effector. As long as the line of sight between the end-effector position X and the desired position X_d is obstructed, the desired position is replaced by a virtual attractive point X_v and the end effector will move toward X_v. The resulting perpendicularity of the vectors XX_v and XX_0 leads to a trajectory generation on a path along the coast at a safe distance from the obstacle. Further heuristics can be used in both planar and spatial motion in order to find a feasible path. In spatial motion, the surface navigation scheme defines the virtual attractive point in a plane defined by X, X_d and X_0. These schemes can be further improved based on minimum energy requirements.

50. Another difficulty analyzed in this paper refers to a general problem of Cartesian-based controllers. Given the particular situation in which the actuators and the sensors are located at joints and the errors are controlled in Cartesian space, the verification of nonviolating the actuators' saturation limits is not straightforward. In the case of the artificial impedance approach applied to a Cartesian decoupled robot a solution to this difficulty is a linear rescaling of the Cartesian force F defined by equation (23) using the instantaneous linear dependence

$$F = J^{-T}(\Theta,)\tau \tag{24}$$

In case the resulting torque command, say τ_i, violates one of the joint actuation saturation limit $\tau_{i,max}$, i.e. $\tau_i > \tau_{i,max}$, the linear rescaling results in a feasible torque command τ_f defined by

$$\left(\frac{\tau_{i,max}}{\tau_i}\right)F = J^{-T}(\Theta)\left(\frac{\tau_{i,max}}{\tau_i}\right)\tau = J^{-T}\tau_f \tag{25}$$

where $\tau_{i,max}/\tau_i$ is a scalar recalculated at every computation step. This scheme is not applied when all joint torques are within the saturation limits, $\tau_i \leq \tau_{i,max}$. The result is a set of commands for a slower but feasible motion. A computationally efficient solution has been proposed for a joint space dynamics formulation [46].

5.3 Simulations of a 2 DOF Manipulator Using Impedance Control of the Free Motion

51. The simulations are for a 2 DOF jointed manipulator. The desired impedance parameters are

$$M = I_2,$$
$$B = 4I_2,$$
$$K = 4I_2,$$

where I_2 is the 2x2 identity matrix. The manipulator is frictionless and operates in a vertical plane with gravitational forces included.

The inertia matrix is defined using the conventions given in [14]

$$M(\Theta) = \begin{bmatrix} (\ell_2^2 m_2 + 2\ell_1\ell_2 m_2\cos(\Theta_2) + \ell_1^2(m_1+m_2) & \ell_2^2 m_2 + \ell_1\ell_2 m_2\cos(\Theta_2) \\ \ell_2^2 m_2 + \ell_1\ell_2 m_2\cos(\Theta_2) & \ell_2^2 m_2 \end{bmatrix}$$

The vector of velocity dependent and gravitational terms is

$$V(\Theta,\dot{\Theta}) = \begin{bmatrix} -m_2\ell_1\ell_2\sin(\Theta_2)\Theta_2^2 - 2m_2\ell_1\ell_2\sin(\Theta_2)\Theta_1\Theta_2 \\ m_2\ell_1\ell_2\sin(\Theta_2)\Theta_1^2 \end{bmatrix}$$

$$+ \begin{bmatrix} m_2\ell_2 g\cos(\Theta_1+\Theta_2) + (m_1+m_2)\ell_1 g\cos(\Theta_1) \\ m_2\ell_2 g\cos(\Theta_1+\Theta_2) \end{bmatrix}$$

52. In these equations m_i, ℓ_i and Θ_i (for i=1,2) represent the mass, length and joint angle of the appropriate link. The matrices $M_x(\Theta)$ and $V_x(\Theta,\dot{\Theta})$ are determined using Eqs. (19) and (20).

53. The paths from an initial position **I** to a destination **D** for the three control schemes are compared in Figure 5. Path (a) results from the PD position controller with $K_p=K_v=4$. The path is constrained to start at I and end at D, but is otherwise established arbitrarily by the controller. This scheme requires an inverse kinematic computation. Path (b) is the result for the case of a joint decoupling scheme. The result indicates that the performance of the artificial impedance based controller applied to a joint decoupled-linearized manipulator is poor; however, good performance of the artificial impedance approach is illustrated by path (c) which results for an impedance controlled manipulator in which a Cartesian decoupling scheme is used. The straight line path is obtained without an inverse kinematics computation or a trajectory planning scheme.

54. Several simulations were run to illustrate the obstacle avoidance scheme. The results for single obstacle avoidance are presented in Figure 6. In Figure 6a the positions of I and D are the same as for the simulation which resulted in a straight path in Figure 5c. An obstacle 0 is on this straight line between I and D and the impedance based controller corrects the trajectory to avoid collision. In both Figs. 6a and 6b the avoidance path looks like a reflection on an imaginary wall that protects the obstacle 0. After avoiding the collision, the path returns (in Figure 6a) to the vicinity of the straight line path of Figure 5c.

55. Multiple obstacles avoidance is illustrated in Figure 7. Figures 7a and 7b represent simulations of the same situation except for the repulsive stiffness which is two times higher in Figure 6b (K_0=200) versus Figure 7a (K=100). In Figure 7a the path goes between the two obstacles. Higher repulsive stiffness diverts the path around both 0ℓ and 0ℓ as shown in Figure 7b. Also shown in Figure 7a is the straight line path between I and D, which is obtained when no obstacles exist.

56. In Figs. 7c and 7d the same data are used except for a five times higher stiffness in the case of Figure 6d (K_0=500) versus Figure 6c (K_0=100). The path in Figure 7c results from a first correction from the repulsive force associated with 0_1 followed by that produced by the repulsive force associated with 0_1 and so on until it returns toward a path leading towards D. In Figure 7d the reflections between 0_1 and 0_2 are much stronger, actually preventing the manipulator from proceeding past the objects to D. The repulsive force is produced here by a nonlinear spring and the motion is unstable. This result suggests that repulsive forces used in collision avoidance should contain a damping term to avoid instability in some cases. The case of four point-obstacles is illustrated in Figure 7c. The value of the chosen repulsive impedance (K_0=100) leads to a smooth path which reaches D. These simulations show, in general, that the choice of the structure and the gains used for repulsive forces are important and require a design technique.

57. The simulations illustrated in Figures 5 to 7 assume that there is always enough actuator torque to produce the command torque required by the controller. Separate simulations were performed in which a Cartesian rescaling scheme based on Eq. (25) is used to correct the command

