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# Development of Robotics Applications in a Solid Propellant Mixing Laboratory

June 1988

Authors:
G. B. Kniazewycz
A. R. Darvish

KLM Technologies, Inc.
P. O. Box 30306
Walnut Creek, CA 94598

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Air Force Space Technology Center
Space Division, Air Force Systems Command
Edwards Air Force Base,
California 93523-5000

## NOTICE



## FOREWORD

This final report was submitted by KLM Technologies, Inc., Walnut Creek, CA on completion of SBIR contract F04611-87-C-0056 with the Air Force Astronautics Laboratory (AFAL), Edwards AFB, CA. AFAL Project Manager was Roger Benedict.

This report has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the DD Form 1473.

ROGER E. BENEDICT
Project Manager

FRANCISCO Q. ROBERTO
Chief, Propellant Development Branch

FOR THE COMMANDER

DAVID P. KING, Lt Col, USAF
Deputy Director
Propulsion Division

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Mixing of novel solid rocket propellants in R&D laboratories requires extensive safety precautions due to the explosive nature and, in some cases, unknown hazards of the materials. Current operations including ingredient weighing and prebatching, ingredient addition, on-line monitoring of relevant mix parameters, propellant casting, and cleanup involve elaborate facilities, are very labor intensive, and contain an element of risk to the personnel.

Under Contract No. F04611-C0056, KLM has investigated the use of robotics and other automated processing techniques as a means of reducing the cost and improving the safety of operations relating to the AFAL propellant mixing laboratory. To justify the capital outlay and minimize risk for robotic/automation implementation, KLM has considered the implementation of "Islands of Automation" strategy. This strategy will allow only one process (ingredient weighing, addition and prebatching, propellant mixing, casting and cleanup) at a time to be automated and allows the results to be monitored. KLM believes that all of the above processes are potential candidates to be implemented as "Islands of Automation."


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# INTRODUCTION

The following report provides the results of KLM Technologies, Inc's. (KLM) study of the potential robotic automation of a Solid Propellant Mixing Laboratory located at Edwards Air Force Base. This work was performed under Contract No. F04611-87-C-0056.

Department of the Air Force Needs

The Department of the Air Force identified the need to investigate the role of robotics in a solid propellant mixing laboratory environment in its solicitation for the FY-1987 Defense Small Business Innovation Research Program. In particular, the objective for this program was:

> "To investigate the use of robotics and other automated processing techniques as a means of reducing the cost and improving the safety for solid propellant mixing."

Further, the description of the proposed workscope was as follows:

> "Mixing of novel solid rocket propellants in R&D laboratories requires extensive safety precautions due to the explosive nature and, in some cases, unknown hazards of the materials. Current operations used throughout the industry involve elaborate facilities, are very labor intensive, and still contain an element of risk to the personnel involved. This program will investigate the use of robotics and other automated processing techniques as a means of reducing the cost and improving the safety of these operations. Specifically, the contractor shall develop, or modify existing equipment to automate a one-pint solid propellant mixing operation. Operational steps that should be considered for automation include ingredient weighing and prebatching, ingredient addition, on-line monitoring of relevant mix parameters, propellant casting, and cleanup. Emphasis shall be placed on approaches that minimize human intervention and enhance safety. Modifications to the mixing equipment are acceptable if necessary."

Toward this end, KLM Technologies, Inc., proposed a project entitled, "Development of Robotics Applications in a Solid Propellant Mixing Laboratory" which was subsequently funded for Phase I implementation.

KLM Technologies' Approach

KLM proposed a two phase program to build upon its practical laboratory system integration experience by substantially expanding the use of robotics in developing potential applications in solid propellant mixing laboratories. For R&D laboratory automation, KLM believes that a system should be able to monitor, trend, store and print experimental data, while providing both batch and continuous control to a wide range of robotic, automation and analytical devices. Special emphasis should be placed on specific operational steps such as ingredient weighing and prebatching, ingredient addition, on-line monitoring of relevant mix parameters, propellant casting and mixing equipment clean-up. Further, the need was recognized to have many safety features including explosion proof components, fail safe shutdown and manual overrides. The system has to be safe, flexible, cost effective, simple to use, and not require that the user be in computer programming, robotics or electronics. Most of the technology is commercially available, but a single cost effective package that contains everything is not. KLM proposed to develop and implement such an automation system.

Successful robotics programs, whether in a research and development setting or within a commercial environment have one, single underlying characteristic: special attention is paid to the organizational structure, operational environment and history, and real needs within the setting under study. Without this critical component, acceptable, recommended courses of action and successful fielding of robotic solutions are undermined. The KLM methodology developed to meet the requirements of the Phase I study emphasizes this fact. Additionally, the successful implementation of robotic hardware and software into a laboratory environment requires a carefully structured series of phases which examines, in detail:

- The operational requirements of a system designed to satisfy specific R&D objectives.
- The development of an implementation and integration strategy for creating the optimal relationship between researcher, laboratory operator and machine.
- A firm basis for establishing costs and capabilities (value).
- Appropriate equipment testing and evaluation to increase the likelihood for a successful implementation program.

The strategy established by the Air Force for the Solid Propellant Mixing Laboratory incorporates these major components and the methodology used by KLM compliments this strategy. The general methodology utilized in this project is discussed in Appendix A.

The proposed laboratory robotics development program was structured into two distinct phases:

- Phase I: Mission Analysis and Establishment of Performance Requirements
- Phase II: Development, Test, Implementation, In-Service Test Demonstration and System Performance Evaluation

Each phase consists of distinct tasks which are logically structured to ensure that the objectives of each and all subsequent tasks will be met. For example, the Phase I objective (Mission Analysis) must be well established prior to development, testing and system performance evaluation during Phase II.

The objectives of this automation project are to:

a) Establish the feasibility of a general purpose robotic-based laboratory automation system that could handle a vast array of laboratory development applications in a Solid Propellant Mixing Laboratory.

b) Develop a multiphase program which will be designed to realistically analyze various stages and operations necessary in solid propellant mixing operations which are potentially applicable to automation and/or robotic modifications. These processes include: ingredient weighing and prebatching, ingredient addition, mixing, propellant casting and equipment cleanup.

c) Implementation of a Laboratory Information Management System (LIMS) in a Solid Propellant Mixing Laboratory environment.

d) Study of existing equipment in the Solid Propellant Mixing Laboratory and, if necessary, propose certain modifications for system enhancement, time and labor savings and increased safety and productivity.

The feasibility analysis activities of this program represents the first major task prior to defining the detailed performance requirements for the technology being assessed. The first phase of the program examined the candidate missions and general performance requirements for robotic and other automated equipment. The following items represented the major feasibility issues to be addressed:

1) Can the robotic devices and/or automated equipment operate and perform useful tasks in a Solid Propellant Mixing Laboratory?

2) Can various processes such as ingredient weighing and prebatching, monitoring of relevant mix parameters, propellant casting and clean-up be automated and robotized?

3) By automating, would the element of risk to the personnel involved in handling explosive and hazardous materials be eliminated?

4) Can LIMS be implemented in a Solid Propellant Mixing Laboratory to save time, labor and improve safety and productivity?

5) Would automation be cost effective?

These issues were addressed within the context of specific operational steps which would be considered for automation including ingredient weighing and prebatching, ingredient addition, on-line monitoring of relevant mix parameters, propellant casting, clean-up, testing, and within certain performance boundary conditions, such as, time constraints, accuracy, speed and cost.

Once the feasibility was established within the context of particular applications and performance constraints, detailed applications and performance parameters were established to better define the specific design requirements of the fielded laboratory equipment. This phase of the program forms the foundation for the development, test, implementation and evaluation tasks of Phase II which will be designed to examine the performance of the individual components and fully integrated systems. It should be noted that the flexibility required in a R&D laboratory will result in versatile hardware general purpose interfaces and application software that will be readily configurable to handle a range of laboratory activities.

Phase I - Work Plan

The primary objectives of the Phase I study were to conduct an analysis which would identify specific requirements to which laboratory robotic and automation technology must comply, and to identify system requirements for each automation research area (application) of interest. These areas represent those activities currently required to support on-going research and development efforts within the Solid Propellant Mixing Laboratory. The application requirements which will be identified form the foundation for establishing the environmental and performance parameters associated with these activities and which are major inputs into the automation system's specifications.

Within Phase I, it was important to establish specific tasks, followed by the identification of application areas within laboratory research activities. Consequently, *the mission analysis phase was structured to: identify specific tasks; define* environmental, safety and performance parameters inherent in the research environment and required of the equipment, respectively; and complete a general cost/capability evaluation to support Phase II implementation. These efforts resulted in particular decision points on various automation applications relating to manual processes occuring in the Solid Propellant Mixing Laboratory including:

- Ingredient weighing and prebatching
- Ingredient addition
- On-line monitoring of relevant mix parameters
- Propellant casting
- Clean-up
- Testing support

The major activities of Phase I can be broken into the following tasks:

1. Define Research Areas Requirements
2. Identify Research Robotic and Automation Activities
3. Establish Laboratory Performance Parameters
4. Conduct Cost/Performance Trade-off Analysis
5. Identify Laboratory Hardening/Safety Requirements
6. Develop Phase II Implementation Plan
7. Project Documentation

Each of these will be briefly discussed below to provide a basis and focus for the remainder of this report.

Task 1: Define Research Areas Requirements

KLM proposed to consult with responsible solid propellant mixing laboratory personnel at various facilities such as government laboratories and private sector firms to help identify design requirements of possible laboratory automation applications.

In particular, KLM considered items such as:

a) Solid propellant mixing laboratory equipment
b) Sensor data acquisition (optical, proximity, and others)
c) Robot configuration and end-of-arm tooling
d) Laboratory information management system integration

Task 2: Identify Research Robotic and Automation Activities

These included:

a) Ingredient weighing and prebatching
b) Ingredient addition
c) On-line monitoring of relevant mix parameters
d) propellant casting
e) Clean-up
f) Testing
g) Existing equipment modification
h) Other labor intensive and hazardous operations

The survey of present and proposed robotic applications provided the foundation for Task 2 and assisted in:

a) Specifying potential robotics or remote technology applications associated with propellant research activities.

b) Specifying locations associated with each task.

c) Defining environmental and performance parameters and required equipment inherent in the laboratory environment.

d) Identifying the equipment field - hardening requirements.

Task 3: Establish Laboratory Performance Parameters

This task examined each of the major parameters identified below in sufficient detail to assess the design impact of the proposed applications.

a) Robot Specifications

- Configurations
- End-of-arm tooling
- Reach (horizontal, vertical)
- Speed, accuracy and repeatability

b) Physical Sensor Parameters

- Physical properties
- Collection medium
- Frequency, deviation and rate of sampling, etc.

c) Laboratory Information Management Systems (LIMS)

- Sample tracking
- Long-term data storage
- Trend analysis

d) Laboratory Equipment

- Reliability and maintainability
- Accessibility
- Potential modifications
- Safety precautions

e) Robot Transport

- Slider mechanisms
- Linear tracks
- Gantry configuration
- Mobility

f) Environmental Constraints

- Available space
- Temperature
- Humidity
- Air quality
- Explosions
- Sparks
- Solvents
- Other

Task 4: <u>Conduct Cost/Performance Trade-off Analysis</u>

Initial cost/tradeoff information is generated for analysis during Task 4. The result of this approach is:

1) The development of a Task Identification Matrix.

2) An assessment of potential capability and general cost associated with a given capability.

3) An immediate indication of the need for state of the art for development vs. commercialized hardware.

An equipment performance criteria is used to determine the feasibility of specific capabilities. A profile is established which evaluates various equipment alternatives and their ability to satisfy particular requirements. Finally, an assessment of costs and benefits associated with the selection of particular robotic configuration is made.

Task 5: Identify Laboratory Hardening/Safety Requirements

For the final configuration of the Solid Propellant Mixing Laboratory automation system, KLM identified the potential field hardening requirements to support various laboratory activities including the following areas:

a) Robotic devices (manipulator and/or end-effectors
b) Physical sensors (contact and/or noncontact)
c) Robot transport (linear and/or mobile)
d) Electronics (controllers and/or device interfaces)

Task 6: Develop Phase II Implementation Plan

Based upon the previous tasks, KLM developed a comprehensive Phase II plan to develop, test, implement and enter production of the desired low-cost laboratory robotic system.

Task 7: Project Documentation

Complete project documentation was developed. The remainder of this report meets this requirement and supports KLM's Phase II proposal.

KLM's Phase I Activities

KLM's personnel performed two facility visits at Edwards Air Force Base on July 1 and September 4, 1987, respectively. During the visits, typical manual solid propellant mixing processes including ingredient weighing and prebatching, ingredient addition, on-line monitoring of relevant mix parameters, propellant casting and cleanup, were demonstrated and discussed. These project site visits were very informative and provided insight into the activities and restraints within the multi-cell propellant laboratory/test facility.

KLM performed extensive research and analyses of various manufacturers/vendors in areas including automatic dispensing equipment, laboratory automation software, laboratory robotic systems, automatic guided vehicles and general automation related devices such as viscometers, balances, ovens, ultrasonic cleaners, power protection systems and static control equipment (see Appendix D for a listing of manufacturers/vendors). In addition, KLM conducted an automation screening evaluation based on "Environmental Conditions" criteria, which refers to the operation conditions under which various operations are performed. This method proved that various propellant mixing processes mentioned above are potential applications for robotic and/or automation. However, it is apparent that certain modifications to the existing equipment and laboratory cell layout are needed for successful robotic implementation. To justify the capital outlay and minimize risk for robotic/automation implementation, KLM Technologies has considered the implementation of "Islands of Automation" stragtegy. This Phase II strategy will allow one process at a time to be automated and the results to be monitored, and the experience to be incorporated into the next automation step. KLM believes that ingredient weighing, propellant mixing, casting and cleanup are potential processes to be implemented as "Islands of Automation". Subsequently, application software will be written and other system integration activities will be completed to allow the "Islands" to communciate and perform their interrelated functions.

KLM submitted monthly progress reports during the Phase I implementation plan. These reports provided detail and up-to-date information pertaining to Phase I objectives/tasks.

The remainder of this report will introduce the laboratory applications for automation, the technology of automation considered, and develop a conceptual design and approach which includes the tasks making up Phase I. This report serves as the technical support for the Phase II automation of the Solid Propellant Mixing Laboratory at Edwards Air Force Base.

## TRENDS IN LABORATORY AUTOMATION

The purpose of this section is to provide an overview of the status of automation in the laboratory environment. This information was developed from numerous sources listed in the Reference Section and is oriented to provide the reader with sufficient information to understand KLM's approach to automation in a Solid Propellant Mixing Laboratory.

Many industrial laboratories have greater demands for analytical support than they can meet. Early developments in laboratory automation such as autosamplers and simple data handling devices gained rapid acceptance, because they replaced manual tasks where people were poorly suited to perform these tasks. Such immediate needs allowed many laboratories to justify the moderate investment in automation. Today, improving laboratory productivity has reached a strategic urgency in many organizations which face intense, world-wide competition or scarce R&D funds. To meet this challange, their strategies demand the following:

1. Develop innovative new products often tailored or optimized for a defined (specialty) use.

2. Efficiently manufacture these products to the highest possible quality standards.

Improved laboratory productivity is not primarily motivated to save money, but rather to better utilize a very limited resource - qualified scientists and technicians. Because of the nature of a laboratory, there are many tasks currently performed manually which can be transferred to automated instruments, thereby, freeing people to make more productive and challenging contributions. The easy advances in laboratory automation have been implemented with automated instruments; while the next step requires higher level systems capabilities, the potential benefits are expected to be worth the investment and are essential to the strategy.

### Laboratory Automation and System Integration

In the early phase of laboratory automation, the normal conditions resulted in fragmented laboratory operations where days, or sometimes weeks, elapse between sample submission and the final result. Today, laboratory instrument manufacturers, as well as scientists working in industrial and academic laboratories, are developing and enhancing tools to improve laboratory productivity by linking these new tools together into integrated systems.

Traditionally, analytical methods have been separated into three distinct functions (Figure 1). In this representation, the primary purpose for the analysis, that is, "make timely, quality decisions based on valid data" is often lost.

Figure 2 illustrates real-time systems integration with validation and decision making as the primary focus. This level of integration is the foundation of an automated laboratory. Regardless of the degree of automation, people must control

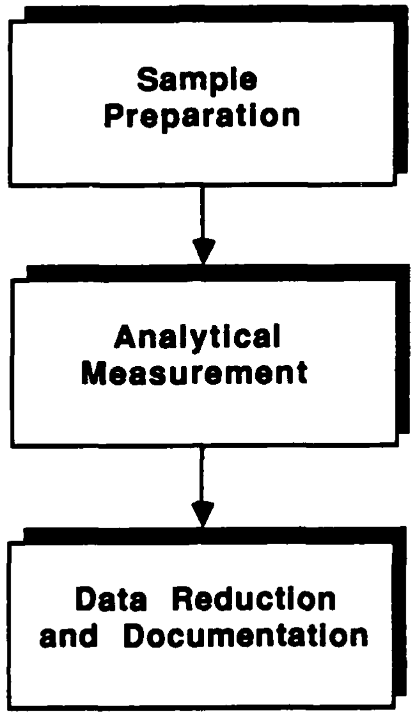


**FIGURE 1 ANALYTICAL METHODS**

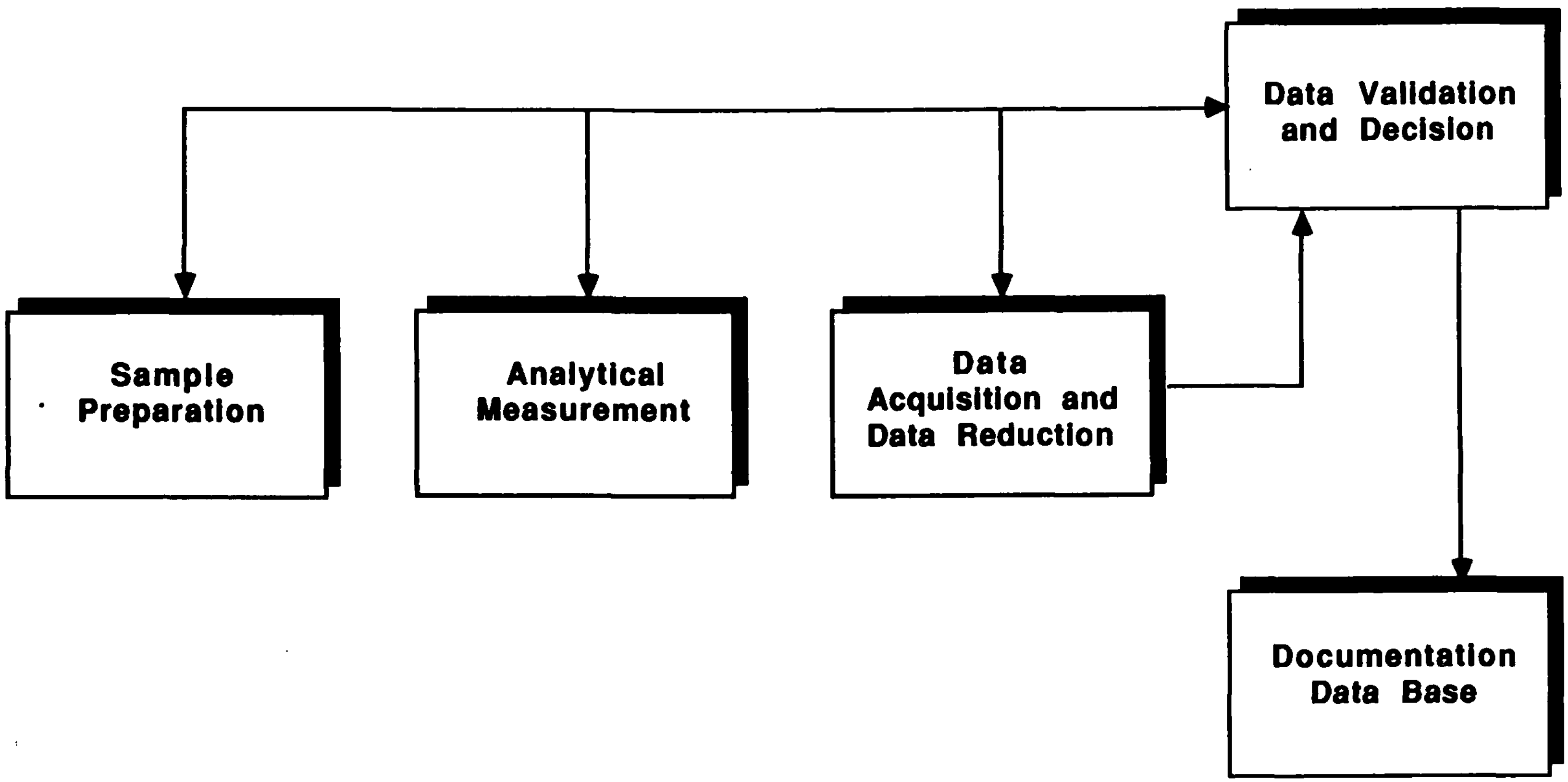


FIGURE 2 INTEGRATED ANALYTICAL LABORATORY METHODS

the process and make any judgements required by extraordinary conditions. The approach proposed bridges the gap between automated instruments and higher level laboratory information management and data base (LIMS) systems. Such systems make possible real-time systems integration.

These systems, as shown in Figure 2, require compatible interfaces between each instrument or subsystem. Differing application needs determine the specification for these interfaces and where systems integration takes place. For example, applications may be either data intensive or control intensive with the following implications:

- Data Intensive Applications - Large numbers of data points are acquired and processed using sophisticated software to determine analytical results. In these applications, systems integration may best be performed by the data processing workstation.

- Control Intensive Applications - Limited data points are acquired and processed using straightforward mathematical equations. In these applications, data reduction and systems integration may best be performed directly by the control workstation.

Laboratory Robotics

As one begins to consider utilization of robots to perform specific tasks, whether in the laboratory or in other manufacturing environs, it is most important that a clear understanding of the particular expectations of the robot be in hand. The field of robotics is an extremely rapidly developing one. As the variety of equipment from which to choose increases, the need for clear understanding of capability and performance characteristics becomes most important. Where failure in a robotics application occurs, it is more frequently the improper match of robot and task rather than a failure of robotics technology per se.

Frequently, new technology in testing/analysis is adopted in the industrial laboratory only after an extended "shakedown" in the research area. In studying laboratory robotics, one thing rapidly becomes apparent - industrial laboratories, rather than those in academia are the ones making the major use of laboratory robots. This fact stems from the usefulness of laboratory robots in preparing large numbers of samples for analysis in the chemical laboratory or placing them into test instruments in either the chemical or testing laboratory. Both of these steps are generally personnel intensive and, thus, costly. The major benefit of the incorporation of a laboratory robot, in addition to improved precision afforded by the laboratory robot, is reduction in the personnel effort required for analysis. It is not surprising that robots are finding rapid acceptance in industrial laboratories where procedures which are precise and cost effective are required.

Laboratory robotics emerged in the early 1980s as a new approach to improve sample handling and sample preparation technology to the level attained by laboratory instruments and data handling computers. Following hundreds of successful laboratory robotics installations over the past decade, laboratory robotics is now recognized as the next step in laboratory automation.

Prior to laboratory robotic, justifying an investment in automating laboratory procedures required large numbers of identical, repetitive operations. Today, rapidly improving computer technology, particularly powerful microprocessors, makes available easy to use and low cost programmable computers. Robotics is the logical extension of programmable computers which allows computer technology to do physical work as well as process data.

In considering the use of robots in the laboratory, it is generally found that their effectiveness will be maximized when they are utilized for infrequently performed yet highly complex tasks - at least from the manipulative perspective - or for frequently performed, routine tasks which may be quite simple in nature but must be performed many, many times in a given work period. In the first case, the robot, once trained, will perform even the most complex task in exactly the same way even after a lengthy period of nonperformance. The human worker on the other hand is much more susceptible to error in performing highly complex tasks infrequently. On the other end of the spectrum, the repetitive performance of very simple tasks by humans is one of the most error-prone operations in the laboratory because of the boredom or "drudgery" factor. The robot does not suffer from boredom.

In the chemical laboratory, the complexity range of tasks varies greatly from very simple tasks such as pH measurements on aqueous solutions to the extremely complex reaction/separation/measurement tasks involved in measurement of trace process chemicals or unreacted raw materials in a finished material, a specific compound in an effluent stream, etc. In the physical testing laboratory, much of the activity is manipulative - placing samples in test instruments, closing instrument grips, and, of course, making frequent notations of results. While some of the manipulations are quite complex, once taught to the robot, they may be repeated in a very straightforward manner. The laboratory robot may be effectively utilized for both chemical and physical testing in the research or manufacturing laboratory.

In a practical sense, laboratory robotics is far more than a programmable mechanical arm. It is a programmable system for performing laboratory procedures - automatically and unattended. Combined with other instrumental technologies, it makes possible a true automated laboratory. Laboratory robotics goes beyond information management - it interfaces with physical operations in the laboratory. Initially, the goal was to emulate people, but experience shows that creative approaches building on the strengths of laboratory robotics lead to more effective systems.

The major consideration in choosing a laboratory robot is the requirements of the task to be performed. In the case of chemical testing, the laboratory robots already on the market, as well as those which are just becoming available, are generally well-suited for tasks such as weighing, mixing, casting, extracting and dissolving. Vendor support for use of laboratory robots in chemical testing is generally very good. Other variables such as cost, availability and compatibility with existing equipment become important in the choice of a robot to be used in chemical testing.

Productivity enhancement when laboratory robots are used is significant. Obviously, laboratory robots also enables the one shift laboratory to significantly extend the effective working day by allowing the robot to run unattended after normal working hours. The exact productivity enhancement (payout from the purchase of a robot) must be calculated for the individual laboratory based upon the particular testing being done, frequency, laboratory organization, etc.

In an evolutionary way, future laboratories, laboratory equipment and laboratory procedures will be designed to work effectively as part of laboratory robotics systems.

Laboratory robotics provide tremendous opportunities to optimize the effectiveness of laboratory activities in both the chemical and materials science areas. Combined with data acquisition systems, which are a must when robots are used, laboratory robotics have the ability to make many additional hours of effort available to laboratory personnel to spend on new testing tasks or in refining existing ones. Computer skills, improved mechanical skills and the ability to conceptualize and develop testing procedures using new equipment are all opportunities given to the laboratory worker when robots are used. People spend less time on sample manipulation and more time in thinking about the meaning of the data, appropriate tests to be used, and how they may be applied to optimize productivity and profitability.

Definitions

There is some confusion over the exact definition of a laboratory robot. In order to understand what a robot is, it is best to start by reviewing the various categories of automation. Automation ranges in degree from simply the use of powered or nonpowered tools to the complete control of a task by a computer-aided system involving high storage memories, sensory devices, and periodic changes in programming. Between these extremes fall the categories of "hard automation" and "flexible automation".

In hard automation, a task is performed by a tool which has been set up using mechanical limits and adjustments so that no human control is required during operations. Hard automation is typically dedicated to one application throughout the life of the tool. The primary disadvantage of hard automation is the difficulty of justifying the investment in dedicated equipment for a batch operation, in which changeovers may be required. The alternative to hard automation until recently was to increase the direct labor content of a task. Flexible automation was developed as a means of increasing the range of tasks that can be performed and also to improve the changeover capability of such laboratory tools. In flexible automation, a tool is pre-programmed by a human as in hard automation. In this case, however, the workpiece (e.g., sample) can be manipulated so that a greater number of tasks can be performed in each cycle. In addition, a changeover to another job can typically be accomplished by reprogramming rather than by reworking or replacing the equipment. Machinery and instrumentation can therefore be more productively used throughout their useful life.