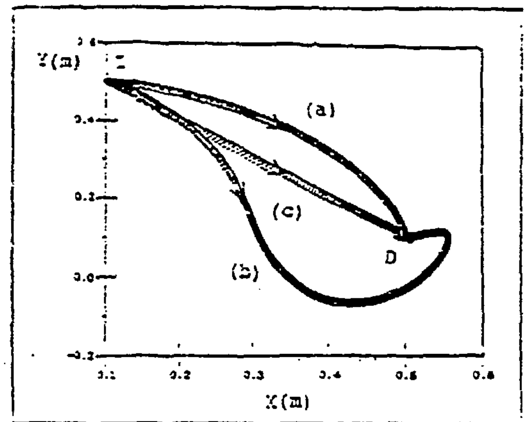

Figure 5. End-Effector Path in the case of a 2 DOF Manipulator

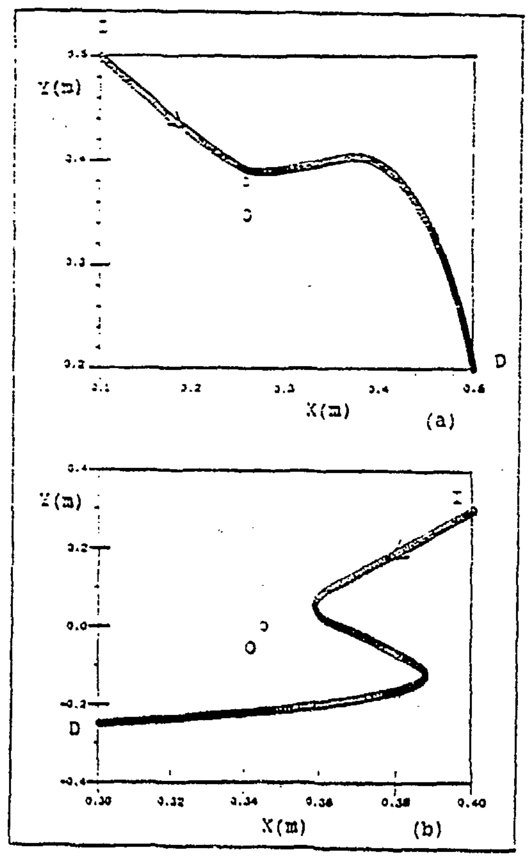

Figure 6. Obstacle Avoidance for a 2 DOF Manipulator

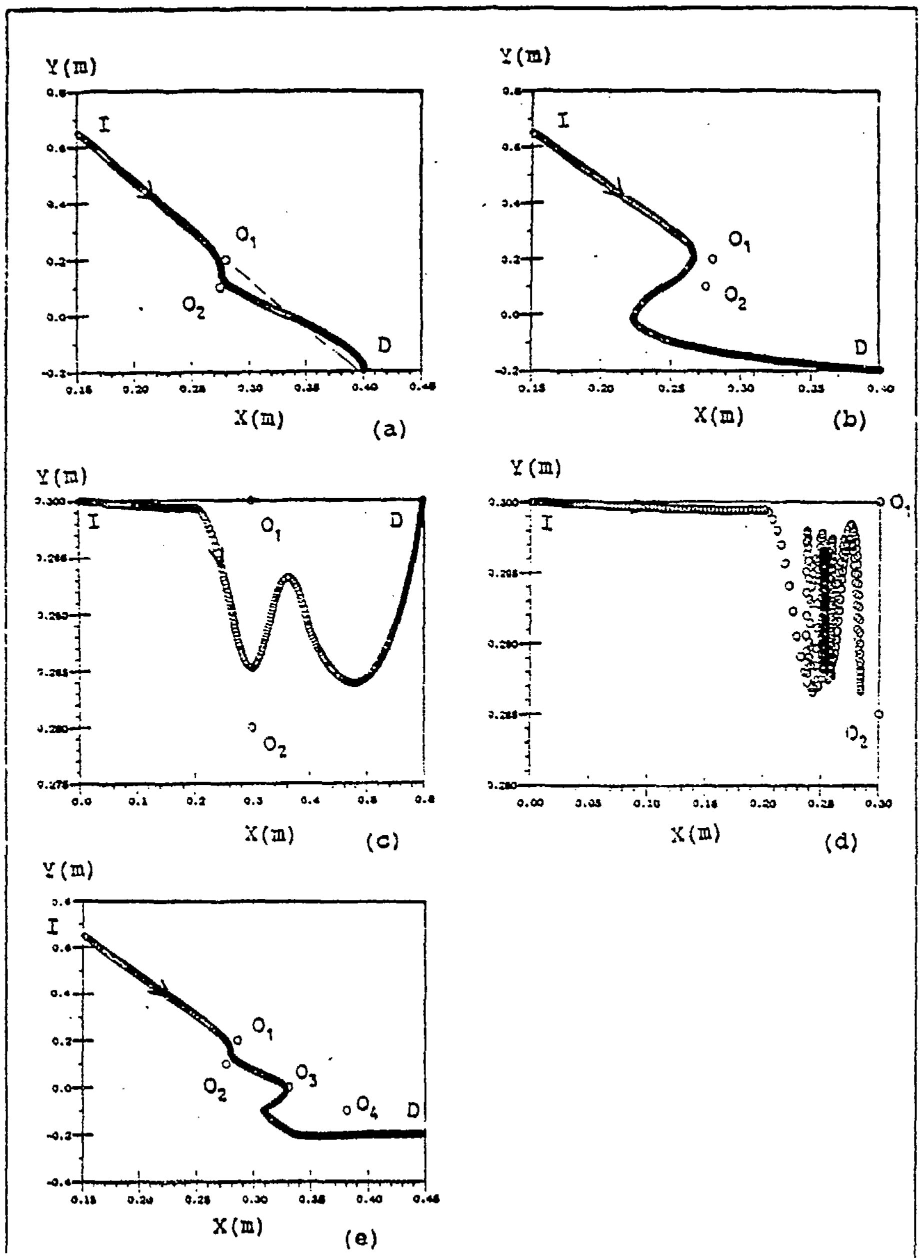

Figure 7. Example of Multiple Obstacle Avoidance

torque when the actuator limits are reached (Figs. 11b and 12b). For comparison, the simulations in Figure 8a and 8a show the effect of reaching actuator limits when no correction of the command torque is performed. As seen in Figure 8a, the path in this latter case departs from the straight line I-0.

58. The interception of moving targets is illustrated in Figure 10. In Figure 10a, a target is moving in a straight line starting at D_i and is intercepted by the manipulator at D_i. A target moving in a circular trajectory with an angular speed 0.3 rad/sec is intercepted rapidly (Figure 10b), while if the angular speed is increased to 3.0 rad/sec the target is never intercepted. The artificial impedance parameters, M=1, B=4 and K=4, correspond here to a natural frequency of 2 rad/sec.

6.0 AUTONOMOUS TRAJECTORY GENERATION FOR DUAL ARM ROBOTS USING IMPEDANCE CONTROLLERS

6.1 The Model

59. In this paper a dual arm robot handling a flexible rod and a string is assumed. The model of the dynamics of each arm is an extension of the model developed by Luh and Zheng [21].

The generalized vector of input forces to the joints of the n DOF leader and the n DOF follower arms are

$$T^l-[J_b(\Theta^l)]^T F^l-[J_a(\Theta^l)]^T N^l-D(\Theta^l)\ddot{\Theta}^l-f(\dot{\Theta}^l,\Theta^l)-g(\Theta^l)=0 \qquad (26)$$

$$T^f-J_b((\Theta^f)^T F^f-[J_a(\Theta^f]^T N^f-D(\Theta^f)\Theta^{\ f}-f(\Theta^f,\Theta^f)-g(\Theta^f)=0 \qquad (27)$$

where

$J(\Theta)$ $=[J_b^T(\Theta), J_a^T(\Theta)]^T$

$J(\Theta)$ = the Jacobian matrix

Θ = n-dimensional vector of joint angular displacements

F,N = the vector forces and moments, respectively, applied at the origin of the end effector coordinates

$D(\dot{\Theta})$ = n by n inertia matrix

$f(\Theta,\dot{\Theta})$ = n-dimensional vector of Coriolis and centrifugal terms

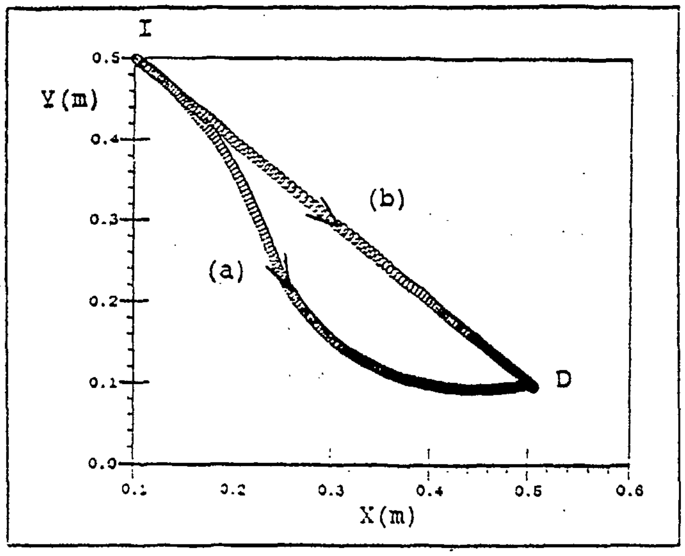

Figure 8. End-Effector Path for the Case of Actuator Torque limits study
(a) No Corrective Action
(b) With Rescaling of the Cartesian Force Vector

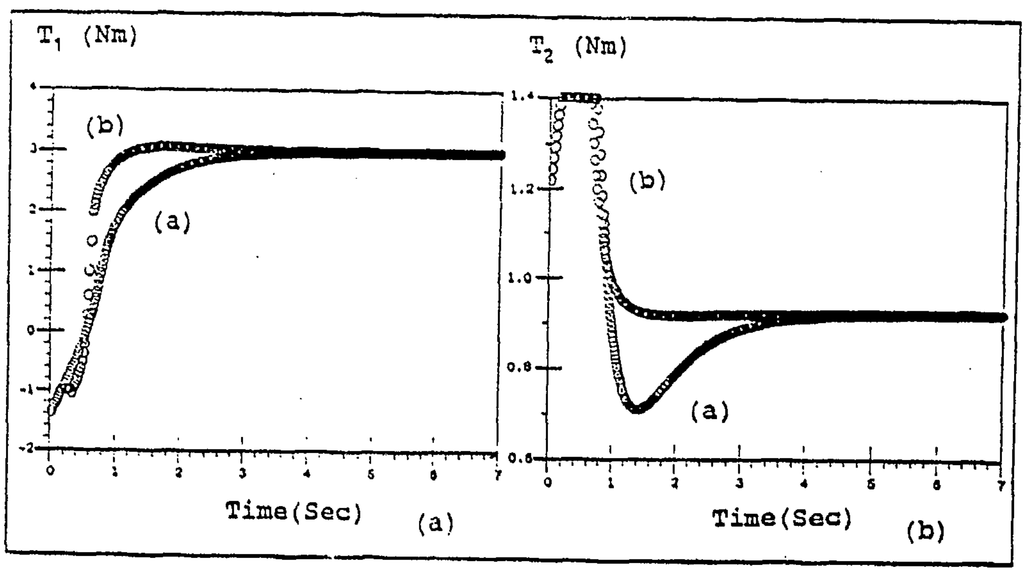

Figure 9. Joint Torques for the Cases (a) and (b) in Figure 8

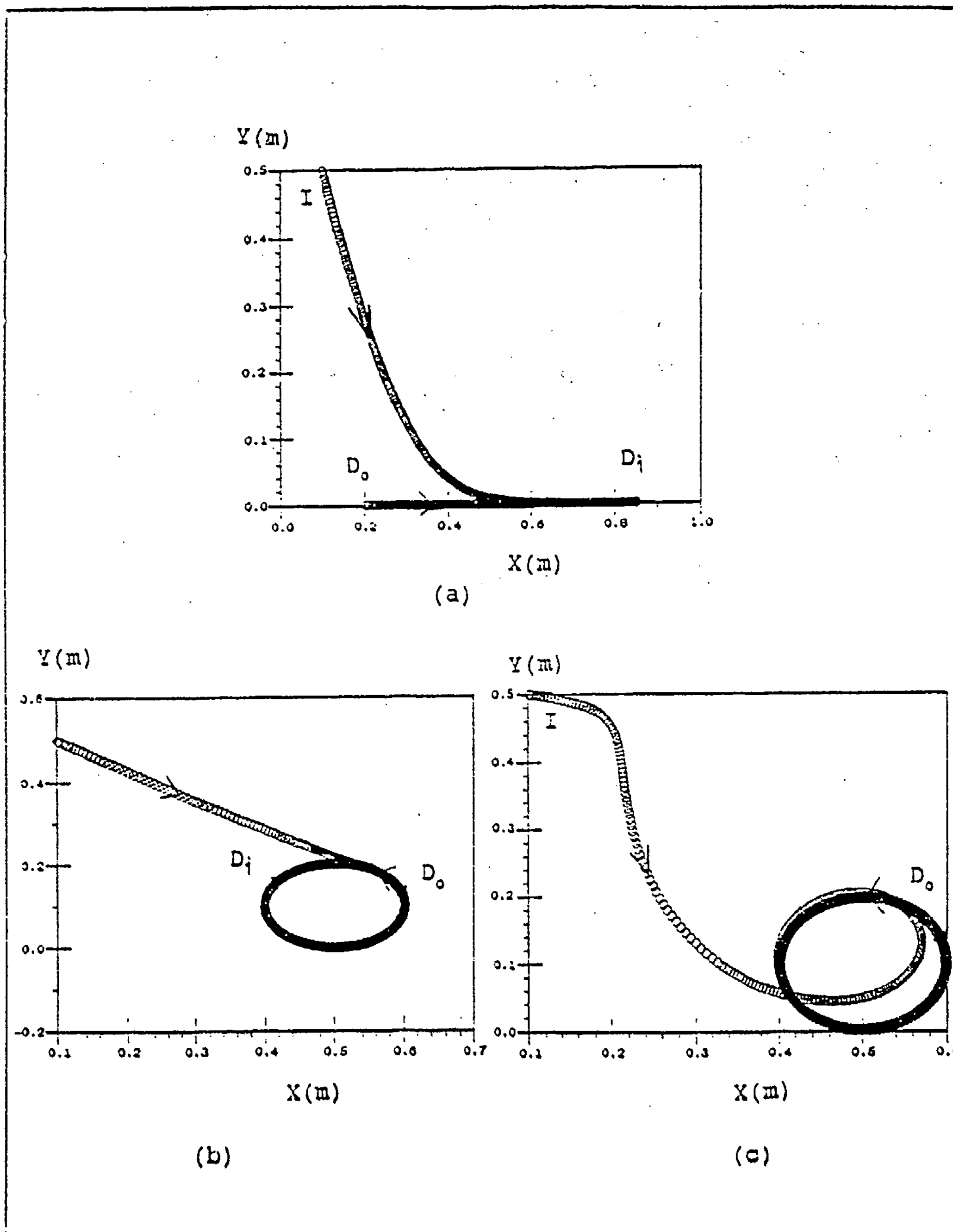

Figure 10. Interception of a Moving Target
(a) Target Moving in Straight Line
(b) Target Moving in a Circle with Angular Rate 0.3 rad/sec
(c) Target Moving in a Circle with Angular Rate 3.0 rad/sec

$g(\Theta)$ = n-dimensional vector of gravity terms and,

ℓ, f = superscripts for the leader and the follower respectively.