Thus, fixed or dedicated automation is utilized for large quantities of standard procedures such as those found in hospital and/or clinical laboratories. Fixed automation follows a predetermined sequence of steps to perform a defined procedure. It is efficient, but programmed to perform only one repetitive procedure.

Flexible automation is programmed by the user to perform multiple procedures. It can be quickly programmed to accommodate new or revised procedures. Laboratory robotics provides the flexible automation required to meet the changing needs typical of industrial and research laboratories. Robotics can be evaluated from the following definition.

The Robot Institute of America (RIA) defines a robot as a "reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motion for the performance of a variety of tasks." The RIA definition of industrial robots is the best one to be presented to date. The first three words in the definition are essential to understanding the basic concept of robot. Although robots are available in a wide variety of configurations all robots consist of three basic elements: (1) a manipulator, (2) a controller and (3) a power supply. The manipulator (and its support stand) is the basic mechanical element of the robots and is responsible for performing the work. The controller is the robot's brain and is responsible for directing the movement of the manipulator. The power supply is the energy source for the manipulator. The following discussion briefly reviews these elements while a more extensive discussion is found in Appendix C.

<u>Manipulator</u>

The most fundamental objective of a robot is to move an object through three-dimensional space. This motion is mechanically accomplished by the manipulator. The manipulator consists of a mechanical "arm" and a "wrist" both of which are mounted on a support stand. A mounting surface is provided on the end of the wrist for attaching the tool (called an "end effector") with which the robot performs its jobs. Typically, the end effector is in the form of a gripper device for grasping and manipulating a part. There are several ways in which a manipulator can be constructed in order to move a part through space. As with the human arm, motion is achieved through a series of mechanical linkages and joints. The basic configuration of the mechanical arm is best described in terms of its coordinate system. There are currently four different coordinate systems being used to move a part from point "A" to point "B". These are rectangular, cylindrical, spherical and joint-arm spherical. These and other robotic terms are defined in Appendix D.

The manipulator arm is basically a series of mechanical linkages and joints that move in a specified sequence. The function of the arm is to bring the end effector to a specified point in space. This motion is accomplished by one of three types of drive systems: hydraulic, electric or pneumatic. The arm mechanisms are driven by several actuators which may be pneumatic or hydraulic cyclinders hydraulic rotary actuators, or electric motors. These actuators either drive the links directly, or they indirectly drive them through gears, chains or ball screws. In the case of hydraulic or pneumatic drives, valves mounted on the manipulator control the flow of air or fluid to the actuators.

An end effector is installed on the mounting surface of the wrist. This is the tooling used to perform the robot's task. The term end effector refers to a gripper (used to grasp a part), a tool held by a gripper, or a tool mounted directly on the wrist.

Robot Controller

The controller or control unit is the "brain of the robot". The basic function of the controller is to direct the motion of the end effector so that it is both positioned and oriented correctly in space over time. The controller stores the required sequence of motions of the manipulator arm and end effector in a memory. When requested by an operator, it directs the manipulator through the programmed sequence of motions. At the same time, it interacts with the manipulator and other machines connected with the robot through a series of feedback devices to insure that the correct motions are being followed.

A variety of robot controllers are available. Robot control can be accomplished through the use of a mechanical stepping drum programmer, a pneumatic logic sequencer, a diode matrix board, an electronic sequencer, a microprocessor, or a minicomputer. The controller may be integrated into the manipulator arm or it may be a separate unit.

In order for the controller to be able to direct the motions of the manipulator, the operator must first tell the controller what to do. The process of programming the controller is referred to as "teaching" the robot.

The robot memory or data storage is an integral component of the controller. It stores the programs and then gives commands to the robot through the controller. The type of memory used is important, since it determines the way in which commands are stored. Memory devices can be as simple as mechanical step sequencers such as rotating drums, pneumatic devices such as patch boards or diode matrices, or more sophisticated electronic memories such as microprocessor devices (ROM, RAM, magnetic tapes or floppy discs). Generally, the degree of sophistication of the memory is consistent with that of the controller and with that of the robot itself.

Most robots need to interact with other machines outside of its immediate environment. For example, a robot cannot transfer a sample until an input signal has been received by the robot that the sample has arrived at the initial position. Input and output signals can be provided in several ways, such as electrical, pneumatic, or electronic signals. It is in the area of interfacing that external sensing capabilities can play a role. Tactile (touch) sensors, proximity detectors, force feedback devices and vision sensors can all be used in applications in which the robot requires data on the location or position of a part.

Power Supply

The third basic component of an industrial robot is the source of energy that drives the manipulator's actuators. The type of power supply required is generally a function of the type of actuators used in the manipulator arm axes. The power system of a robot must be considered in choosing a type of robot since the performance and capabilities of each type vary according to the type of application being considered. Electrically powered robots tend to run quieter than others and their motors can be enclosed and protected from dirty environments. Pneumatically powered robots are generally used in light duty applications requiring fast operation. Hydraulically powered robots tend to be stronger than others. They are also more accurate, since hydraulic fluid is not compressible.

Robot Performance Characteristics

The previous sections described the basic physical structure of an industrial robot and the types of applications in which it is used. In this section, the parameters by which the performance of a robot is measured are defined. These characteristics represent some of the more important considerations which need to be studied when deciding on what type of robot to select for a particular application.

In general, a robot must satisfy three basic requirements. First, it must be flexible. By definition, a robot is not a dedicated machine, but rather offers the advantage of being "multifunctional" or reprogrammable as discussed earlier. Therefore, a robot should be capable of being used in several operations.

Secondly, an industrial robot must be reliable. The advantage of high utilization because of a high degree of flexibility will be lost if the robot is out of service often for maintenance or repairs. Reliability means a relatively low requirement for maintenance, dependable operation requiring few repairs, and the ability to function satisfactorily in a hostile operating environment (e.g., high temperatures or corrosion).

Finally, a robot must be easily programmed. Since a robot can be used for many different tasks, it is likely to require constant reprogramming to change its operating cycle. Because programming causes a certain amount of downtime. it is essential that a minimum amount of time be devoted to this activity. This is one reason that the use of off-line programming is likely to increase in the future.

In addition to these basic general requirements, there are several specific performance characteristics that should be analyzed when considering the use of a robot. These include positioning accuracy, repeatability, reliability and payload capacity.

Data and Information Management

In 1987, the design of an automated laboratory or the retrofit of various degrees of automation into an existing laboratory requires the careful evaluation and consideration not only of the handling, manipulation, testing and recording of how a sample is tested within the facility, but also how the data resulted from the laboratory activities are acquired and utilized within the overall structure of the laboratory's mission. Over the past decade, the potential for robotics, advanced automated instruments and laboratory information management have been explored. Through 1987, well over 1,000 robotic devices have been placed into the U.S. laboratory environment in a wide myraid of applications ranging from hazardous waste handling and analysis to production support and standard chemical analysis. Similarly, thousands of automated specialty instruments have been sold and installed and numerous laboratory information management systems (LIMS) ranging from large mini-computer-based to PC-based have been installed. It is clear from the experience to date that most of these applications have been well received and have performed satisfactorily. Indeed, continued growth of both automated instrumentation systems as well as robotics-based systems illustrate that the potential market for automation applications should be quite extensive. Similarly, information management systems, while commonplace in many other parts of industry, have only just entered into the laboratory environment.

For the purpose of this discussion, laboratory automation systems will encompass both robots and advance analytical instruments and other devices which perform in an automated fashion. Laboratory Information Management Systems (LIMS) are considered to be fully integrated data handling systems typically encompassing several analytical instruments and devices and allowing for the collection, manipulation and evaluation of laboratory data on an as required basis. It is clear that to fully realize the benefits of automating a laboratory requires the successful integration of both the robotics systems and the LIMS with supporting instruments and devices within the overall mission and environment of the particular laboratory. This, when coupled with interfaces to various manual practices and procedures, allows the full potential of present day technology to be realized. It is, however, clear that this technology is only in its infancy and that present day robotics, which require the placing of components, equipment and support facilities about a robot (i.e., the robot "Island" architecture), must evolve to allow the full potential of automation to be realized. The recent development of robot arms moving on linear tracks is the first step in the eventual development of a useful "robot" laboratory technician which would emulate the human and utilize present facilities with only minimal physical change. The present limitations of a robot arm requiring access and support by a scientist or technician clearly limit the potential of robotics in the laboratory environment since the many thousands of present day laboratories have layouts and facilities which do not readily accommodate such speciality support facilities. Similarly, the potential of laboratory information management systems are limited by the lack of standards for communications between all instrumentations as well as the lack of fully developed technology to allow for voice entry of data as well as other user-friendly mechanisms for accessing data and information contained within the LIMS. Thus, in 1987, the "automated laboratory" basically consists of sample preparation and limited analytical activities as well as data collection with minimal manipulation and integration into the total laboratory environment within a facility.

Present architectures for robotic systems as well as LIMS are somewhat limited by the nature of the equipment and the commercial realization that standards, while desirable from an end-users point of view, conflict with the marketing and philosophical direction of most instrument and automation manufacturers. Indeed, many of the potential restrictions and lack of penetration and marketplace of both laboratory robotic systems and LIMS can be directed to the lack of standards and the lack of "open" architecture which would allow for similar explosive growth and potential as experienced by IBM-compatible microprocesses to be realized. A lesson can be readily learned from the personal computer marketplace where the early philosophy for the Apple Macintosh computer and the IBM PC differed significantly in that the success of the IBM PC was assured because of the open architecture which allowed for not only the success for IBM and its many clones, but also assured the success for the various users who are able to pick from a myraid of hardware options and software packages which not even IBM could bring to the marketplace. Indeed, the announced changes by Apple clearly point out the limits of their earlier approach. A similar lesson undoubtedly will be learned by the laboratory robotics and information management system community, especially by those commerical firms which have modified existing hardware to insure a dependent end user as well as increasing first costs and spare parts costs for the end user.

Two general conceptual ways have been identified to organize the automated laboratory. The first considers the advanced instrumentaiton and robotic systems as completely intelligent instruments capable of performing their functions and of acquiring the necessary analytical data. In this architecture, the LIMS interfaces to the instrumentation and robotic systems via a robotic controller or instrument controller and utilizes some standard interface such as RS-232 or RS-428 interface. The alternative architecture would interface the robotic system as a series of subsystems. Thus, the robot per se would interface to the LIMS as would the various components and instrument which the robot manipulates. Figures 3 and 4 illustrate data flow diagrams concerning the two general ways to organize the automated laboratory.

Each of these architectures has certain advantages. The first approach allows a "distributed" processing philosophy to be implemented and thus the robotic system operates, to a great extent, independent of LIMS and is capable of acquiring, storing and possibly manipulating data locally. The second architecture considers the robotic system per se as another instrument and allows the interface instrumentation to be operated either in conjunction with or independent from the robotic system through centralized processing philosophy.

The following discussion will explore both robotics and LIMS and identify the technical factors which must be considered in any successful implementation program.

<u>Laboratory Robotic Systems</u>

The present generation of laboratory robotic systems generally involve five major activities:

1. Automated sample preparation
2. Sample transport
3. Control of analytical instruments
4. Acquisition and storage of data
5. Inter-computer communications

Depending upon the level of sophisitication of the laboratory facility, automated sampling and sample preparation may range from simple identification and minimal

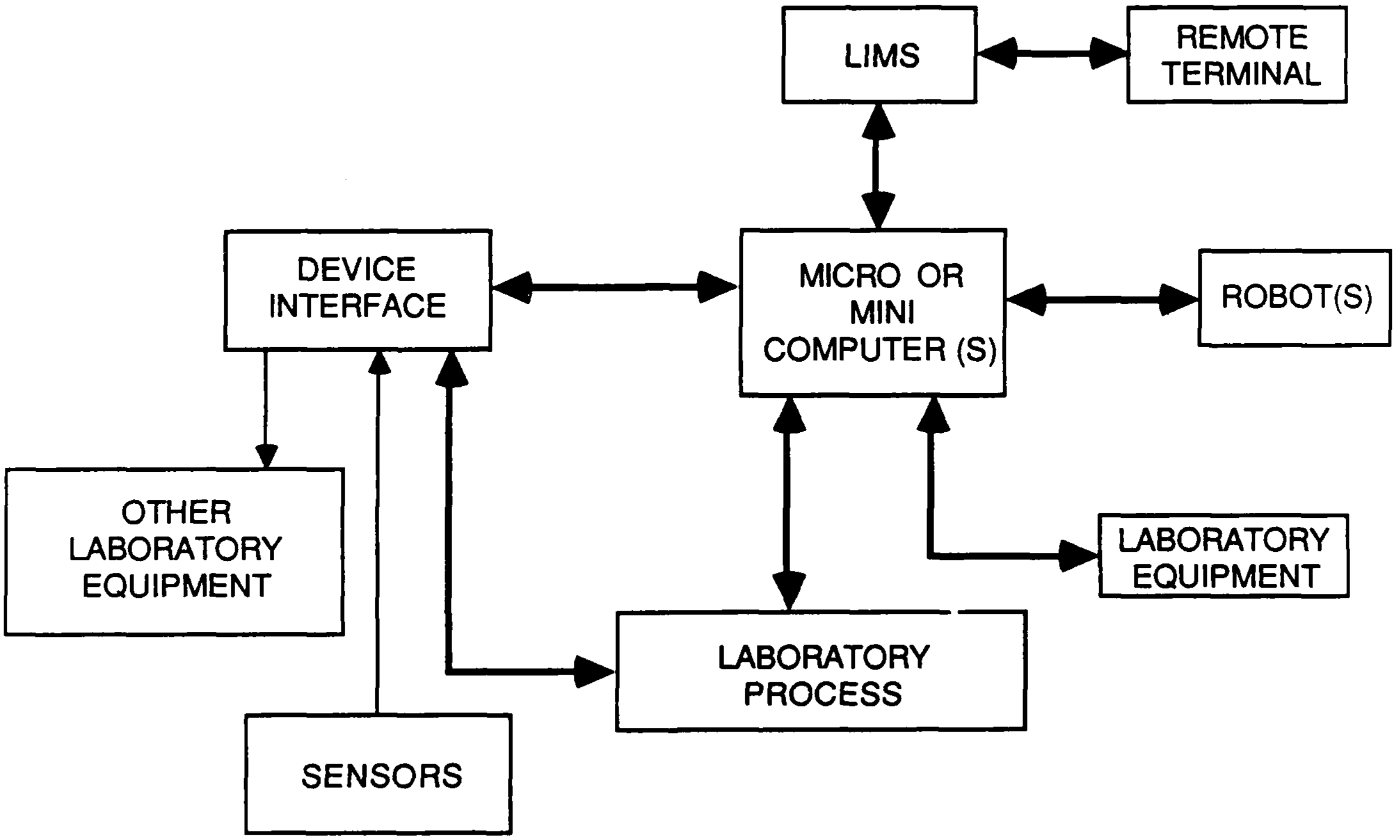


**FIGURE 3 LIMS WITH DISTRIBUTED DATA FLOW**

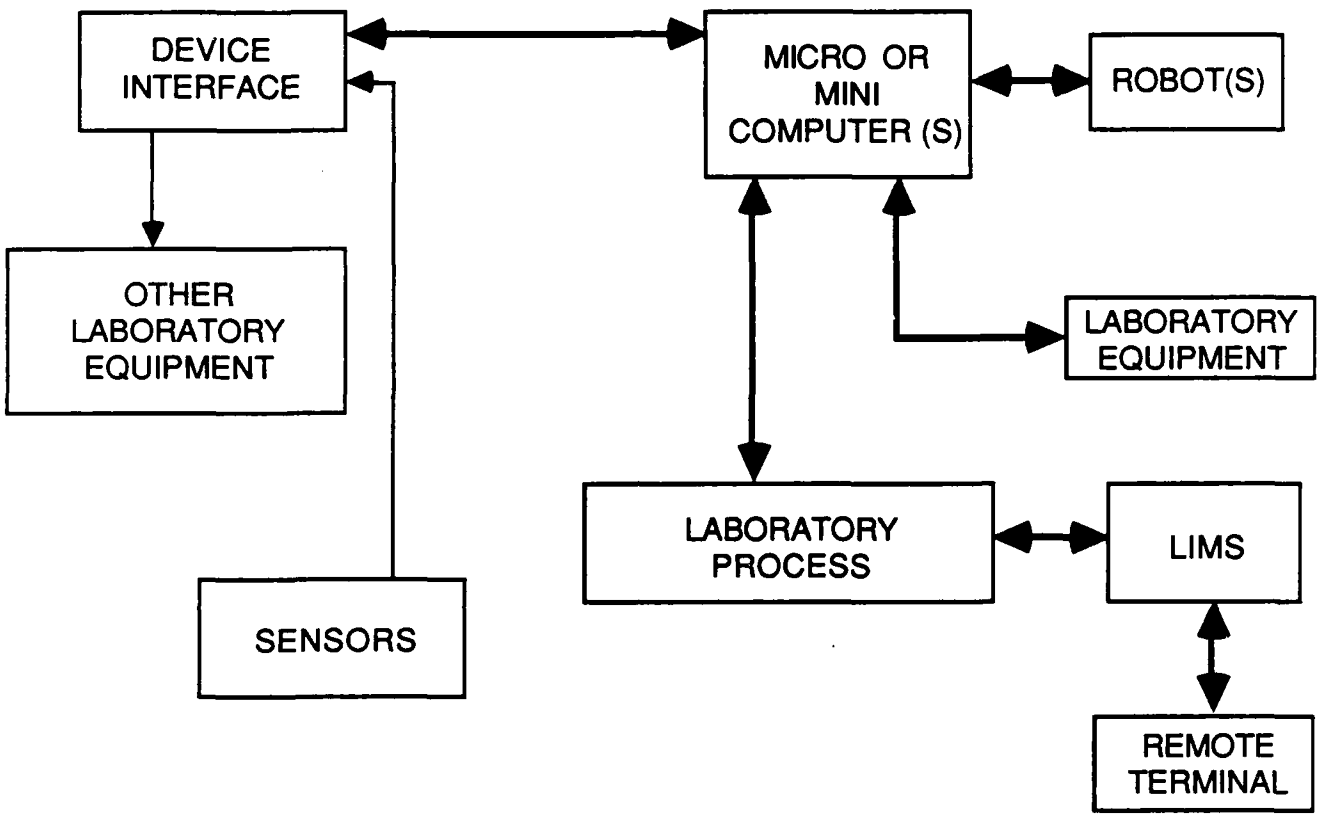


**FIGURE 4 LIMS WITH CENTRALIZED DATA FLOW**

preparation for sample transport to various complex support modules and analytical stations especially for complex or hazardous samples. Typical activities might include sample identification (either by a technician or by use of bar codes or other optical identification techniques); liquid, solid as well as gaseous handling; mixing, separation and weighing activities. Other activities such as capping, sample divisions, etc., can also be performed. The second major activity, sample transport, primarily refers to the manipulation and moving of the prepared sample between various support modules and the appropriate analytical instrumentation. The present day robotics generally requires the extensive planning and establishment of support modules to ensure the presence of a sample as well as the condition and/or orientation of a sample relative to various handling configurations and activities.

The third activity involves the control of various analytical instruments and depending upon the architecture utilized to interface the robot with its environment, includes the communication of various control activity plans as well as the comparison and monitoring of analytical instrument parameters. Similarly, depending upon the nature of the instrument, various analyses and decision processes are also peformed. The result of this activity involves the acquisition, manipulation and storage of the data. Such activities include the request and receipt of information from the various analytical devices, the storage of data and eventual handling and reduction, as appropriate, including output and various formats, written and graphical. Intercomputer communications basically involves data transfer from the robotic computer or controller as well as the communications with outside networks, such as LIMS, which may result in the initiation of additional sample activities or may terminate activities based upon results or conditions reported to the main network. Computers, whether a part of the robotic system or a part of a larger network, are notorious for their storage of data and, as with other applications, it is important to realize the difference between "data" and "information" and to minimize the storage of trivial or unimportant parameters, logs, etc., while assurring the end users obtain the information and results that they require when they need it.

Laboratory Information Management System

A typical Laboratory Information Management System (LIMS) will provide the end user with the capability of handling the extensive data and information which is generated in the course of the operations of the particular laboratory. Depending upon the type of laboratory, scope of work and magnitude of sample analyses, the LIMS can even operate distributed process in a centralized processes mode and can utilize a variety of data base formats and communication architectures. Typical activities and data handled by the LIMS include:

1. Sample entry

2. Results entry

3. Status query

4. Standard reports

5. System management

Sample entry will include everything relating to the sample handling and tracking, including it routing throughout the laboratory, with appropriate documentations and priorities. Such samples typically would be numbered with identification designations and might include some method such as a bar code.

Results of data entry by the end-user (in a manual format) may be from a data entry terminal or from automated instrumentation in a robotic system. This entry could include a wide variety of parameters and information as well as various calculations and analyses.

Status query is the capability to determine the status of a sample, including any location within the laboratory and test cycle, as well as its historical past.

Standard reports could include any of a wide variety of reporting formats and information relating to the status of a sample or sampling activities, and reports in a variety of formats and configurations. Much of this is dependent upon the software design and the end-user requirements. Indeed, sophisticated systems such as relational data bases provided with fourth generation data base management capabilities are capable of extensive and fairly sophisticated data manipulation and handling. This, to a great extent, results in user reports in a format defined by the end-user requirements. Typically, extensive search, merge capabilities are available as are various graphic representation and displays. The fourth generation languages and data base management systems might be capable of full relational data handling and includes such capabilities as boolean search.

A final typical capability of a system is the system management which is associated with the data handling, system utilities, including archiving of data, as well as the important input/output capability.

Automated Equipment, Robotic Systems and LIMS

Depending upon the sophistication of the laboratory and degree of automation desired, a wide variety of capabilities for the integrated instruments subsystems and information management systems are possible. Such things include down-loading of daily work lists, transfer of data to and from the LIMS and system management activities. A typical work list would include the sending of requirements for robotic systems and personnel daily activities. This, of course, must be coordinated with support services necessary for the robot itself. Other factors might include a re-definition of sample priorities as well as identification of other analytical activities associated witn the laboratory operations. Inventory, equipment calibration, work assignments, etc., are typical of the requirements. The transfer of data to the LIMS include local data transfers between the LIMS and the various instrumentation and robotic systems. This typically would take the format of tables, files, raw data or calculated results. Typically, multitasks, multiuser environments might be available with the system depending upon the sophistication and requirements of the laboratory end-user. The typical interaction between the equipment and LIMS also includes the requirement for system management. This allows numerous management tools to be utilized, typically ranging from scheduling and resource management to more advanced operation research capabilities. Items such as budget, decision support and various spread sheet capabilities will be readily available. In such a system, major aspects of automating the laboratory would, in some ways, emulate the problems faced by factories including items relating to inventory, maintenance, upset conditions and normal problems associated with complex analytical equipment.

The initial architecture addressed previously involves the use of a distributed processing environment where the robotic system operates its functions autonomous of the LIMS and interacts with the various components and modules of the system independent of outside requirements. Data and information, including calculations, would typically be stored locally and would be down-loaded to the LIMS on an as-demanded or as-instructed basis.

This architecture, in many ways, is very advantageous to the user inasmuch as it is an open architecture which probably results in a more effective and, in some ways, less expensive LIMS while ensuring that laboratory operation continue if problems occur with the LIMS system. This local independence is typical of a distributed process application and is typical of the management information systems generally found in more sophisticated networks presently available. Depending upon the nature of the interface with instruments and the robotic system, the possibility of data not being able to be transferred from the instrument, because of a robotics system control failure, may occur. However, if a standard interface exists, this type of a problem should be minimized especially with the advent of "smart" instrumentation and capabilities which are readily expected in the foreseeable future.

The second approach is where the LIMS is utilized for direct linkage to the instruments and where the robot subsystem is independent of those instruments. In this centralized mode the robotic system carries out sample preparation. The analytical insturmentation operated independently and sends data to the LIMS on an as generated basis; the LIMS is utilized to control the robotics subsystem in coordination with the instrument package. Such a system has certain limited advantages, including the fact that the instrumentation can be utilized in the manual mode and that the LIMS is updated frequently. However, it should be noted that the earlier approach is capable of providing updates on a frequent basis, if this is appropriate, and even manual operations could be arranged if appropriate consideration is given to this requirement. The potential disadvantages include the fact that the robotic system must be manually initiated and that more intelligent instrumentation may be required to ensure interface to LIMS. However, it is expected that this will be a feature of future instrument packages and, in any case, it may even be retrofitted into existing systems.

Justifying Laboratory Automation

Improving productivity has become a priority need in most laboratories. Trained technicians and scientists often perform repetitive tasks rather than delegate them to less skilled personnel. A robotic laboratory automation system can automate a wide range of laboratory procedures - with better precision and at a substantially lower cost than manual techniques. Most laboratories have more work than they have time available to do it, and low priority projects may never be completed. Increasing laboratory productivity means getting more work done with:

1. Limited additional people, and
2. Utilizing instrumentation more than eight hours per day.

Scientific instruments are often justified as the "right" technique for the required analysis. A laboratory robotic system offers an alternative approach to manual laboratory procedures and must be justified on a comparative basis. This justification will likely include both economic and non-economic factors.

Economic Justification

Economic justification for advanced laboratory technology requires:

1. Unattended operation
2. Extended operation - more than eight hours per day.

A laboratory robotic system design features the high reliability necessary for unattended operation. Techniques are added to each application to automatically verify successful operation. Careful bench layout and application planning will minimize set-up and clean-up time. Extending operation into the evening or overnight will substantially improve economic justification.

Non-economic Justification

Automation using laboratory robotics creates several benefits beyond cost savings. These tend to be qualitative in nature, but, nevertheless, important.

1. Improved Precision

   - Is there a history of human errors which can be eliminated by automation?
   - Will running more standards, replicates and controls identify errors caused by reagents and changing experimental conditions?
   - Is there a benefit to having a common sample preparation history for each sample?

2. Faster Sample Turnaround Time

   - Will extended operation reduce the delays in obtaining analytical results?

3. Automatic Data Reduction and Documentation

- Is there a benefit to automatic data reduction and documentation compared to manual calculation and manual logging in a laboratory notebook?
- Is automatic transmission of results to a laboratory information system of value?

4. Safety

   - Is the laboratory area hazardous to people?
   - Will laboratory personnel contaminate sensitive experiments?

5. New Methods

   - Should new methods be developed around automated technology for efficient transfer to repetitive laboratory environments?

6. Other Applications

   - What additional applications may be automated in the future?

7. Capital Avoidance

   - Will automation delay replace the need to acquire expensive equipment or instrumentation?

System Implementation

Rarely can something of value be achieved without an investment. Laboratory automation and laboratory robotics offer great potential value, but requires an investment in personnel as well as capital equipment and facilities. Successful laboratory automation requires commitment of qualified people with sufficient time to design, implement and support the system. If these people lack experience, additional time must be available for training and familiarization prior to implementation - and, this must be quality time. Laboratory supervisors responsible for daily operating results should not be asked to implement a major laboratory automation project in their spare time.