60.The vectors $\bar{F}$ and N result from specific load dynamics model. The leader and follower end effectors are assumed linked by artificial mechanical impedances to the target position. The control scheme is similar to the control scheme for single arms, given in Figure 4.

61. A dual-arm planar horizontal robot with two degrees-of-freedom arms is simulated (Figure 11) [31]. The handled object is assumed massless, with an unstressed length of 0.2 m. The parameters of the two arms are L_1^l=0.5m, L_2^l=0.4 m, m_1^l=0.4 kg, m_2^l=0.4 kg, L^f=0.5 m, L_2^f=0.4 m, m_1^f=0.4 kg. m_2^f=0.4 kg, d=1.0 m. The artificial impedance parameters are M=1.0 kg, B=4.0 Ns/m and K=4.0N/m.

6.2 Simulations of a Robot Handling a Flexible Rod

62. The flexible rod is modelled as a linear spring with a damper in parallel, having a spring constant of 1.0 N/m and a damping constant of 1.0 Ns/m. The end effectors are located initially at R_i^l and R_i^f, respectively, and move in the approaching phase to R_1^l and R_1^f where the flexible rod is grasped (Figure 11). In the next phase the flexible rod is transported to $R_{d2}^f$and R_{d2}^f where the leader reaches the final position. Subsequently, only the follower moves, rotating the rod until the follower reaches its final position in R_{d3}^f. The length of the flexible rod varies in time within ± 1%. Further simulations in which the sampling time is reduced from 0.005 s to 0.001 s leads to a reduction of the length variation by a factor of 50. These simulations show that the impedance-based controller can coordinate the motion of a two-arm robot in a sequential fashion. Improvements to the control scheme discussed in the next section,eliminate this sequential approach and result in a smooth simultaneous motion of the two arms to the final positions. This control scheme is tested in handling a string.

6.3 Simulations of a Robot Handling a String

63. The string is modelled, when stretched, as a very compliant spring and, when compressed, as producing no reactive forces on the end effectors. Only the phase in which the object is actually handled is simulated here since the approaching phase poses the same coordination problems for all tasks. The initial positions of the end effectors are R_1^l and R_1^f, respectively, where the object is assumed grasped (Figure 12). The artificial impedances created between the initial positions of the end effectors and their desired positions R_d^l and R_d^f, respectively, generate straight line trajectories in the case of a string which when compressed does not produce any reactive forces (Figure 13). The distance between the two end effectors varies during the motion with a minimum value of 0.14 m (Figure 14), which leads to a large sag in the string of 0.2 m. An artificial impedance approach overcomes the problem of the lack of reactive forces when compressing a string in length by creating

an artificial impedance in parallel with the string. Simulations were performed for an artificial parallel impedance with a spring constant of 1.0 N/m and a damper constant of 2.0 Ns/m. Simulations results in Figure 15 show that the leader's end effector keeps the straight line trajectory while the follower's end effector trajectory is generated such that the string during the motion has practically no sag, as shown on Figure 16.

7.0 IMPEDANCE CONTROL OF MOBILE ROBOTS

64. In the last few years impedance control and artificial impedance approach were used for mobile robot motion control and collision avoidance [48] to [50]. The results were presented for a simplified case which the dynamics of the mobile robot body can be neglected and direct speed control is possible. Full dynamic models for mobile robots were reported recently [51,52]. We are currently developing an impedance controller based on a complete robot dynamics model.

8.0 IMPEDANCE CONTROL IMPLEMENTATION ISSUES

65. In order to achieve the target impedance described by Eq. (11) in Cartesian space, the overall system dynamics of the robot arm-controller-actuator have to be reduced to independent second order linear passive systems. A 6 DOF robot arm would behave, then, as 6 independent passive inertial systems in Cartesian space.

8.1 Nonlinear State Feedback Compensation

66. The implementation of the Artificial Impedance approach was initially based on using a two-part control [34] or a partitioned control law [14] which contains a linear servo control law in Cartesian space and a nonlinear state feedback compensator. In Figure 4, Eqs. (22) and (23) are represented in a diagram in which the linear servo control output $\ddot{X}^{(c)}$ is applied to a nonlinear state feedback compensator which consists of $M_x(\Theta)\ddot{X}(c) + V_x(\Theta,\dot{\Theta})+F_{ext}$. For $F_{ext} = 0$ this type of Cartesian space control has been known earlier as Resolved-Acceleration Control [17].

67. The decoupling method for nonlinear systems has been formulated by Freund and has been illustrated for a joint decoupling case [20]. An interesting implementation of the two-part control scheme consists of generating the joint trajectory by tracking a "false target" point in the phase space of each de- coupled joint [32]. Cartesian tracking of virtual attractive points, described in Chapter III, can be seen as a Cartesian translation of the "false target" method for joint space. Generally, joint space decoupling has been more extensively analyzed than Cartesian space decoupling [34,35,36].

68. The artificial Impedance approach and its continuum mechanics counterpart the artificial Potential Field approach, are special cases of Cartesian control in which, not only the errors are controlled in Cartesian space, but the robot arm is reduced for the linear controller to a decoupled Cartesian system of independent inertial systems. Khatib formulated the problem in the operational

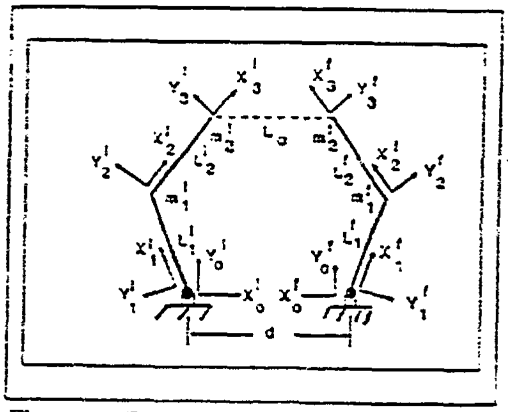

Figure 11. Dual-arm planner robot used for simulations

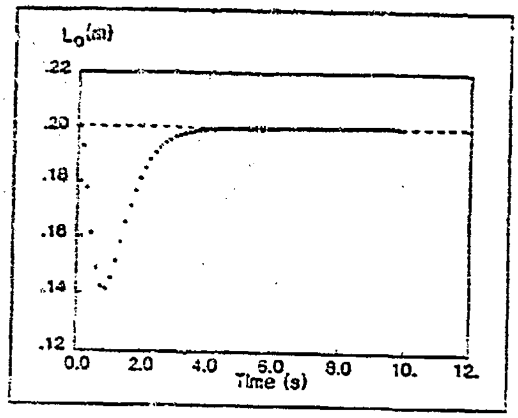

Figure 14. Time variation of a the distance between the two end effectors for the case simulated in Fig. 13.

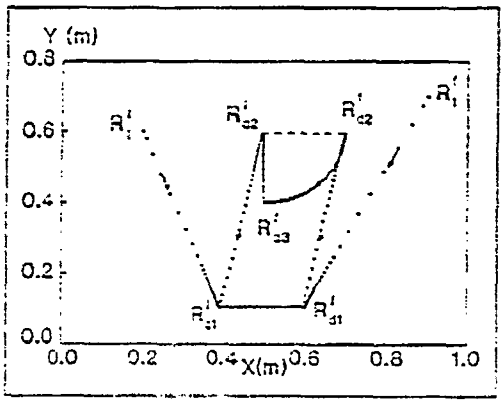

Figure 12. Simulation of a robot handling a flexible rod

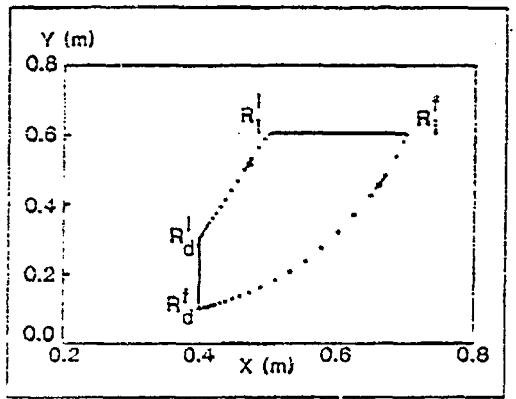

Figure 15. Simulation of a robot handling a string when a artificial impedance is created in parallel to the string

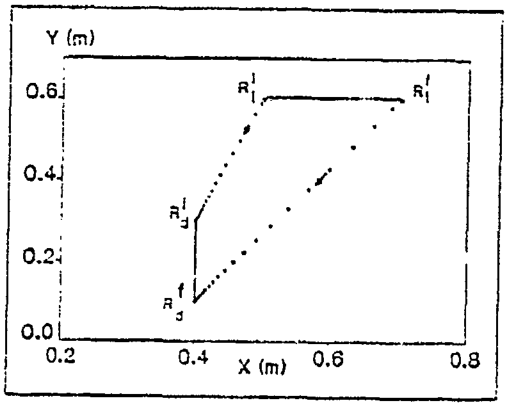

Figure 13. Simulation of a robot handling a string

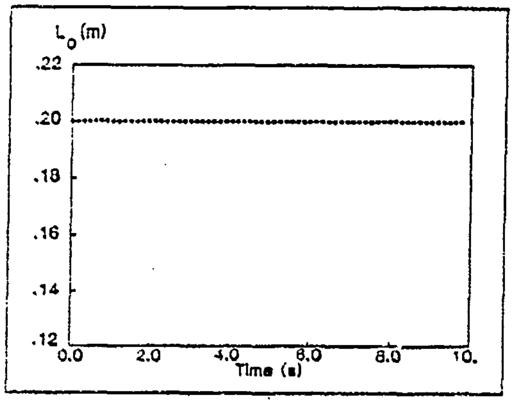

Figure 16. Time variation of the distance between the two-effectors for the case simulated in figure 15.

space of the robot end-effector [1,19]. Given a variety of terms for similar concepts (task space, end-effector space, hand space, operational space) which all refer to a Cartesian space we have used in this paper only Cartesian space terms. Khatib results are similar to those incorporated in Figure 3, i.e. a Cartesian two-part control scheme, except they were developed originally in continuum mechanics (Artificial Potential Field) formulation. Hogan et al developed a further Artificial Potential Field approach and an Artificial Impedance approach using also a Cartesian two-part control law [3,7,8]. An inverse kinematics scheme for Cartesian space control has been proposed without the coupling considerations [33]. The implementation issues of a Cartesian two-part control law refer here mainly to difficulties in achieving the Cartesian decoupling of a highly nonlinear robot arm. The parameters of the dynamic equations, for example the load parameters, are often imprecisely known and an analysis of the uncertainty effect on the Cartesian controlled robot arm motion is needed. The error dynamics equation in this case is still describing a coupled nonlinear system as a result of uncertainty of the parameters of the dynamic model used for nonlinear compensation [36]. This situation led to various solutions proposed for improving robustness of the Cartesian control law, in general, and of the Artificial Impedance approach, in particular.