Programming laboratory automation is analagous to training people to perform similar work. Automation generally requires more disciplined planning, but, when complete, has permanent value. People, on the other hand, require training or retraining with each assignment change. Once adequate funds and people are available, the following four requirements are key to all successful automation projects:

1. Motivated personnel
2. Proven analytical chemistries
3. Discipline planning
4. Creative implementation

Motivated Personnel

Major laboratory automation projects are strategic investments similar to product or process development. While some benefits come quickly, the strategic benefits will accumulate over time and grow to be substantial. Questions regarding the impact on personnel jobs and careers should be discussed openly since the goal isn't to make personnel obsolete, but rather to free them from repetitive or hazardous tasks so they can make more valuable contributions. There should be a sense of shared risk between management and personnel assigned to these projects. The project's importance should be clear to everyone and the implementation team should be protected from short term problems and interruptions.

Proven Analytical Chemistries

Variability in analytical results is often automatically blamed on "human error". Variations in chemistry due to reagants, standards, adsorbants and filters may also be the cause. More reliable chemistry will lead to more precise results using automation.

Discipline Planning

When provided incomplete instructions, people improvise to obtain acceptable results. Automated systems require complete, detailed instructions, and with proper planning and programming, will deliver consistent results. Manual procedures are typically a series of tasks sequentially linked together where the contribution of each step to the final result may be lost or obscure. The best approach to laboratory automation planning is to invert the orientation and start with the desired result and systematically break it down into functional procedures with individual operations derived from the functional requirements. Often this results in improved procedures and practices.

Creative Implementation

While using the demands of proven chemistries, it is critical to look beyond direct emulation of the manual procedure. Creatively building on the strengths of automated equipment permits greater precision and productivity than possible through direct emulation.

Trends in Laboratory Automation Technology

Robotics has already begun to change the laboratory - some of the emerging trends are highlighted below:

- Laboratory Layout and Work Organization - Laboratory walls are being removed. The laboratory of the future will be open with "Islands" devoted to integrated systems. Laboratories will be more decentralized with clearer responsibility for final results including precision, cost and turnaround time. With automated sample preparation, procedures are being serialized rather than performed in batches as had been done manually. Serialized leads to improved staff and equipment utilization, uniform sample history and faster availability of results.

- Laboratory Staffing - Automation specialists play an essential role in the laboratory. System integration is a complex function and laboratory personnel require specialized technical support. As this technology is more widely used, the specialized knowledge will be dispersed within the organization.

- System Integration - Key elements of system integration include:

  - Intelligent System Modules: Automated systems require instruments and modules capable of unattended operation which means the human tasks must be transferred to the instrumentation.

  - Automated Laboratory Systems: Sample preparation, analytical measurement and data acquisition will be integrated into Automated Laboratory Systems (ALS). Data will be acquired and validated followed by automatic method corrections as required.

  - LIMS Networks: ALS systems will be networked into higher level Laboratory Information Management Systems for overall laboratory administration and data base management.

  - Reliability: System reliability will be increased through use of automatic verification techniques. Positive sample identification will be confirmed throughout the procedure. Automatic data acquisition and validation insure reliable operation just as vision systems improve reliability of industrial robotics.

  - System/Application Software: Software integration is equally important as hardware integration. Application software modules provided for laboratory unit operations and other instrumentation will have to be compatible.

- Laboratory Disposables - New laboratory disposables with automatic dispensing will be developed for more efficient and reliable operation within an automated system. Disposables will truly be part of the system and "special" techniques used by skilled technicians may be designed into the disposable.

- Automated Methods Development - With the growing use of integrated analytical systems, new methods will be developed around this technology. Improved methods validation will be possible because of the ease of performing sensitivity experiments. Once developed, these methods can be easily delegated or transferred to other laboratories for routine operation.

- Automated Research and Product Development - Research and product development often requires multiple experiments under varying parameters. In many ways, this extends the role of laboratory automation by building upon its power to perform repetitive tasks in an experimental protocol. The addition of physical property sensors and process control capability will further extend the system boundaries.

- User/Vendor Partnerships - Laboratory instrumentation vendors recognize their growing role as system architects - compared to their traditional role as makers of laboratory tools. Most laboratory personnel, while skilled in chemistry, have limited experience in mechanical and electrical engineering and advanced computer techniques. Effective laboratory automation requires technical support. Many customers will create strong internal support organizations while others will look to the automation system integrator for support. Ultimate system responsibility must remain with the end user.

- Cooperative Relationships Between Instrumentation and Computer Manufacturers - The absolute need for system integration requires new behavior from instrumentation, laboratory equipment and computer manufacturers.

Laboratory automation is essential for increasing the productivity of skilled scientists and technicians. Robotics is an emerging technology for the laboratory and user experience, product capability and applications know-how are rapidly improving.

Based upon this background, the development of the automated Solid Propellant Mixing Laboratory proceeds in the next section to review the approach taken to define potential applications for automation.

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## SELECTION AND IMPLEMENTATION OF LABORATORY AUTOMATION

The successful development and implementation of automation (e.g. a laboratory robotic system) requires that the entire process be planned and carried out in a logical sequence from initial planning through development, installation, integration, user training and operational support. Although the basic steps to be followed are similar to those in any other type of project, automation and robotics in particular have unique capabilities and limitations that make it especially important to carefully plan the implementation process. Disappointments can result in cases where users have unrealistic expectations of robotic capabilities or performance. Robots combine certain capabilities of both manual labor and hard automation, and so the types of applications for which they are best suited and the way they are likely to perform may not be immediately obvious.

The entire process of implementing a laboratory robotic system from the initial planning through the ongoing operation of the system in the operating laboratory environment, requires that four general steps be completed, as illustrated in Figure 5 and briefly discussed below:

1. Planning - Before selecting and installing specific robots and supporting automation, a planning phase is required to evaluate the nature of the operation(s) for which robots are being considered and to determine that robots are justifiable. By the end of this phase a decision will have been made that automation (and possibly robotics) should be used, and likely candidates for applications will have been determined.

2. Applications Engineering - During this phase, the candidate applications are studied in more detail, a specific first application is selected, and a specific robot is selected. This continues on each application until the entire integrated system is engineered. In addition, detailed requirements for the application are analyzed, such as layout requirements, workplace modifications, and robot accessories required. The entire group of applications is then evaluated for compatability and integrated into a system.

3. Installation - This phase covers the time from the preparatory work performed in the laboratory workplace through the installation and start up of the robotic system(s).

4. Integration - Once the robotic system has begun initial operation, an ongoing process is required to insure that it continues to perform its job in an effective manner. Activities to be performed during this phase include training maintenance, monitoring, human relations, and the constant upgrading of the robot system through the use of new technologies or the application of the system to new operational demands. It should be noted that there is an integration associated with applications engineering by the system integrator and should not be confused with the integration of system into the laboratory environment.

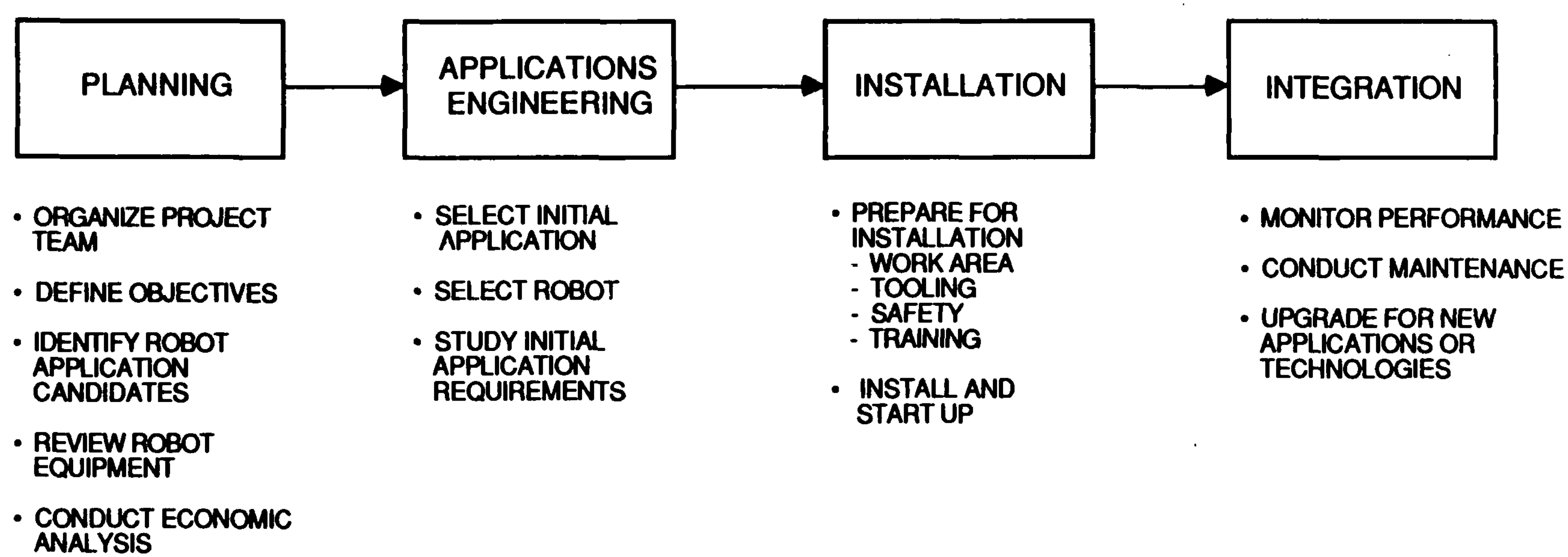



**FIGURE 5 PROCESS OF PLANNING, SELECTING, AND IMPLEMENTING ROBOTS**

The remainder of this section examines the specific activities that should be performed during each of these phases in order to insure that a robotic system is implemented in an orderly, logical manner. This approach represents the implementation of KLM's methodology as utilized on the Solid Propellant Mixing Laboratory Project. It will be discussed in a more general sense to provide background for KLM's proposed approach and Phase II implementation plan presented in the next section.

Planning

This essential first step in a laboratory automation project implementation process can have a major impact in determining the eventual success of a robotic system installation. During this phase, the question of whether or not an automated system makes sense is considered, and a go/no-go decision is made. As in the case of other types of automated machinery, the initial decision to begin considering robots for use in laboratory operations typically begins with engineering personnel. However, because robotics represent a progressive new technology, many current users report that top management is involved in the initial decision to consider robots. Most users now using robots did not conduct a formal audit of their operations to evaluate the feasibility of using robots or to identify likely applications. Quite often, it was an R&D project or an "experiment"; however, they usually conduct cost studies to evaluate the economics of using robots/automation rather than manual labor. In typical manufacturing/laboratory operations, it makes sense to conduct both a cost study and an audit of involved operations.

Specific steps that should be followed during this phase are discussed in the following sections.

Organize Project Team

The first step that should be completed during this phase is the selection of a group of individuals to carry out the implementation program. This group typically includes the laboratory management, production supervisory personnel, and engineering support personnel. All three operational levels must actively participate in the entire process in order to insure a successful implementation. The laboratory management must be involved to provide overall policy direction for the project and to provide inputs into the evaluation process. Although the laboratory management will not become involved in the details of applications engineering or installation, it is important that the benefits and limitations of the system be clearly established so that the decision to proceed can be properly viewed within the context of the laboratory's objectives and mission guidelines.

The production management representative should be involved in the entire process from beginning to end, since this is the individual(s) who understands the characteristics of each operation better than anyone else. The engineering support staff representative should become thoroughly familiar with these technical and performance characteristics of the system. These individuals will be involved in the applications engineering and installation phases.

In addition to this group, it is important that others within the laboratory hierarchy be provided with ongoing information regarding the status of the project. Typically, a series of progress reports will be utilized. It is important to ensure that there is a consensus on the project and to minimize the risk of the "human factor" during the implementation and operational phases.

Define Objectives

Once the project team has been assembled and responsibilities have been defined, it is necessary to define the objectives to be accomplished in implementing automation in the laboratory. As discussed earlier, there are a number of potential benefits to be realized in using automation, including improved safety, higher productivity, reduced costs (labor, materials, and others), higher product quality, improved employee morale, or simply the enhanced image resulting from the use of a sophisticated technology. The specific objectives of management should be clearly defined as a basis for evaluating the desirability of using automation.

Identify Automation Application Candidates

The next step is to conduct a review of the laboratory environment being considered for automation. The goal of this review is to identify a set of suitable application candidates for the use of robotics and automation. It is important that the concept of automation be considered as a whole when examining potential applications. The entire laboratory operation should be studied as a system for compatibility with the concept of robotics and advanced information management. In this way, patterns will begin to emerge in various applications where automation clearly would offer certain advantages.

It is useful to use some form of a "robot application checklist" for assessing the general feasibility of automation in each application being considered, such as the example shown in Table 1. The method described here involves determining the state of the operating conditions that adversely affect workers. The process involves two steps. The first step is to calculate the impact of the operating conditions on manpower and the second is to decide whether to select or reject an automated system, based on the total impact of the operating condition.

Calculating the impact of the operating conditions involve four steps. In the first step, each condition is assigned a weight factor. This is a purely subjective process in which the only consideration is the operating conditions' relative importance with respect to the human working environment. Table 3-1 lists the 15 operating conditions under consideration in this project and their respective assigned weight factors. It is by no means a comprehensive list, but the conditions listed represent the type of basic factors considered for the Solid Propellant Mixing Laboratory environment. Mental strain is given the highest weight because it is usually associated with situations in which an operator must be alert at all times, gather information, process the information mentally, make decisions, and implement those decisions instantaneously. The weights assigned to the other conditions in the list are only relative weights.