8.2 Robustness Issues

69. Several solutions were proposed for robust robot control. Some solutions are applicable to the Artificial Impedance approach as for example Model Reference Adaptive Control [37,38,39] and Second Method of Lyapunov-based designs. Model Reference Adaptive Control can be formulated for a reference model which represents a set of three independent translational mechanical impedances and three independent rotational mechanical impedances, i.e. six second order linear, constant parameter differential equations. The error between the reference model positions and Cartesian end-effector positions would be used, in this case, for the adaptation mechanism. This approach benefits from the robustness of the MRAC approach, but only asymptotically the robot arm would behave like the desired Cartesian space impedances.

70. Second Method of Lyapunov-based designs have been used for obtaining sliding mode controllers for single [41] and dual arm robots [23]. The application of a sliding controller for implementing an Artificial Impedance approach has been explicitly formulated by J.J. Slotine [41, pp. 214-215]. In this case, sliding surfaces are chosen as linear functions of the errors, for the Cartesian state variables, and of the environment contact forces. In sliding mode, the controller would make the robot behave like the desired impedance. The resulting discontinuous control law, inherent to the application of the second method of Lyapunov, can be approximated by a boundary layer-based continuous control law. Maintaining sliding mode requires sufficient torque output, large actuator bandwidths and fast closed loop components other than the robot arm.

71. Second Method of Lyapunov can be applied directly for obtaining a corrective term added to a linear control law in order to compensate for the errors resulting from inexact cancellation of the nonlinear dynamic terms by nonlinear state feedback compensator. Again, a discontinuous corrective term would result and a continuous approximation solution is proposed for joint decoupling case [18, pp. 227-236]. A similar formulation can be developed for the Cartesian decoupling case and the Artificial Impedance approach case. An interesting alternative in this case, to the use of

Lyapunov functions, is the use of Hamiltonian functions. This has the advantage of interpreting the time derivative of the Hamiltonian of the conservative part of the system as describing the power transfer from the conservative part to the dissipative part of the system [16]. An application of a nonlinear version of MRAC to a two DOF robot arm modelled by Hamiltonian dynamics using a single rigid link reference model led to a nonlinear discontinuous control law [44]. The Cartesian space control and the Artificial Impedance approach for the Hamiltonian systems were not formulated in [44]. An interesting alternative to the joint torque computation using the inverse dynamics (contained in the nonlinear state feedback compensator) is the use of a disturbance observer for estimating the same torque, but using measurements of the actuator currents and joint accelerations (or computations of the derivatives of joint speeds)[42]. This results in a suitable joint decoupling if sensors bandwidths are sufficient and the computation time for the disturbance observer is sufficiently short. Later formulation of the Cartesian control of a joint decoupled robot arm was based on resolved acceleration control scheme and can also be used for Artificial Impedance approach [43].

8.3 Computational Complexity Issue -- Three-Part Control Scheme

72. The implementation of a Cartesian two-part control law represented in Figure 4 requires extensive computations of the highly nonlinear terms $M_x(\Theta)$ and $V_x(\Theta,\dot{\Theta})$ besides the kinematics computations present in all Cartesian control schemes. Compared to Cartesian decoupling schemes, joint decoupling schemes are computationally less intensive. The proposed disturbance observer scheme proposed in [43] is an example of computationally efficient joint decoupling scheme.

In what follows is a proposed scheme based on a three-part control scheme which can be obtained from Eqs. (18) and (22)

$$\ddot{\Theta}^{(c)} = J^{-1}(\Theta)\{\ddot{X}^{(c)}-\dot{J}(\Theta)\dot{\Theta}\} \tag{28}$$

$$\tau = M(\Theta)\ddot{\Theta}^{(c)} + V(\Theta,\dot{\Theta}) + J^T(\Theta)F_{ext} \tag{29}$$

73. These equations are represented in Figure 17 where the three parts of the control scheme are identified. Eq. (29) corresponds to a joint decoupling scheme, while Eq. (28) contains the Cartesian decoupling scheme of a joint decoupled manipulator. As remarked earlier, with regard to Eq. (21), for

$$M = M_x(\Theta) = (J^{-1})^T M(\Theta) J^{-1}(\Theta) \tag{30}$$

74. F_{ext} does not influence any more the position control commands for the contact motion. We note that no desired contact force is considered in this scheme. Condition (30) would require, however, a desired impedance term M which would be equal to the configuration dependent $M_x(\Theta)$. In cases when the desired impedance would not require a configuration independent mass

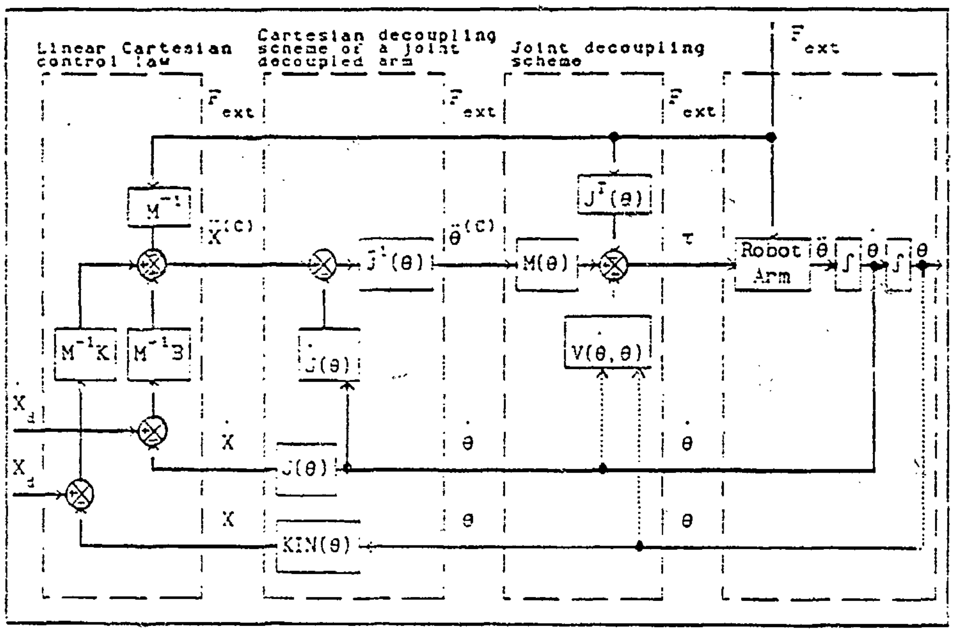

Figure 17.Artificial Impedance Approach in a Three part Control Scheme

term, the computation of $M_x(\Theta)$, as shown in Eq. (30), is not particularly difficult given that it uses matrices which are anyways needed for decoupling computations. Moreover, for the case that all elements of the vector **X** are defined with regard to the inertial frame, $M_x(\Theta)$ is a diagonal matrix with configuration dependent diagonal elements. It can be observed that the two-step control of Figure 3 has been replaced in Figure 17, by a three-step control:(a) linear Cartesian control law, (b) Cartesian decoupling of a joint decoupled arm and (c) joint decoupling. In this scheme, step (b) requires only manipulations of the Jacobian matrix, i.e. only kinematics computations. In the case of no contact force, $F_{ext}=0$, this scheme is the same as Figure 6 in [17] for the Resolved-Acceleration Control for which the PD gains can be interpreted as $M^{-1}K$ and $M^{-1}B$. Artificial Impedance approach brings extra compensation for the contact force and a physical interpretation of the PD gains. In fact, Resolved Acceleration control did not produce the development of collision avoidance schemes probably because of not incorporating the Cartesian control of actuators in an overall dynamic model in which the actuator effects are replaced by passive artificial impedances in Cartesian space.

9.0 CONCLUSIONS AND RECOMMENDATION

75. Artificial Impedance approach is an important candidate for manipulation control of complex tasks. Collision avoidance, actuator limits and moving target interception are features that can be naturally implemented in an impedance controller without need for complete geometric description of the work volume and of the intruding obstacles.

76. Further research in the implementation of the artificial impedance approach holds the promise of an autonomous manipulator which generates and corrects on-line the trajectory when obstacles or actuator limits are encountered.

77. The coordinated motion of a dual-arm robot can also be controlled by applying the Artificial Impedance approach. The simulations were performed to illustrate the manipulation of non-rigid bodies such as a flexible rod and a string. The results show that this control approach is a candidate for solving some of the difficulties of coordinated dual-arm robot operation both in the approaching phase and in the object handling phase, in particular, for the case of handling a string with sag constraints and other non-rigid objects. Further simulations and experiments are required at this stage to show the practicality of the Artificial Impedance approach to dual-arm trajectory generation. The implementation of the Artificial M-B-K Impedance approach is proposed in the form of a three-part control scheme: (a) a linear Cartesian control law with position gain $M^{-1}K$ and velocity gain $M^{-1}B$, (b) a Cartesian decoupling scheme of a joint decoupled manipulator using only Jacobian manipulations, and (c) a non-linear feedback joint decoupling compensator. In the case of non contact motion, this scheme is identical to Resolved Acceleration control. The importance of an Artificial Impedance control scheme results from the physical interpretation of the linear controller gains and the possibility of generating and correcting robot trajectory in case of detecting obstacles by posing artificial impedances in the robot workvolume.

78. The Impedance Controller as proposed in this paper is embedded in a multipurpose hierarchial control structure. Such hierarchial control architecture provides a means to introduce

higher level autonomous operational capabilities which are of critical importance to many military operations. Supervised Autonomous Robots and eventually Fully Autonomous Robots will employ hierarchial control architecture which basically consists of three modalities: sensing, action and planning with their interactions within a uniform structure. Unfortunately, Autonomous Robotic Systems are still at their infancies due to various reasons. Some of them are:

(i) Manipulation tasks are highly unstable;
(ii) Sensory feedback is often inadequate;
(iii) Performamce of manipulators is limited;
(iv) Computational complexity is intractable;
(v) Theoretical foundation do not yet exit (i.e. nonlinear system).

79. However, current research activities focus on the development of robots sensing, action (execution) such as trajectory planning and object avoidance and planning and an overall system concept where all these modalities are uniformly integrated. Military operations will greatly benefit from these developments.

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14. Abstract:

Robotic Systems Technology is under contract to build and deliver 14 Surrogate Teleoperated Vehicles (STV) to the DoD Unmanned Ground Vehicle Joint Program Office. The STV system consists of two parts - the Remote Platform (RP) and the Mobility/RSTA Module (MOB/RSTA). The RP is based on an off-the-shelf Polaris six-wheel drive, Ackerman-steered all-terrain vehicle. Its full suspension allows the operator to drive at speeds exceeding 58 kph. The current automatic drive train will be modified using a unique dual motor hybrid concept that incorporates an electric motor to provide slow speed mobility when an ultra-quiet mode is required. All electronics are packaged in waterproof enclosures that allow for easy changeout of electronic components for simple and rapid maintenance operations. The modular MOB/RSTA module consists of an elevating mast and a pan and tilt turret with a variety of sensors, including a laser designator and a FLIR. The mast will extend 3 meters from the resting position, allowing the cameras to be 5 meters from the fround. The electronics for the control of all turret functions, including sensor interfaces, are totally self-contained within the turret.

SURROGATE TELEOPERATED VEHICLE (STV)- A MODULAR TESTBED

1.0 INTRODUCTION

Robotic Systems Technology (RST) is under contract to design, build and deliver 14 Surrogate Teleoperated Vehicles (STV) by December, 1991 to the Department of Defense (DoD) Unmanned Ground Vehicle Joint Program Office. This office is located at the U.S. Army Missile Command in Huntsville, Alabama.

The STV is a critical step in the acquisition of unmanned ground vehicles for combat and combat-support missions. The STV will provide a system for the service user to develop and validate his employment concepts and complete Early User Test and Evaluation to aid in the development of requirements for future unmanned ground vehicle systems. In these days of declining force structure and the increasing emphasis on low-intensity conflict scenarios, these systems will provide the Services with increased force multiplication and soldier survivability

The key features of our STV design, shown in Figure 1, are as follows:

- The use of a proven, commercially available, highly capable platform to minimize technical and schedule risk and maximize testing availability.
- An automatic transmission and easy-to-operate controls to minimize the time required to learn how to operate the system.
- Six-wheel drive to provide maximum all-terrain mobility and excellent stability.
- Ackerman steering and full suspension chassis design to permit safe high-speed driving in excess of 58 kph.
- Rugged, proven chassis frame that supports up to 682 kg of payload.
- Wide wheelbase and low center of gravity to allow for operation on a 35-degree slope.
- Increased combat survivability due to the small physical signature of the platform — 1.3 meters wide, 2.75 meters long, 3 meters tall.
- The use of pneumatic shocks to raise and lower the chassis, thus providing the ability to create a rigid suspension, minimizing vehicle body swaying when the sensor mast is erected.
- Instantaneous switching between direct and remote driving with fully backdrivable remote actuation components.
- The capability to be transported in the bed of a HMMWV or to be towed, reducing logistics requirements.
- Versatile dual-engine hybrid design with a 25-hp diesel engine providing high-speed/high-power mobility needs and a DC electric drive motor allowing for an ultra-quiet mobility mode.

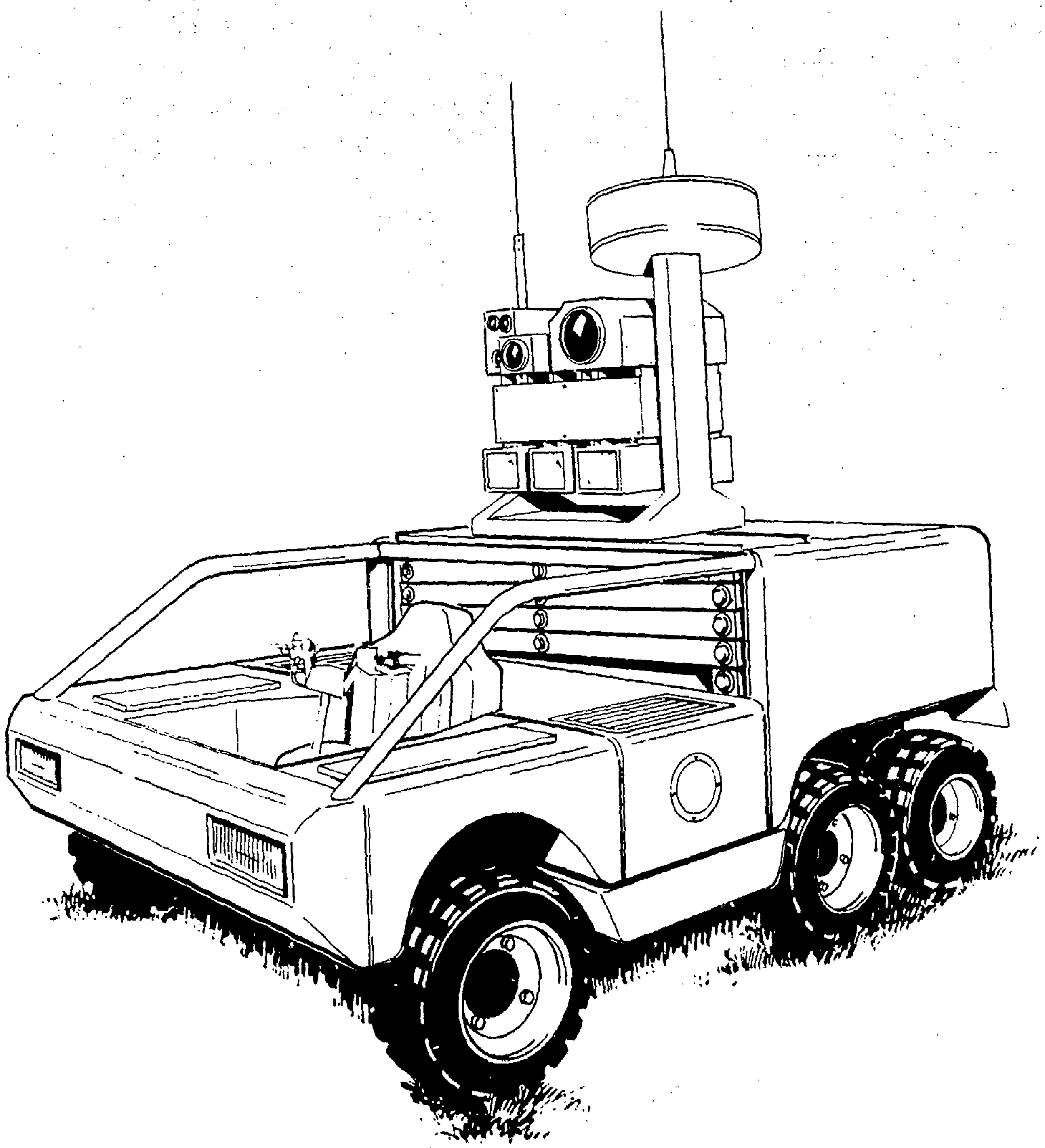

Figure 1 The Surrogate Teleoperated Vehicle Concept

- Fuel capacity of 40 liters to provide a driving range of 450 km.
- 200 A-hr of batteries that provide 3 days of operation in the limited surveillance mode.
- Swimming capability using dual high-speed propellors for water mobility.
- Innovative driver-down position for lower center of gravity, true roll-over protection, and the capability to add lightweight armor for increased protection.
- An open architecture with an industry standard VMEbus and VxWorks software development system to facilitate the addition of increased technology.
- A modular design that utilizes the concept of line replaceable units to minimize system repair time.
- Proven elevated mast design that provides 3 meters of extension, placing the sensor module cameras at a total height of 5 meters feet above ground level.
- A MOB/RSTA sensor module with ±270 degrees of pan motion and ± 90 degrees of tilt motion.
- Turret interface and control electronics are totally self-contained in the turret structure, reducing the required size and complexity of the MOB/RSTA interface wire harness from 150 to 25 wires.
- High-precision, high-speed pan and tilt DC servo gearmotors with the dynamic range and system response needed to support accurate target tracking and the use of head tracking display systems.
- A modular, "mix and match" turret design that allows for the simultaneous use of four different day/night stereo driving cameras or targeting camera systems for maximum mission flexibility.
- A differential GPS receiver and a proven dead reckoning approach providing accurate location and navigation information.
- A proven, field-tested passive acoustic detection system that not only provides true 360-degree binaural hearing, but also provides automatic target cuing to reduce operator workloads.

The STV system consist of four parts - the Remote Platform(RP), the Mobility, Reconnaissance, Surveillance, and Target Acquisition Module (Mob/RSTA), the fiber optic and radio frequency Communication System, and the man-portable Operator Control Unit.. This current paper will only discuss the design of the RP and the Mob/RSTA components.

2.0 REMOTE PLATFORM

The remote platform (RP) system consists of the carrier base, the and the remote control electronics that provide an interface to all systems on the STV and the communication system. Each system has been carefully designed to work as an integrated system with maximum capability and minimum risk for assembly and integration. Each subsystem is described individually in the following subsections.

2.1 Carrier Base

The Remote Platform carrier base is a modified Polaris Big Boss six-wheel, six-wheel drive, all-terrain vehicle. This American made, commercially available platform sells for $4,899. The full suspension used on all of Polaris' ATVs allows for routine safe travel to speeds exceeding 58 kph. The use of six wheel drive offers a 50% increase in mobility over a four-wheel drive vehicle and provides reduced tire ground pressure when compared to a four-wheeled platform.

With a wheelbase of 1.9 meters,a total length of 2.76 meters, a total width of 1.3 meters, and a total weight of 455 kg, the carrier base will fit in the rear bed of a HMMWV. In addition, the carrier base is fully towable to allow a two-man HMMWV crew to transport more than one vehicle at a time.

The proven frame, suspension, and drivetrain for the carrier base has been in production for 3 years on the Big Boss 4 X 6. The are no changes in the frame between the 4 X 6 and the 6 X 6; only the drivetrain changes.The frame will be slightly modified in the area that mounts the existing gasoline engine to allow for mounting of the larger diesel engine . The frame is designed to easily support a payload of 682 kg. The operator's seat is moved forward and downward to lower the center of gravity of the entire system and to give the driver roll bar protection. This will also allow for the future addition of lightweight composite armor to protect the driver from small arms fire or top armor for fragment protection.

The suspension provides for maximum mobility in rough terrain and safe high speed travel on relatively smooth terrain. The existing mounting locations for the suspension will not change. The front two wheels use a MacPherson strut assembly. Dual shocks are used on the rear in a trailing arm configuration. The standard coiled springs will be replaced with pneumatic springs. These pneumatic springs allow the STV system to raise or lower by 15.24 cm. At the springs bottom position, the spring effect is eliminated, making the platform very rigid, with the tires providing the only suspension. This will eliminate any swaying of the MOB/RSTA module due to motions of the suspension, a common problem when mounting a mast on a vehicle with a suspension. The ability to vary the height of the vehicle also will allow the operator to reduce the vehicle's visible signature if needed for stealth or transportation purposes.

The main motive power source is a Fuji 25 hp, 997 cc, diesel engine. This three-cylinder, water-cooled engine has five more horsepower than the commercial Big Boss 6 X 6 two-stroke, gasoline engine. This engine incorporates the latest in sound quieting technology that makes it 4 dB quieter than any other known diesel engine in its power range. To further muffle the diesel engine, the engine and drive train will be placed in a sound-quieting box in the middle of the vehicle behind the driver.