## TABLE 1. LABORATORY ROBOTIC APPLICATION CHECKLIST

| Operating Condition | Weight Factor | Level of Impact | | | | Weighted Impact | Maximum Impact |
|---|---|---|---|---|---|---|---|
| | | None=0 | Low=1 | Medium=2 | High=3 | | |
| Mental Strain | 7 | | | | | | 21 |
| Accident Risk | 7 | | | | | | 21 |
| Laboratory Safety | 7 | | | | | | 21 |
| Hazardous Material | 6 | | | | | | 18 |
| Monotony | 6 | | | | | | 18 |
| Vapors | 5 | | | | | | 15 |
| Cleanup | 5 | | | | | | 15 |
| Chemical Spills | 4 | | | | | | 12 |
| Heat | 3 | | | | | | 9 |
| Lack of Ventilation | 3 | | | | | | 9 |
| Dust/Dirt | 2 | | | | | | 6 |
| Muscular Strain | 2 | | | | | | 6 |
| Second-Shift Operation | 2 | | | | | | 6 |
| Heavy Safety Clothing | 1 | | | | | | 3 |
| Lack of Light | 1 | | | | | | 3 |
| **TOTAL** | | | | | | | **183** |

Total Impact ------ < X -- Reject Automation
\> Y -- Accept Automation
X < T.I.< Y -- Conditional Automation Acceptance

The second step in the process involves determining the level of impact of each of the operating conditions in a given laboratory facility. Four levels are identified: "no impact," "low impact," "medium impact," and "high impact." The third step involved determining the weighted impact of the operating conditions on workers. This is done by multiplying the level of impact by the weight factor of the operating condition (weighted impact = level of impact x weight of the operating condition). The fourth step involves calculating the total impact of all the operating conditions. This is done by adding the weighted impact for the operating conditions.

The total impact calculations lead to the second step in the decision-making process: deciding whether to accept or to reject automation on the basis of the following guidelines:

- If the total impact of the operating conditions is equal to or below **X**, the decision should be to reject automation. The limit is derived based upon an agreed upon formulation reflecting the goals of the organization. Such a level might be one-third (1/3) the maximum impact value.

- If the total impact of the operating conditions is above **Y**, then the decision should be to accept automation. Such a limit might be two-thirds (2/3) of the maximum impact value.

- If the total impact of the operating conditions falls above **X** but does not exceed **Y**, then automation should be accepted conditionally.

In general, the best initial applications for automation are those in which there have been safety problems in the past. Another good area to consider is an operation that is boring, fatiguing, or environmentally unpleasant. Finally, an operation in which there has been a high degree of wasted materials or scraps as a result of human efforts, can be a good initial candidate for automation. The most difficult are those requiring human decision making, adjustment or highly skilled multisensory actions.

Throughout this process, it is important to continually think in systems terms. The goal is not to identify applications in which robots can be modified to meet the needs of the work environment; rather, the goal is to effectively integrate the robot, the laboratory work environment, the samples, other machines and instruments, human workers, facilities and computers into a productive laboratory system. In such case, the whole is greater than the sum of the pieces since synergism and improved operations often lead to new capabilities and enhanced operational capabilities.

<u>Conduct Economic Analysis</u>

The final step during the planning phase is to conduct a cost justification study for several of the most likely initial application candidates, using the automation that appears to be most suitable as examples for initial cost estimates. Although certain non-economic factors, such as worker safety and morale, are often cited as being justifications for the use of automation, it is ultimately the economic considerations which determine whether or not a laboratory will use them. Economic considerations are especially important when deciding whether or not to implement automation that can easily cost as much as several hundreds of thousands of dollars. Although justification criteria are often divided into economic and non-economic factors, all factors have an economic impact in a laboratory environment. For example, in a hazardous environment, there are specific costs associated with the safety precautions necessary to protect human technicians. These costs can be compared with the costs of using robots in place of human workers.

There are two general ways of examining the costs to be considered in analyzing the use of automation versus manual skilled labor. The first approach, cost avoidance, is used to evaluate the least costly of several alternative investments. For example, in a propellant mixing operation involving mixing of several ingredients, the cost of automation would be compared with the cost of safety clothing, goggles, special ventilation, and guards for human technicians. The robotic/automation system would require none of these safety features, and therefore, certain costs would be avoided. In addition to these costs, an analysis would then have to be performed on the potential labor cost savings or change in productivity in using a robotic system.

The second type of analysis is a study of cost savings. In this case, one or more alternatives are compared with the "do nothing" alternative to evaluate the likely investment return to be achieved under each alternative. Although a detailed discussion of the various approaches used to evaluate investment alternatives is beyond the scope of this report, it is useful to note that three basic approaches are commonly used in manufacturing firms today to compare alternative projects:

- <u>Return on Investment (ROI)</u> - This is probably the most commonly used tool for comparing alternative investments. A series of annual cash flows are developed for each alternative, taking into account both expected annual cost savings and expenses. These cash flows are then compared with an initial investment, or cash outlay, to determine an overall annual rate of return on the investment. This return is then compared with a minimum investment criterion to evaluate the attractiveness of each alternative.

- <u>Net Present Value (NPV)</u> - Under this approach, a series of discounted annual cash flows are generated for each alternative over the life of the project (e.g., 10 years). The discount rate is usually equal to the cost of securing capital for the laboratory. These discounted cash flows (which are hopefully positive numbers) are added and compared with the initial cash investment. If the sum of the discounted cash flows is larger than the initial investment number, then the difference between the two represents the present value of the alternative to the laboratory. Typically, this must be a positive number in order for the alternative to meet the investment return criterion.

- <u>Payback Period</u> - This is a measure of the time required to recover the initial investment costs for each alternative. For example, if a payback period is three years, this means that the sum of the cash flow during the first three years is equal to the initial investment cost. After three years, the project will then generate positive net dollars.

Typically, the net present value approach provides the most realistic and meaningful comparison of several investment alternatives. In the case of a new technology such as robotics, however, payback period may be a more useful short term means of preparing an economic justification of a potential robot installation. Most robot manufacturers claim that a payback period of from one to two years is likely. Laboratories that have used robots report an average payback period of two years, which is generally an acceptable number for most laboratory equipment. To evaluate the net present value or payback of a particular automation in a particular application, a financial analysis is used.

In actual cases, there are many areas of potential cost savings that may be realized. Some of the more common categories of cost savings include the following:

- Direct labor (assuming one human worker per robot per shift)
- Cost avoidance (e.g., a potential lawsuit because of an explosion in the laboratory environment)
- Elimination of safety clothing items, such as safety shoes, goggles, gloves and aprons
- Elimination of guards around exposed tools
- Reduced scrap rate and rework
- Reduced energy costs (robots don't need lights, heat, etc.)
- Reduced administrative/supervisory costs
- Elimination of human facilities such as washrooms, parking and dining area

Although some of these items represent areas of relatively small savings they should all be considered in the cost analysis in order to further justify the use of a robotic/automation system.

Applications Engineering

The second phase of the process involves the selection of the specific application area for which the first robotic/automation system(s) will be employed, the selection of the robotic system to be developed and the detailed analysis of the application in order to prepare for installation.

<u>Select Initial Application</u>

The list of application candidates can be narrowed by reviewing them with system integrators and manufacturers/vendors who produce robotic systems that appear to be suitable. A more detailed study of each application can also help narrow the list. It is extremely important that the correct initial application be selected. If this first application fails, it could also be the last. It is probably best to select the simplest application from the list of candidates assuming that the potential benefits appear to be reasonable. The objective of the first installation is to prove that the technology works, and minimize negative human factors, and often can significantly improve some aspect of the laboratory environment. As discussed earlier, an application in which there is a record of safety or potential health problems is an ideal first application.

The selected first application should be studied in detail. Every task that must be performed should be documented, not in human terms, but in terms of the end result to be achieved. This is important since the human way, while a guide, is not necessarily the best robotic way. The required robot work envelope should be defined, and all capabilities (load, speed, cycle time, accuracy, etc.) should be specified. If at any step a task is discovered that is beyond the capability of a robot, another alternative should be considered. It is important at this point to "think" like a robot and consider all of the possible things that can go wrong.*

Another consideration is a potential backup for the robot during the 2-4% of the time that it is likely to be out of service for maintenance or repairs. Space requirements, safety considerations and load capacity should be also considered during this time. The objective during this step is to make certain that the selected application(s) is the best one possible for testing the performance of the robotic system.

Select Robot

The process of selecting the robot is the same as that for any other piece of automated equipment. Several manufacturers should be contacted for information and advice. Although the robot manufacturer is the most important source of information in learning about robots, many users have obtained valuable information by talking to others who had used robots in their laboratory operations. It is probably more important to review several sources of information when selecting a robot than for other types of equipment, in part because the capabilities and performance of robots are not always immediately obvious. Many robot users also find valuable information available at conferences and trade shows such as those sponsored by the Society of Manufacturing Engineers. Although very few independent consulting firms exist to provide assistance in selecting robots, it is likely that the number of such firms will increase in the future as the number of robot installations increase. A demonstration of a robot in operation can be extremely helpful. Also films of robots in operation are provided by many robot manufacturers. It may also be possible to visit a facility that is using robots, although many laboratories are reluctant to allow outside visitors to observe their robot operations.

* KISS - "Keep it simple, stupid" is appropriate since the robotic system in today's technology can only do what it is programmed to do. The simplist human interventions are not possible.

Study Initial Application Requirements

After selecting various components of the automation system, the application should be studied to prepare for the installation. A layout of the installation should be prepared to determine what engineering requirements will need to be satisfied before installing the robotic system. The specific areas to be studied include the following:

- Protection for the robotic system from environmental hazards such as dust contamination, metal particles, heat, chemical corrosion, cold, etc.

- Obstacles or interferences with the movement of the manipulator arm.

- Interfaces required between the robot and other machines, instruments, utilities, computers, or other items.

- Tooling requirements such as special fixtures or end effector changes required to locate the sample at a precise position relative to the robot.

- Safety precautions to protect personnel working near the area. Although the overall safety record of robots has been good, the manipulator arm can impart serious injuries to workers who mistakenly enter the work envelope of the robot. Therefore, guard rails are essential. The control console should also have an emergency stop button.

- Provisions for utilities such as electricity, compressed air and water.

- End-of-arm tooling or gripper design. Although robot manufacturers are working on the development of standardized grippers, it is still normally the task of the system integrator to design end-of-arm tooling. A great deal of creativity can be applied here.

- Spare parts and test equipment for the robotic system.

- Other changes in facilities, equipment, or laboratory layout that may be required, especially during installation to minimize impact on laboratory activities.

Most robotic system users agree that the applications engineering step is an extremely important part of the automation implementation process. During this step, a creative approach to automated applications should be followed. For example, laboratory procedural design changes may result in a much improved system performance, whereas human performance might not be improved. Creative layouts, using upside-down robots, represents another approach, as does the reorientation of samples being handled by the robot.

Installation

Installation times for robotic/automated systems currently in use have ranged from 3-4 days up to 90-100 days. On the average, a typical laboratory installation requires a total time of about three weeks. This is a significant amount of time, and it pays to prepare for the task by completing several preparatory activities.

## Prepare For Installation

It is beneficial to perform as much preparatory work as possible before the system is installed in order to insure a smooth operation. Preparation for installation requires that facilities, equipment and personnel are prepared for the robotic system.

### *Work Area*

Utility service drops and preparation of the floor can be completed before installing the system, based upon the requirements determined during the applications engineering step. Certain interfaces with other equipment can be prepared. If a laboratory procedure is being modified or if the work flow from an upstream work station is being changed, this can also be accomplished before installation. Equipment can be relocated and access can be rearranged. The work area must be rearranged in about three-fourths of all system installations, especially in material handling operations.

### *Safety*

Guard rails and safety chains can be prepared before the robotic system is installed. The Occupational Safety and Health Act (OSHA) is the primary government regulation that affects the safety requirements of robotic systems. Although present OSHA regulations do not govern robotic system usage directly, the use of robots for reducing or eliminating risks tends to satisfy many OSHA standards. Therefore, when robots are being considered for use in potentially hazardous environments, it is useful to consider their ability to satisfy such safety regulations concerning factors such as:

- Occupational health and environmental control
- Hazardous materials
- Personal protective equipment
- Fire protection
- Materials handling and storage
- Machinery and machine guarding
- Electrical

### *Training*

It is extremely important that all individuals who will be involved in the operation of the system be thoroughly trained in its technical capabilites, operation, programming, and maintenance. This training should be conducted before startup and turnover of the system. At least two people, including maintenance, laboratory operations and applications engineers, and in some cases the laboratory management, should attend a training program typically 3-5 days. These programs can be held either at the system integrator's facility or in the customer's laboratory. Programming training is especially important since robotic system programming capabilities have not yet been standardized.

*Human Relations*

The importance of securing the support of laboratory personnel should not be underestimated. Many people believe that robots are likely to replace laboratory workers rather than displace them. Two key areas of human relations must be attended to before installing a robotic system. First, the commitment of management must be assured. This is readily accomplished if the planning and applications engineering phases have been correctly conducted and a logical justification for the robotic system has been presented.

The second area is more complex, since it requires that the laboratory workers who are either being displaced or who must work with the system accept it willingly. Workers must be shown that the use of robotic/automated systems mean that they will no longer be required to perform certain unpleasant activities. They must be convinced that their jobs will be upgraded, not eliminated. The experience of laboratories using automated systems has been very favorable in this area, with workers generally being positive about the robots.

*Install and Startup*

If the preliminary preparations have been properly conducted, the actual installation of the system should be smooth. Most system integrators will offer installation assistance. Several days or weeks of testing with the robotic system would be necessary before installing it in a laboratory. Robotic systems do not experience a learning curve as do humans. However, there is likely to be a start-up period required during which initial problems must be resolved. Most of the difficulties experienced by laboratories in installing robotic systems are related to problems in programming, which during testing period by the system integrator will be resolved. Typically a period of less than one day up to several weeks or even months may be required to reach a 100 percent production level.