In addition, the exhaust manifold will be routed through the long suspension tunnel that runs down the middle of the back part of the vehicle. This long sound chamber will further dissipate the sound levels of the engine exhaust and will direct the exhaust toward the ground to reduce the transmission distance of the noise. Also, since the outside walls of this tunnel are not visible from the side, this will act as a thermal cooling tunnel (like the cooling tunnels on stealth aircraft) to reduce the thermal signature of the platform due to exhaust emissions. Beneath the engine compartment are two 20-liter fuel tanks that provide a total operating range of 450 km.

The drive train, shown in Figure 2, is a modification of the current 6 X 6 drivetrain. The rotational speed of the output shaft of the diesel is increased from 3600 rpm to 7200 rpm to allow Polaris to use standard 6 X 6 drivetrain components. This is accomplished by adding a 2:1-cog belt overdrive to the output shaft of the diesel. This feeds a standard Polaris Variable Belt Transmission (PVT) that provides power to the gearbox. This PVT is used on each of the 80,000 snowmobiles and ATVs that Polaris produces each year.

The output of the PVT goes into a gear box that allows changing of gears into either neutral, reverse, or a low or high speed range. The low speed range provides extra pulling torque for steep hill climbing or vehicle towing but limits the maximum speed to around 33 kph (similar to the low gear range in an automobile automatic transmission). In normal operation, the driver will use only the high range.

On the opposite side of the gearbox, on the same shaft, is an electric clutch attached to a dependable 2-hp electric golf cart motor made by General Electric and used in almost every golf cart made in the world. This electric motor will provide a maximum speed of only 8 kph, but allows for extremely quiet mobility operations. With a range of more than 4 km, this will allow the silent movement of the STV near hostile forces. This innovative dual motor hybrid design combines the high power capability and flexibility of a diesel with the quiet operation of an electric motor in a single system that provides our STV system with unique operational capability.

The output of the gearbox is connected to a drive shaft that extends through a watertight seal to the outside of the engine enclosure to deliver power to the front and back wheels using chain drives. The front wheels incorporate Polaris's "on-demand" front-wheel drive that only activates when slippage is detected in the rear wheels. This reduces the effort required by the operator to turn the steering wheels, reduces front wheel wear, and allows for the distribution of maximum horsepower to the rear wheels if needed for high speed mobility. This capability can be turned off by a switch on the steering column or remotely.

Attached to the frame will be six sealed, waterproof, fiberglass boxes of varying sizes. These boxes provide enough volume to allow the system to fully float with a rider. One of the boxes will house the engine, radiator and drive train. Two boxes under the engine compartment will hold the diesel fuel. Two other boxes will be up front to hold the remote operator pendant and to serve as additional storage area. The area behind the engine compartment in the center of the vehicle is reserved for the MOB/RSTA module. Directly behind this area is a large cargo box that houses all vehicle electronics, 200 A-hr of batteries, the navigation electronics if necessary, and the 10 km.fiber-optic/RF communication and payout system. This last compartment has a hinged lid like the trunk of a car to provide easy access for maintenance or rapid replacement of the fiber-optic cable.

Manual operation of the STV will be identical to that of the commercial 6 X 6. All current controls will stay the same except the operation of the gearbox from neutral to reverse to high or low forward which will be performed by the pushing of a button instead of using the shift lever. This feature makes our system "ready to drive" with no need for the operator to disconnect actuators before manual operation.

2.2 Vehicle Control System

An interconnect block diagram of the platform control system components can be seen in Figure 3. The vehicle control system uses a VMEbus for the primary means of communication between system-level boards. The VMEbus standard was selected as the backplane of choice to reduce electrical reliability problems. The STV will be subjected to a high-shock, high-vibration environment, and the DIN-type connector used for VME boards is ideal for providing

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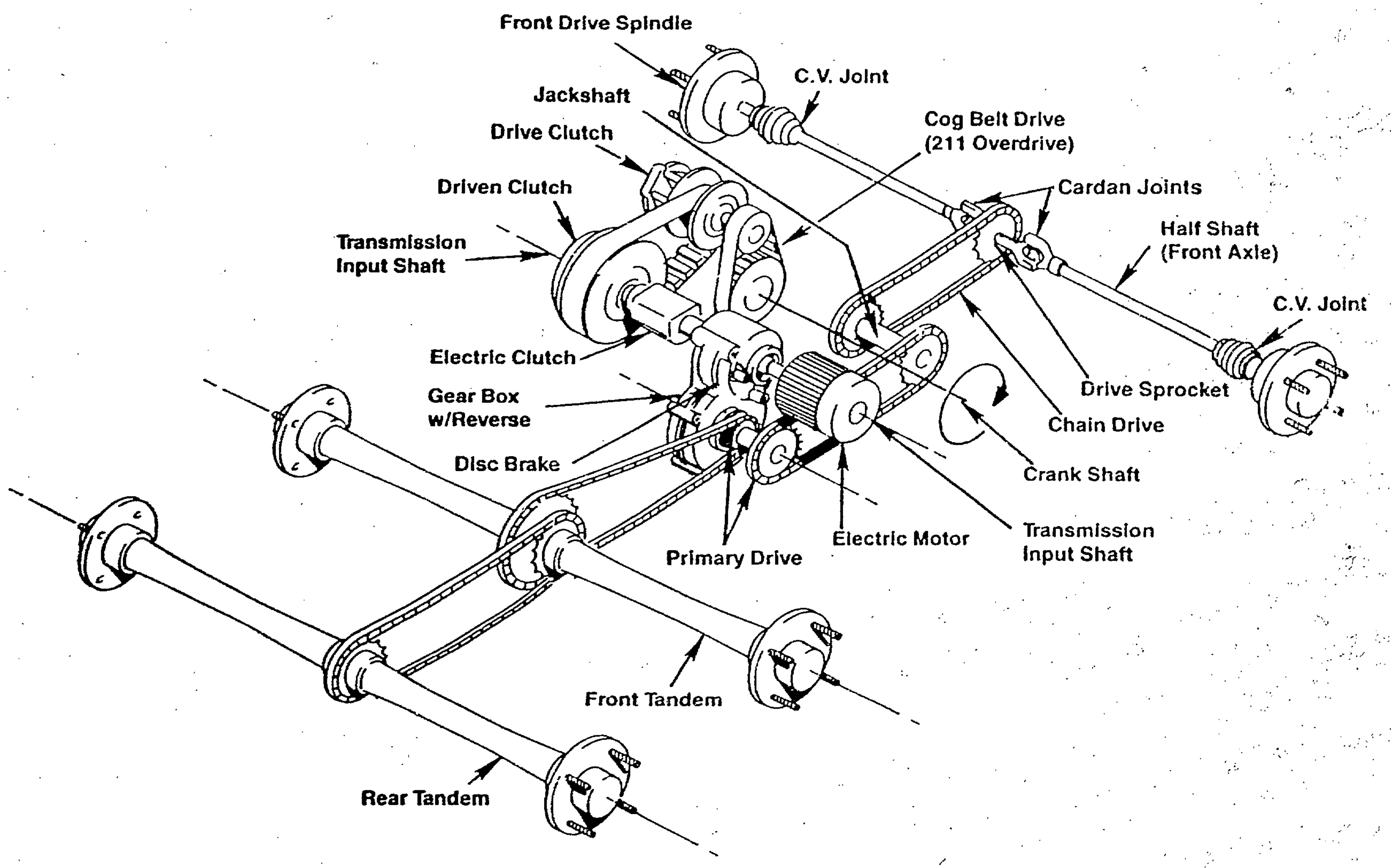

Figure 2 Hybrid Dual Motor Drivetrain Concept

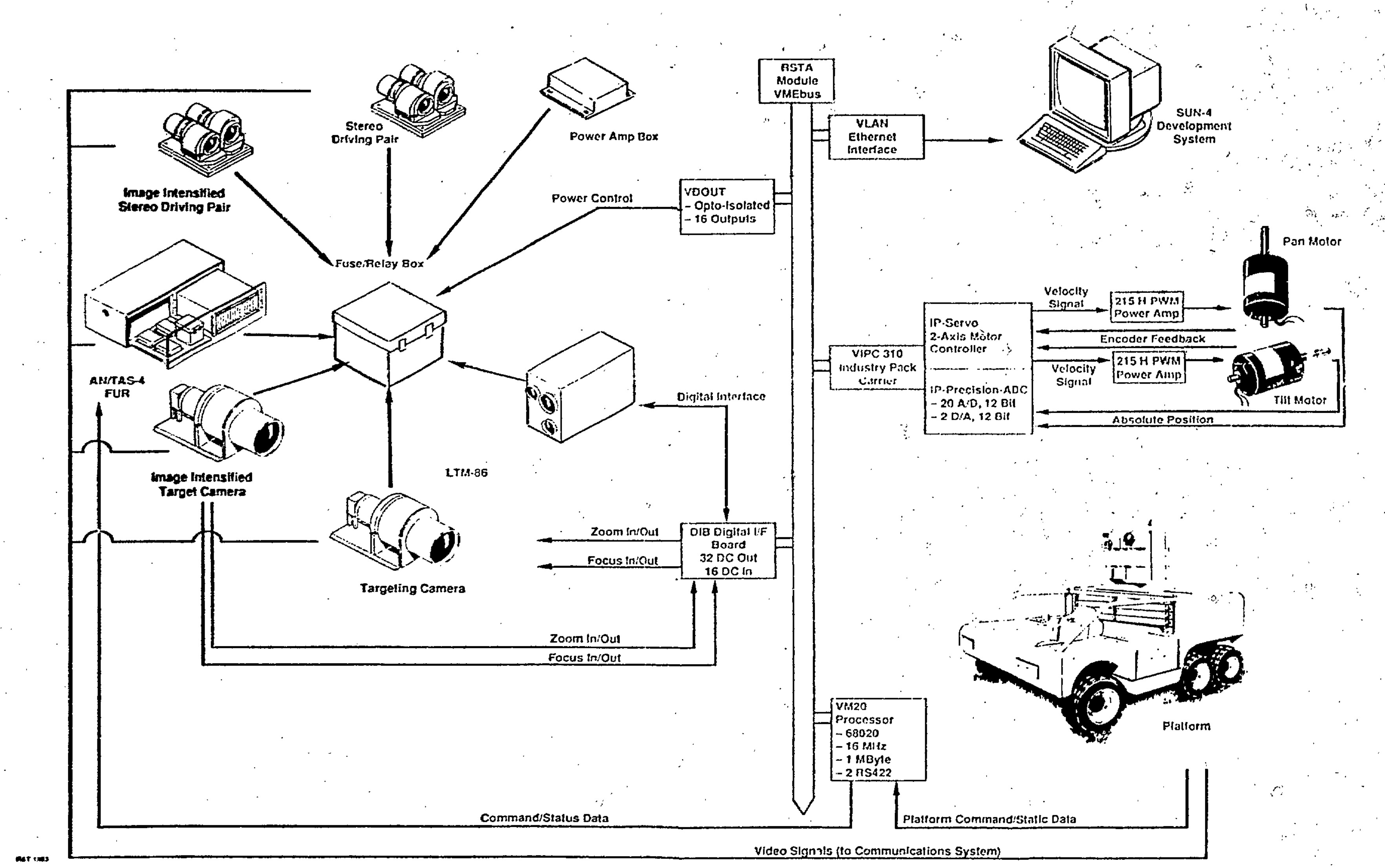

Figure 3 Remote Platform Electronics Interconnect Diagram

a reliable electrical connection. Additionally, every highly integrated printed circuit board selected utilizes the 3U VME format, which is even further resistant to shock and vibration due to its much smaller surface area. Finally, the entire cardcage is shock mounted inside its sealed enclosure.

The processor board chosen is a powerful 25MHz Motorola 68020 processor, with floating point expansion capability (Motorola 68881). The 68020 board is 100% CMOS design and dissipates less than 6 watts. It supports up to 8 Mbytes of on-board dual-ported DRAM, which is more than enough for the STV application. There are seven additional boards on the VME backplane, with two spare slots available for expansion. In addition, the platform power supplies are mounted to cards and slid into the cardcage to make component-for-component swaps simple.

Each of the additional boards are also 100% CMOS designs, allowing the primary electronics enclosure to be a sealed unit, requiring no outside air for cooling. The total power consumption of all the boards within the electronics box is less than 30 watts. Every board on the backplane, except one, is off-the-shelf, and in stock. This eliminates the possibility of schedule delays for delivery, as well as design and debug time.

The vehicle includes eight 12-Volt, 50 A-hr sealed lead acid batteries, providing 200 A-hr at 24 Volts. The raw power is available for additional subsystems to tap off via two high capacity power strips located in each battery compartment. In both the diesel driving mode and the trolling mode, the output of the 100 amp alternator more than compensates for the current required for the actuators and control electronics.

When the engines are off, two basic modes are supported. In surveillance mode, power to all the actuators on the platform are turned off (under computer control) and only the main control electronics, and platform status sensors are operable. The power draw is less than 2 amps at 24 volts, and with full battery capacity, the platform will remain in surveillance mode for over 3 days, with enough reserve power to start the engine.

The second mode of operation is a standby mode. Only the watchdog safety system is active, consuming an insignificant amount of power (less than 0.5 watts). The amount of time the system can remain in standby mode will be driven by the power required by the GFE communications system. Using the power requirements of the communication system, the time in stand-by mode will exceed 5 days.

The control system allows for a very simple in-the-field calibration routine, and automatically updates EEPROM as necessary. The calibration procedure is invoked using the calibration buttons on the membrane switch panel. Once in calibration mode, the platform prompts the operator to move each actuator (all are backdriveable) to a particular position. Once in position, the operator presses the confirm button, and the computer will read the appropriate position indicator and store its value in EEPROM. A checksum is maintained for each platform so the validity of the EEPROM is checked every time power is applied. If the checksum is not correct, calibration mode will be entered automatically, and the operator will be prompted to calibrate all actuators before beginning operation.

The rear cargo area houses most of the electronics required to control the STV, and provides ample room for the GFE communications system and fiber-optic payout canister. The electronics box contains the Vehicle Control System (VCS), as well as the power supplies for all vehicle components. It is a shock-isolated unit, and because of the selection of low power CMOS boards, requires no outside air for cooling.

The power amplifiers, also located in the rear cargo area, are separated from the main electronics to eliminate noise and heat problems within the electronics box, and to greatly simplify all high-power wiring.

Space has been allocated on the right rear of the platform cargo area for the mounting of a fluxgate magnetometer, used for navigation. Isolation of this heading sensor from the rest of the platform electronics and actuators should greatly reduce the amount of compensation required for the dead-reckoning navigation calculations.

The STV is programmed using the "C" programming language for all software development, using the VxWorks development system. This decision was based on the immediate availability of the real-time kernel for the CMOS microprocessor board chosen, the familiarity of the RST personnel with the development system, and its low cost per target system. It allows for real-time data capture and display on a Sun workstation as well as both symbolic level and source-level debugging.

The vehicle control system is responsible for receiving commands and providing status information to the communication system, while maintaining stable control of each element of the system. Provisions have been made for the command data to include a vehicle I.D. for multiple vehicle control. This is required to allow multiple platforms to operate on common RF frequencies. All signals being used conform to commercial computer interface standards (RS422, TTL levels, ±10V analog signals, etc.) and will readily interface to the communication system, turret control system or any additional future platform components.

The RST team is using a proven software design methodology — a task decomposition approach originally developed at the National Institute for Standards and Technology (NIST). The control system architecture for the VCS is shown in Figure 4. Each control block ("level") can be thought of as a person in a management chain. Its responsibility is to receive a command from its supervisor, gather the appropriate status information relative to that command, and generate a command to each of its subordinates, coordinating their efforts as necessary.

As an example of how the system works, if the current command into the MOBILITY level is "Drive_Diesel", the level would gather current operator command sensory information (such as the operator pushing on a joystick), and use that information to coordinate the activity of its subordinates. In this case it would send a "Steer_Pos" command to the STEERING level and a "Set_Throttle" command to the D_THROTTLE level, with the appropriate parameters. As the command into the MOBILITY level is changed, so is its response. i.e. if the "Drive_Diesel" command is changed to "Troll_Mode", the joystick input would then be used to send a velocity vector to the TROLLING level.

All task decompositions continue down the diagram until commands can be directly executed in hardware. For example "Fuel_Solenoid_On" is simply a high-current output from the VDOUT-32 that throws the relay that applies power to the fuel solenoid.

3.0 MOBILITY/RSTA MODULE

The Mob/RSTA module has three parts - the elevating mast, the turret, and the control electronics.

3.1 Elevated Mast

Our elevating mast design is shown in Figure 5. The mast is a scissors type design, similar to the configuration used in the elevating mast on the TOV system. In the stowed configuration, the mast is only 0.46 meters tall. The mast will raise to 3.54 meters, providing a total extension of 3 meters. In the stowed configuration the mast has a footprint of 0.46 meters by 1.15 meters. Even with a design factor of safety of three, we were able to get the weight of the mast entire mast down to 50 kg.. Mounting the mast to the platform is very simple, requiring only 4 bolts.

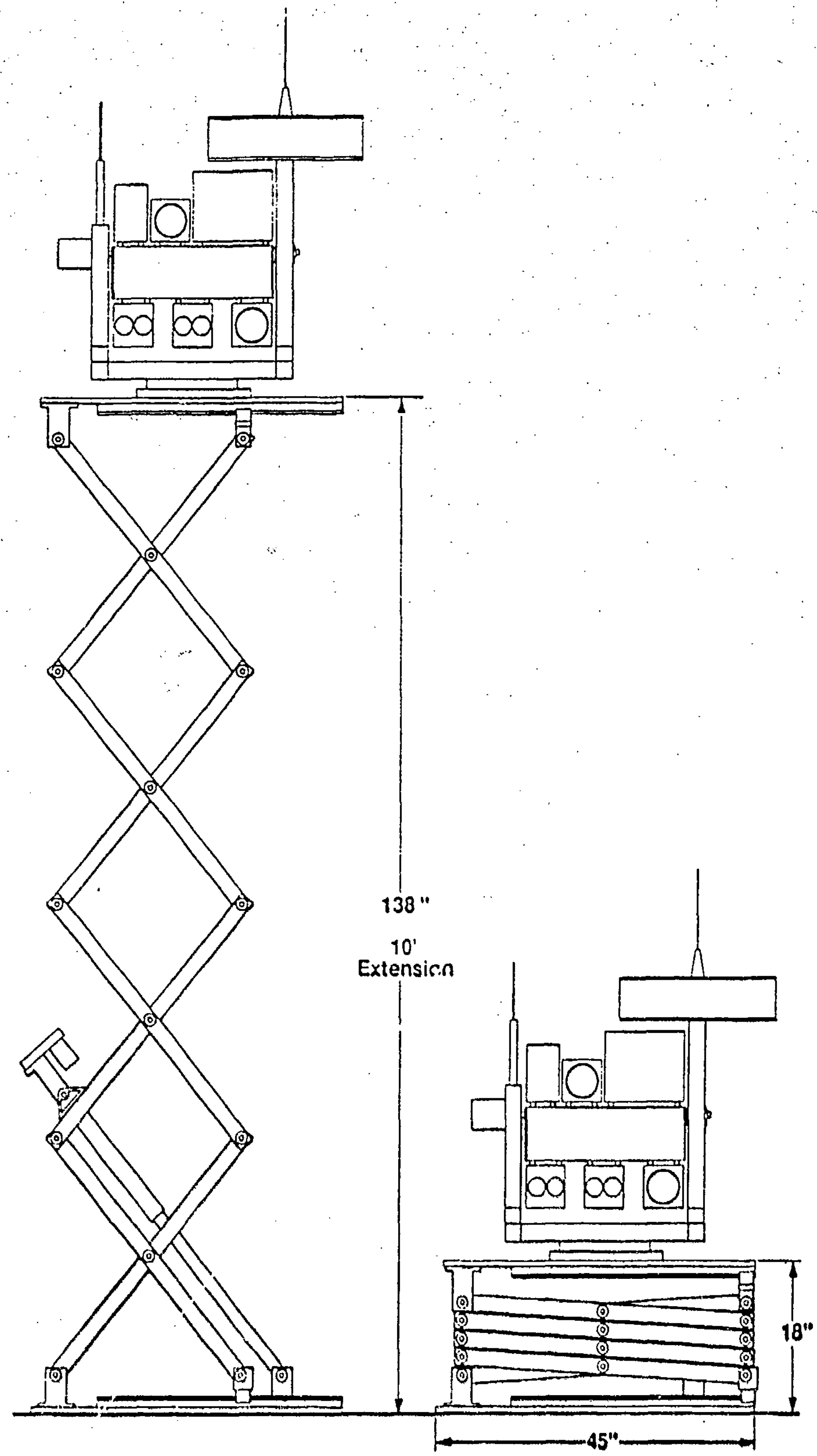

Figure 5 Elevated Mast Concept

3.2 Turret

Our sensor turret design is shown in Figure 6. The turret control electronics necessary to communicate to and control all of the sensors and motors are housed in the tilt structure enclosure. The turret has mounting locations to simultaneously hold four camera enclosures, an LTM-86, and an AN/TAS-4. The ability to quickly mount up to four different camera systems provides the user with the capability to tailor the the sensor suite to a particular mission. By carrying both day and nights camera systems, the STV system can be used in 24 hour day/night combined missions.