Integration

After the robotic/automation system has begun production operations, the period of integrating the system into the laboratory production environment begins. This is the period during which the system is transformed from a curiosity into an accepted, standard piece of laboratory equipment. It is difficult to estimate a time for this phase, since it is an on-going task. The first part of this phase begins with the monitoring of the system to watch for recurring problems, keep track of system performance, monitor downtimes, and evaluate the acceptance of the system by management and by the laboratory workers. In addition, the system should be monitored to insure that the benefits of the operation are achieving the predicted results.

On-going maintenance is also a part of the integration phase. It is advantageous to have an in-house maintenance capability rather than to rely on the manufacturer service contract. Maintenance personnel should be given total responsibility for the performance of the system. One difficulty with this approach is that robotic systems are highly reliable, and so it may be difficult for an in-house maintenance staff to achieve a constant level of proficiency. One way to offset this is to provide for periodic retraining of the maintenance staff.

Another area of activity during this phase is to constantly search for ways to upgrade the robotic systems by using laboratory robotic cells in new applications, by adding on new technological developments, or by using groups of robotic/automated islands working together. As new ways of using robotic systems are learned, their overall performance will improve, and worker acceptance is likely to increase. The ultimate goal in using a robotic island is to integrate it into the laboratory environment to the extent that it is viewed as simply a standard type of automation technology rather than as a unique piece of equipment.

The next section addresses applying the above methodology to the Solid Propellant Mixing Laboratory at Edwards Air Force Base.

# AUTOMATION OPPORTUNITIES IN A SOLID PROPELLANT MIXING LABORATORY

The purpose of this section is to apply the analysis methodology discussed in the previous section to the Edwards Air Force Base Solid Propellant Mixing Laboratory automation project.

Mixing of novel solid rocket propellants in a R&D laboratory requires extensive safety precautions due to the explosive nature and, in some cases, unknown hazards of the materials. Current operations used throughout military laboratories and supporting commercial industry involve elaborate facilities, are very labor intensive, and still contain an element of risk to the personnel involved. This study investigated the use of robotics and other automated processing techniques as a means of reducing the cost and improving the safety of these laboratory operations. Specifically, the study considered developing and modifying existing equipment to automate a one-pint solid propellant mixing operation. Operational steps that were considered for automation included ingredient weighing and prebatching, ingredient addition, on-line monitoring of relevant mix parameters, propellant casting, and cleanup. Emphasis was placed on approaches that minimize human intervention and enhance safety. Modifications to the existing mixing equipment as well as implementing procedures will be necessary for successful implementation of automation and robotics.

Expectations in Laboratory Automation

The following questions must be asked to help focus on realistic expectations from laboratory robotics and automation in the propellant mixing laboratory:

- What does the laboratory management expect the robotic system(s) to do?
- What do laboratory operational personnel really expect the robotic system(s) to do?
- How much time and resources will be initially devoted to the automated system?
- Where would the system be placed in the laboratory?
- Have person(s) been assigned to the robotic project?
- Is the user of the system going to attend a complete training session?
- How many samples (propellant mixing) are expected to run in a day?
- When must the system to be able to run real samples?
- Is the robotic system expected to process the samples in exactly the same way as people do manually?

- Are the applications well defined?
- Are the proper power and other utility requirements available?
- Will data from the system be transferred to another computer?
- Have the disposable items been checked out to ensure they are "robot friendly", reproducibly made, and readily available?
- Are the other pieces of equipment that the robotic system will interface with "robot friendly" and compatible?
- What kind of system and application reliability is expected?

The answers to these questions established the framework within which the propellant laboratory robotic applications were identified, developed and implemented.

Based upon the experience gained in numerous laboratory applications of automation and robotics, the following general observations can be made:

1. The system will take some time to become fully operational;
2. Adequate amount of training by the system integrator is an absolute requirement;
3. The applications must be well planned and substantial time must be spent by laboratory personnel on the project;
4. The overall reliability of the system will only be as good as the weakest link; and,
5. The automated robotic system will perform as well as or better than the manual method.

Justification Guidelines

<u>Economic Factors</u>

Economic justification of laboratory automation is new. Since the rapid recovery of the entire investment is desirable, sophisticated return on investment calculations are typically not necessary. Therefore, the justification analysis can be relatively simple.

*Justification Worksheet*

Table 2 illustrates a justification worksheet to be used to compare any manual laboratory method with an automated method. Each step in the worksheet introduces a

## TABLE 2. JUSTIFICATION WORKSHEET

| | | Formula | Present Method | Automated Method |
|---|---|---|---|---|
| A. | Number of samples per day | Input | | |
| B. | Total time per sample (hr) | Input | | |
| C. | Operating hours per day | **AxB** | | |
| D. | Technician cost per hour (including fringe) | Input | | |
| E. | Technician hours per operation day | Input | | |
| F. | Technician hours per sample | **E/A** | | |
| G. | Technician cost per sample | **DxF** | | |
| H. | Instrumentation Cost | Input | | |
| I. | Estimated user setup and programming cost | Input | | |
| J. | Total investment | **H+I** | | |
| K. | Annualized investment (calculated average yearly cost amortized over 5 years) | **J/5** | | |
| L. | Investment cost per day (calculated daily cost over 250 working days per year) | **K/250** | | |
| M. | Investment cost per sample | **L/A** | | |
| N. | Total cost per sample | **M+G** | | |
| O. | Automated/Robotic system saving per sample. (Present method - automated method) | - | - | |
| P. | Number of samples to recover investment | **J/O** | - | |
| Q. | Days to recover investment | **P/A** | - | |

single input or calculation so that the logic behind the analysis remains clear and simple.

An ideal project would offer full investment recovery in less than one year. With very rapid payback, the analysis can be used simplifying assumptions. To further simplify the analysis, any time or equipment which is common to both the present manual method and the proposed automated laboratory method is eliminated.

The following comments apply to each lettered step in the worksheet (Table 2):

A. Number of samples per day

*This is the number of samples that will be run during a 24-hour period under each alternative method.*

B. Total time per sample (hr)

*This is the elapsed time required to process a sample. A technician or scientist may or may not be present.*

C. Operating hours per day

*This is the time required to complete the daily number of samples. Under attended operation in a single shift laboratory, this time should not exceed 8 hours. If unattended operation is possible, this time may approach 24 hours.*

D. Technician cost per hour (including fringe)

*For estimating purpose use the following:*

| | |
|---|---|
| *Low Cost* | *$20.00/hr* |
| *Medium cost* | *$23.00/hr* |
| *High cost* | *$28.00/hr* |
| *Scientist* | *$35.00/hr* |

E. Technician hours per operating day

*This is the total staffed time required for the day's work. If a person is working full time on the procedure, this will be the same as Item above. For automated procedures include the setup and cleanup time in this category.*

F. Technician hours per sample

*This is calculated to distribute the total technician hours between each sample.*

G. Technician cost per sample

*The calculated labor cost for each sample.*

H. Instrumentation cost

*Include the purchase cost of all instrumentation and equipment required for each alternative. Common equipment can be eliminated from the comparison.*

*Certain accessories such as printers and computer interfaces provide added functionality in the automated system compared to the manual system. These may be excluded from the direct comparison or a credit taken for this added functionality.*

I. Estimated user set-up and programming cost

J. Total investment

*Calculated sum of instrumentation and setup investment.*

K. Annualized investment

*Calculated average yearly cost amortized over 5 years; other time periods can be used.*

L. Investment cost per sample

*Calculated daily cost over 250 working days per year. Some laboratories work over weekends and they may choose to increase the days/year to 300 or 350.*

M. Investment cost per sample

*Calculated cost per sample.*

N. Total cost per sample

*Total cost per sample for technician time and instrumentation.*

O, P, Q. Calculated savings and time required to recover the entire investment.

Non-economic Factors

A variety of non-economic factors may contribute to justifying the robotic-automated laboratory system. These include factors such as:

1. Improved precision
2. Faster sample turnaround time
3. Automatic data reduction and enhanced documentation
4. Improved safety
5. New methodology or procedures
6. Other laboratory applications become feasible

Undesirable Environments

Recent developments indicate that an undesirable working environment has also become a reason for automating. "Working environment" refers to the operating conditions under which various operations are performed. The conditions usually include the cleanliness of the working area, cleanliness of the air in the working area, atmospheric conditions, lighting conditions, temperature in the working area, condition of equipment, nature of the raw material, and the hazards involved in handling the material and operating the machines. If the operating conditions in a laboratory facility create an undesirable working environment, worker productivity in the facility will be adversely affected.

Solid Propellant Mixing Laboratory Evaluation

In the previous section entitled, "Identify Automation Application Candidates," a method for making automation decisions was described in detail. Table 3 presents a "Laboratory Robotic Application Checklist" for assessing the general feasability of automation in solid propellant mixing laboratory.

A solid propellant mixing laboratory requires the implementation of numerous procedures to develop a solid propellant including: ingredient blending and drying, oxidizers, fuels and hazardous materials weighing, propellant mixing, casting and cleanup. Figure 6 illustrates a detailed flow chart of operational steps in a solid propellant mixing laboratory. These steps presently are performed by laboratory operators during the manual operation. The detailed study of these operations and the required steps determine sample throughput, outlines the automated method in detail, determines sample output rate, laboratory layout and its capacity.

The Weighted Impact discussed in the earlier section entitled, "Identify Automation Application Candidates," regarding the operating conditions for each of the specific applications in a Solid Propellant Mixing Laboratory was calculated. Tables 4 through 7 present the data sheet for each of the major applications. The Weighted Impacts calculated for each specific application including ingredient weighing, ingredient addition and mixing, propellant casting and cleanup were 132, 148, 142 and 162, respectively. All of the calculated total impacts for the operating conditions fall above 122; consequently the issue of automation should be accepted.

Laboratory Layout

Automating propellant laboratory applications require a systematic approach to the steps involved in producing a propellant sample for subsequent analytical

## TABLE 3. LABORATORY ROBOTIC APPLICATION CHECKLIST

| Operating Condition | Weight Factor | Level of Impact | | | | Weighted Impact | Maximum Impact |
|---|---|---|---|---|---|---|---|
| | | None=0 | Low=1 | Medium=2 | High=3 | | |
| Mental Strain | 7 | | | | | | 21 |
| Accident Risk | 7 | | | | | | 21 |
| Laboratory Safety | 7 | | | | | | 21 |
| Hazardous Material | 6 | | | | | | 18 |
| Monotony | 6 | | | | | | 18 |
| Vapors | 5 | | | | | | 15 |
| Cleanup | 5 | | | | | | 15 |
| Chemical Spills | 4 | | | | | | 12 |
| Heat | 3 | | | | | | 9 |
| Lack of Ventilation | 3 | | | | | | 9 |
| Dust/Dirt | 2 | | | | | | 6 |
| Muscular Strain | 2 | | | | | | 6 |
| Second-Shift Operation | 2 | | | | | | 6 |
| Heavy Safety Clothing | 1 | | | | | | 3 |
| Lack of Light | 1 | | | | | | 3 |
| **TOTAL** | | | | | | | **183** |

| | | |
|---|---|---|
| Total Impact ------ | < X | -- Reject Automation |
| | > Y | -- Accept Automation |
| | X < T.I.<Y | -- Conditional Automation Acceptance |