The pan axis is capable of turning ± 270 degrees (540 total) and the tilt axis ± 90 degrees. The pan and tilt axes are powered with identical PMI precision gear servo motor with 100:1 Revex high precision, low backlash spur gearbox, which provides a velocity range of 0.05 to 150 degrees per second. This rare earth DC servo has a constant torque that will provide the same quick, accurate response, irrespective of rotational speed.

The motors will use an incremental encoder for position and velocity control. They also will each have a two-turn servo potentiometer to furnish the absolute position upon system start-up. Without them, the system would not know the "Home" or "Zero" position.

The structure of the turret is made of a welded combination of aluminum plates and extrusions. The structure for the tilt axis is a sealed box that houses all the electronics to control and power the motors and sensors. The pan assembly sits on top of a Kadon turntable bearing which provides smooth rotational movement and supports the weight of the entire turret. The bearing and motor assembly sits in a watertight housing which is bolted directly onto the top plate of the elevating mast. The combined weight of the motors and structure, two driving and two targeting camera systems, the FLIR and LTM-86 and all electronics are estimated to be around 45 kg.

3.3 Mob/RSTA Control System

The Mob/RSTA Control System (RCS) incorporates the same basic structure as the RST remote platform. An interconnect block diagram of the key control system components can be seen in Figure 7.

Each printed circuit board selected is a 3U format, reducing both surface area and weight, thus allowing for an extremely high tolerance level of shock and vibration. The spare slots in the cardcage are available for power supply mounting and future expansion. The wiring harnesses running to these boards connect at the front panel and run to the cover plate, making testpoints easily accessible.

The cardcage is located within the turret inner gimbal. Shock isolation of the 3U cardcage is not needed because these cards have a much higher natural frequency, and therefore are much better equipped to withstand the low-frequency vibration expected on a small ground based vehicle.

The power amplifiers selected come packaged in metal enclosures which provide for noise isolation and the ability for them to be mounted directly to the surface of the inner gimbal, which provides an excellent heat sink.

The fuse box is a compact off-the-shelf unit used mainly in boating and other marine applications. It can hold 20 fuses and 12 high power relays, is water resistant, and is cost effective because of its commercial availability.

The processor board chosen is a PEP VM20, a 16-MHz Motorola 68020 processor, with floating point expansion capability (Motorola 68881). The 68020 board is 100% CMOS design and dissipates less than 6 watts. It supports up to 8 Mbytes of on-board dual-ported

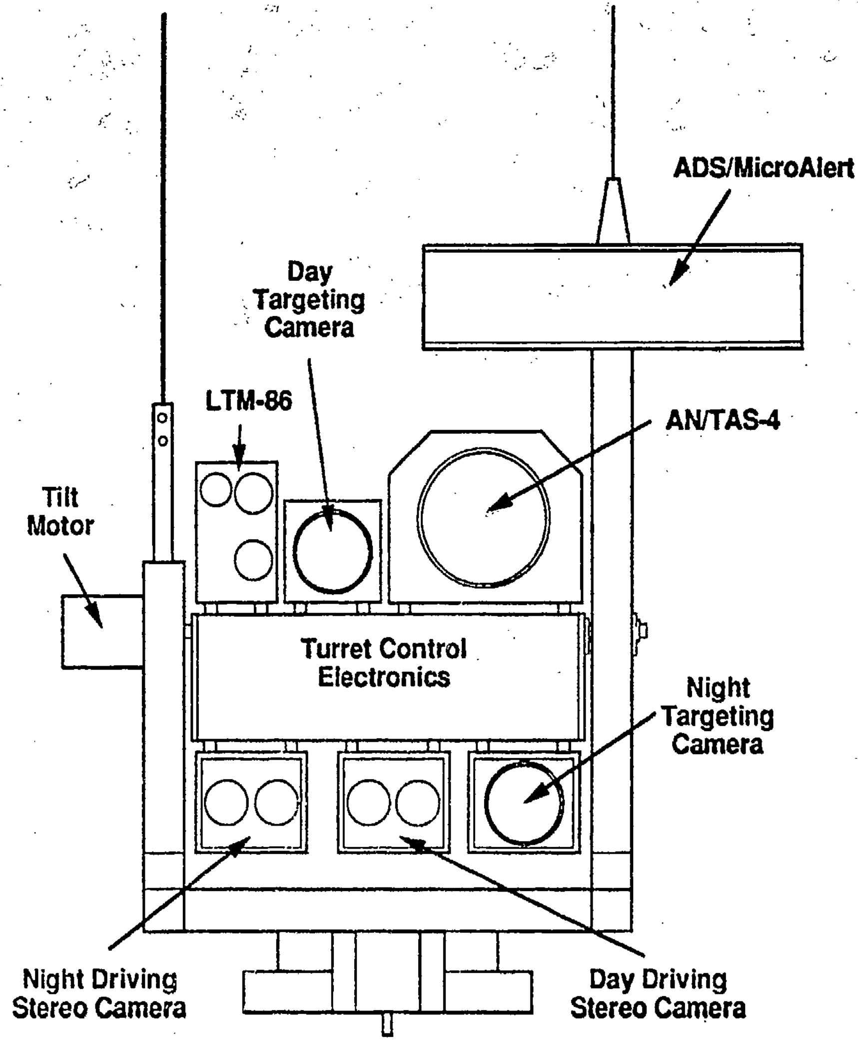

Figure 6 Mob/RSTA Turret Design

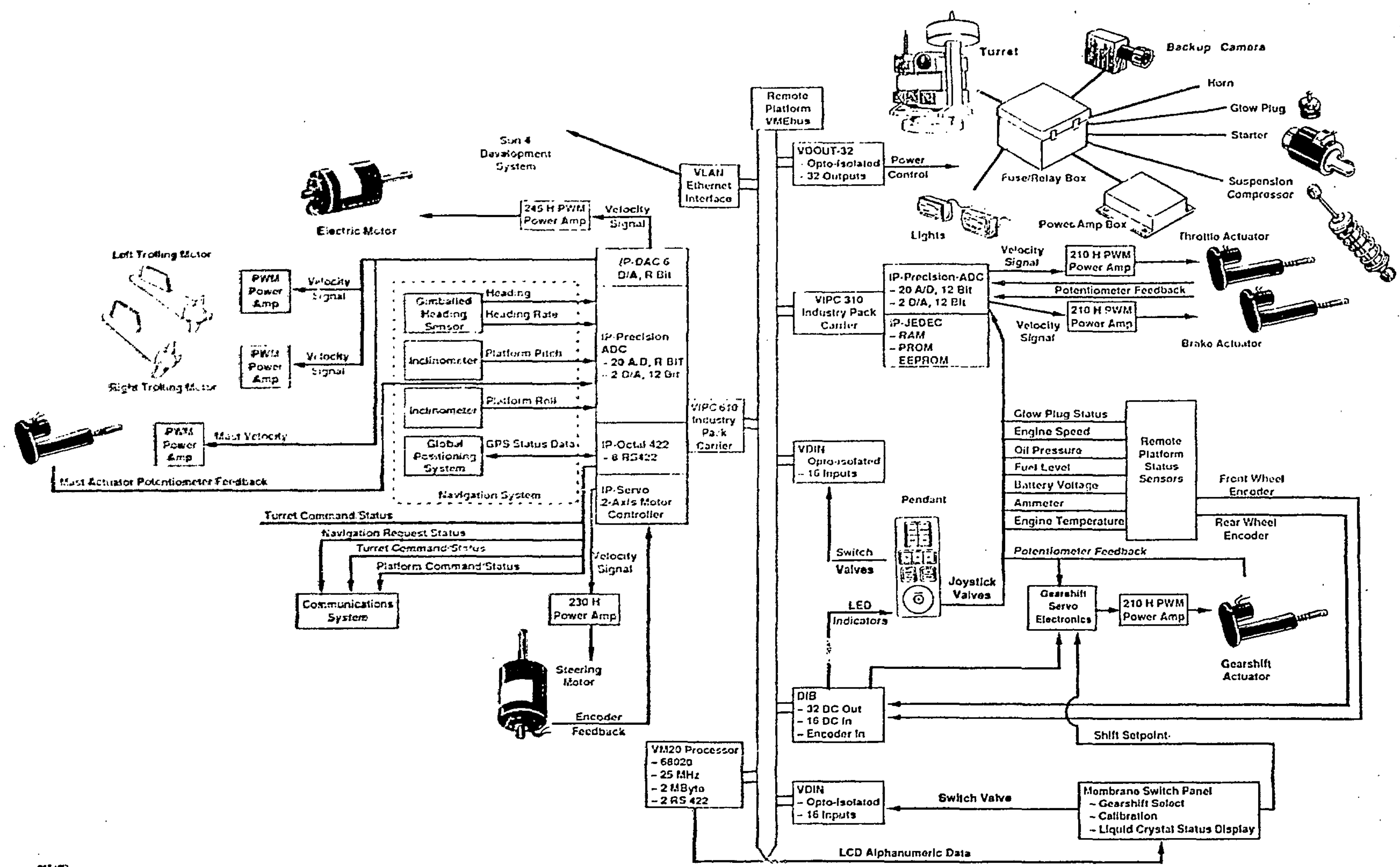

Figure 7 Mob/RSTA Module Electronics Interconnect Diagram

DRAM, which is more than enough given the input/output requirements, and the application. There are two serial ports on the VM20 configurable for either RS232 or RS422. Two additional serial ports can be added as a daughter module if necessary. These serial ports will be used to communicate with the AN/TAS-4B, and the remote platform, or the communications system, depending on the final system configuration.

The remainder of the selected boards are also 100% CMOS designs, allowing the inner gimbal electronics enclosure to be a sealed unit, requiring no outside air for cooling. The total power consumption of all the boards within the cardcage is less than 24 watts. Every board on the backplane, except one, is off-the-shelf, and stocked. This eliminates the possibility of schedule delays for delivery, as well as design and debug time. The only board not available off-the-shelf is the DIB, which was customized to control the complex interface of the LTM-86 laser designator and rangefinder.

The software design methodology for the Mob/RSTA Module is identical to the Remote Platform. Referring back to Figure 4, if TURRET receives the command "Semi_Auto_Track" and a vector specifying the velocity with which to maintain the track, it performs the simple computation to isolate the pan and tilt velocity components of that vector, then issues the command "Move_vel" to each of the PAN_MOTOR and TILT_MOTOR levels with their respective parameters.

Because the methodology is extremely modular, it is easily extendable to include additional levels, or more commands to existing levels. For example, the addition of a video autotrack would not require any significant modification to the present design. A "Video_Auto_Track" command would simply be added to the TURRET level, and the parameters to it would specify a position in space where the cross-hairs of the camera should be maintained. The TURRET level's responsibility for the new command would be to calculate the pan and tilt angles required to point at the given position, and issue the subcommand "Move_pos" to both the PAN_MOTOR and TILT_MOTOR levels with the proper angle parameters. The repetitive execution of these control cycles will cause the system to track the output of the autotracker over time.

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