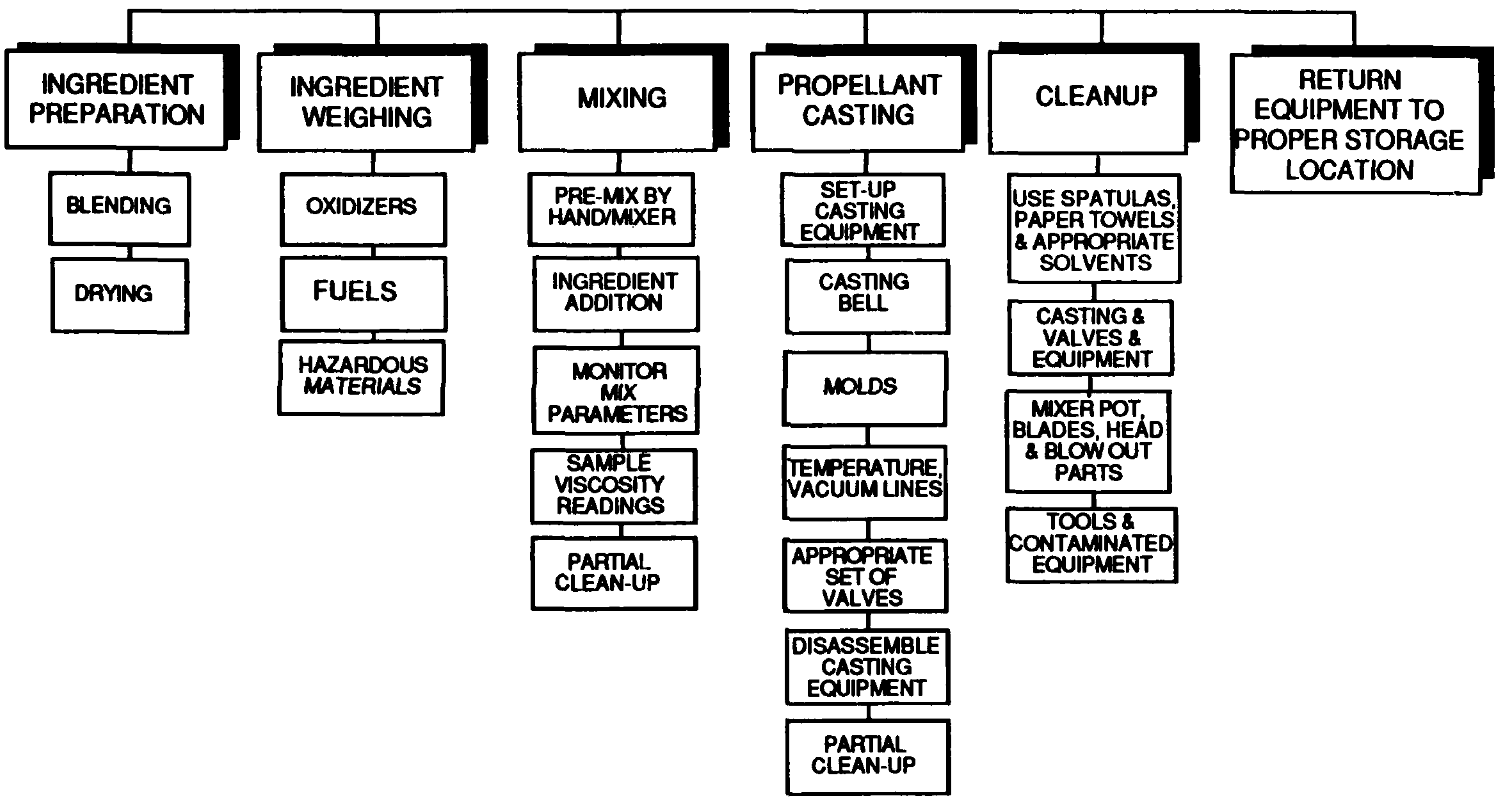



**FIGURE 6** <u>OPERATIONAL STEPS IN A SOLID PROPELLANT MIXING LABORATORY</u>

## TABLE 4

### IMPACT OF OPERATING CONDITIONS DURING INGREDIENT WEIGHING IN SOLID PROPELLANT MIXING LABORATORY

| Operating Condition | Weight Factor | Level of Impact | | | | Weighted Impact | Maximum Impact |
|---|---|---|---|---|---|---|---|
| | | None=0 | Low=1 | Medium=2 | High=3 | | |
| Mental Strain | 7 | | | | x | 21 | 21 |
| Accident Risk | 7 | | | | x | 21 | 21 |
| Laboratory Safety | 7 | | | x | | 14 | 21 |
| Hazardous Material | 6 | | | | x | 18 | 18 |
| Monotony | 6 | | | x | | 12 | 18 |
| Vapors | 5 | | | x | | 10 | 15 |
| Cleanup | 5 | | | | x | 15 | 15 |
| Chemical Spills | 4 | | | x | | 8 | 12 |
| Heat | 3 | | x | | | 3 | 9 |
| Lack of Ventilation | 3 | | x | | | 3 | 9 |
| Dust/Dirt | 2 | | | x | | 4 | 6 |
| Muscular Strain | 2 | | x | | | 2 | 6 |
| Second-Shift Operation | 2 | x | | | | 0 | 6 |
| Heavy Safety Clothing | 1 | | x | | | 1 | 3 |
| Lack of Light | 1 | x | | | | 0 | 3 |
| **TOTAL** | | | | | | **132** | **183** |

Total Impact ------ < 61 -- Reject Automation (1)
> 122 -- Accept Automation (2)
61 < T.I. <122 -- Conditional Automation Acceptance (3)

T.I. = 134 Case (2) is applicable.

## TABLE 5

### IMPACT OF OPERATING CONDITIONS DURING INGREDIENT ADDITION AND MIXING IN SOLID PROPELLANT MIXING LABORATORY

| Operating Condition | Weight Factor | Level of Impact None=0 | Low=1 | Medium=2 | High=3 | Weighted Impact | Maximum Impact |
|---|---|---|---|---|---|---|---|
| Mental Strain | 7 | | | | x | 21 | 21 |
| Accident Risk | 7 | | | | x | 21 | 21 |
| Laboratory Safety | 7 | | | | x | 21 | 21 |
| Hazardous Material | 6 | | | | x | 18 | 18 |
| Monotony | 6 | | | | x | 18 | 18 |
| Vapors | 5 | | | | x | 15 | 15 |
| Cleanup | 5 | | | | x | 15 | 15 |
| Chemical Spills | 4 | | | x | | 8 | 12 |
| Heat | 3 | | x | | | 3 | 9 |
| Lack of Ventilation | 3 | | x | | | 3 | 9 |
| Dust/Dirt | 2 | | x | | | 2 | 6 |
| Muscular Strain | 2 | | x | | | 2 | 6 |
| Second-Shift Operation | 2 | x | | | | 0 | 6 |
| Heavy Safety Clothing | 1 | | | | | 1 | 3 |
| Lack of Light | 1 | x | x | | | 0 | 3 |
| **TOTAL** | | | | | | **148** | **183** |

Total Impact ------ < 61 -- Reject Automation (1)

> 122 -- Accept Automation (2)

61 < T.I. <122 -- Conditional Automation Acceptance (3)

T.I. = 151 Case (2) is applicable.

## TABLE 6

## IMPACT OF OPERATING CONDITIONS DURING PROPELLANT CASTING IN SOLID PROPELLANT MIXING LABORATORY

| Operating Condition | Weight Factor | Level of Impact | | | | Weighted Impact | Maximum Impact |
|---|---|---|---|---|---|---|---|
| | | None=0 | Low=1 | Medium=2 | High=3 | | |
| Mental Strain | 7 | | | | x | 21 | 21 |
| Accident Risk | 7 | | | | x | 21 | 21 |
| Laboratory Safety | 7 | | | x | | 14 | 21 |
| Hazardous Material | 6 | | | | x | 18 | 18 |
| Monotony | 6 | | | | x | 18 | 18 |
| Vapors | 5 | | | x | | 10 | 15 |
| Cleanup | 5 | | | | x | 15 | 15 |
| Chemical Spills | 4 | | | x | | 8 | 12 |
| Heat | 3 | | x | | | 3 | 9 |
| Lack of Ventilation | 3 | | x | | | 3 | 9 |
| Dust/Dirt | 2 | | | x | | 4 | 6 |
| Muscular Strain | 2 | | | | x | 6 | 6 |
| Second-Shift Operation | 2 | x | | | | 0 | 6 |
| Heavy Safety Clothing | 1 | | x | | | 1 | 3 |
| Lack of Light | 1 | x | | | | 0 | 3 |
| **TOTAL** | | | | | | **142** | **183** |

Total Impact ------ < 61 -- Reject Automation (1)
> 122 -- Accept Automation (2)
61 < T.I. <122 -- Conditional Automation Acceptance (3)

T.I. = 144 Case (2) is applicable.

## TABLE 7

### IMPACT OF OPERATING CONDITIONS DURING CLEANUP IN SOLID PROPELLANT MIXING LABORATORY

| Operating Condition | Weight Factor | Level of Impact: None=0 | Low=1 | Medium=2 | High=3 | Weighted Impact | Maximum Impact |
|---|---|---|---|---|---|---|---|
| Mental Strain | 7 | | | | x | 21 | 21 |
| Accident Risk | 7 | | | | x | 21 | 21 |
| Laboratory Safety | 7 | | | | x | 21 | 21 |
| Hazardous Material | 6 | | | | x | 18 | 18 |
| Monotony | 6 | | | | x | 18 | 18 |
| Vapors | 5 | | | | x | 15 | 15 |
| Cleanup | 5 | | | | x | 15 | 15 |
| Chemical Spills | 4 | | | | x | 12 | 12 |
| Heat | 3 | | x | | | 3 | 9 |
| Lack of Ventilation | 3 | | | x | | 6 | 9 |
| Dust/Dirt | 2 | | | x | | 4 | 6 |
| Muscular Strain | 2 | | | | x | 6 | 6 |
| Second-Shift Operation | 2 | x | | | | 0 | 6 |
| Heavy Safety Clothing | 1 | | | x | | 2 | 3 |
| Lack of Light | 1 | x | | | | 0 | 3 |
| **TOTAL** | | | | | | **162** | **183** |

Total Impact ------ < 61 -- Reject Automation (1)
> 122 -- Accept Automation (2)
61 < T.I. <122 -- Conditional Automation Acceptance (3)

T.I. = 160 Case (2) is applicable.

measurement. Before a procedure can be automated, a considerable amount of investigation is required. The procedure should be validated and carefully documented. Human-and chemically-induced variations should be fully understood in terms of how they relate to analytical precision and there should be an additional focus on how the method is performed by an individual - in many cases individual methods differ from the written method.

Planning the robotic system that will best serve the intended application or applications again requires a systematic approach. There may be many decisions that need to be made; even adjustments to a procedure may be necessary before a formal system can be assembled. In general, automating a procedure involves:

1. Setting a goal (e.g., determine the number of samples to be processed per x hours of operation time)

2. Determining the procedural and operational modules to be used

3. Estimating sample throughput

4. Laying out the laboratory benchtop

This approach is discussed in the section entitled, "Application Procedures in Solid Propellant Mixing Laboratory," as it relates to a propellant mixing laboratory.

Establishing a Project

Prior to automating a procedure, expectations for the system should be clearly established. Three such expectations that greatly affect both the procedure and the system are:

1. How many samples are to be processed per day?
2. How long is the robotic system expected to operate per day?
3. Where is human intervention required?

The answers to these questions will have significant impact on the system from the standpoint of the modules and stations used, the program developed to perform the procedure, and even the procedure itself.

If the number of samples and hours of operating time per day must be estimated, the current manual procedure is utilized to establish the baseline. Several possibilities may arise if the procedure is being performed by a number of people, therefore, it is important to consider:

1. The number of samples currently being processed per day [(samples per person) x (number of technicians processing samples)]
2. Time it takes one technician to process the samples
3. Total time it takes to process all samples performed in one day [(time it takes one technician) x (number of technicians processing samples)]

There are several factors that affect where human intervention is required during a sample preparation procedure, and they are often interrelated. To quickly cost-justify a system, human interaction with an automated sytem should be minimized and the system should operate more than eight hours per day. Human intervention affects how long the system can be run unattended. In a single-shift laboratory, a system requiring intervention more than one or two times a day cannot be reasonably run unattended on non-shift hours. Different approaches to automate a procedure may have to be considered. These approaches may require a change in instrumentation, process equipment, laboratory bench layout, or procedures as illustrated in Table 8.

One option that should be investigated is a change from a batch mode of operation, which is typical of the manual procedure, to a serial mode of operation. Table 9 lists the differences between the manual and serial modes of accomplishing various operations.

Identifying Automation Modules

Every automation system will include the robot and the system controller. The controller may be used to operate other laboratory work stations in the area. These laboratory work stations, which include the robot, will be used in varying degrees throughout the procedure. The laboratory work stations will perform specific lab-scale operations. Many lab stations depend on the robot to bring them samples and later to remove them; other stations function entirely independent of the robot.

Of particular concern are the robot-intensive operations. Robot-intensive operations typically have many actions associated with them and usually cannot be performed independently of the robot. Therefore, over-lapping or robot-intensive operations may not be possible. These issues become critical when robot speed is seen as affecting sample throughput.

The following list of laboratory unit operations briefly describe the modules that may be used to perform a specific task. In many cases the module can be used in more than one way and, depending on the module chosen, will determine how robot-intensive the operation is.

1. Weighing - Balance, balance transfer
2. Manipulation - Appropriate robot end effectors
3. Liquid Handling - Liquid dispensing station, syringe hand, remote nozzles
4. Conditioning - Power and event controller with shaker, vortexer, heating block
5. Measurement - Power and event controller, instrument interface, computer interface
6. Control - Controller, computer interface
7. Data Reduction - Computer interface
8. Documentation - Printer, computer interface

## TABLE 8

## RELATIONSHIP OF AUTOMATION FACTORS AND LABORATORY IMPACTS

| Factor | Impacts |
|---|---|
| Number of Samples | Size of the lab stations<br>Supply of reagents<br>Number of disposables<br>Size or number of waste receptacles |
| Size of Lab Stations | Amount of available bench-top space<br>Accessibility of lab work stations<br>Number of different work stations that can be used in a procedure |
| Instrumentation Interface | The robot may be able to directly introduce the prepared sample or human intervention may be required |
| Initial Setup | Regular replenishing of supplies by technicians |
| External Instrumentation | Samples must be transported to other instruments in locations other than the current work area for certain preparation steps and a particular number of available samples may be required available to make the job worthwhile |

## TABLE 9

## CONTRAST BETWEEN THE MANUAL AND SERIAL (AUTOMATED) MODES

Manual Procedures

- Samples are often processed in batches because people perform best when doing one task at a time.
- Equiment has been manufactured to be "human friendly."
- Lab stations typically have capacity for a large number of samples allowing the operator to do each step with a number of samples.
- Lab stations have low utilization, i.e., a mixer may only be used twice a day.

Serial Procedures

- Computers keep track of time and simultaneously control many tasks.
- Samples are processed one at a time and each will have the same history of preparation.
- Robotic lab stations have a much lower capacity in terms of number of samples and take up less space.

The robotic-intensive operations are:

- End effector changing
- Sample transport
- Disposables (attaching and detaching)
- Liquid handling
- Injection

The typical non-robotic intensive operations are:

- Sample conditioning steps
- Weighing
- Measurement
- Data reduction
- Documentation

Estimating Sample Throughput

The process for estimating sample throughput uses six major steps:

1. Outline the method in detail
2. Determine the robotic manipulation time for one sample
3. Determine the non-robotic times for each lab work station and analysis time for one sample
4. Calculate the sample output rate
5. Compute the required sample capacity of the lab stations
6. Compute the input/output sample station capacity.

Outline the Method in Detail

A sample preparation worksheet would be prepared and expanded to include a description of each step in the method. Major robotic manipulation steps such as end effector changes, sample handling, and dispensing operations should be added. In addition, actual parameters such as volumes, weights, apparatus interfaces and operational times should be included. The final step of the procedure should be the analytical techniques utilized and its parameters and time.

Determine Robotic Manipulation Time

Robotic manipulations are viewed as "transfers." A transfer is the movement of an object from one location to another on the laboratory benchtop and typically involves eight moves. Four moves are used to (1) go over the object, (2) down, (3) grasp it, and (4) pick it up; four additional moves are used to (1) go to a new location, (2) down, (3) release, and (4) back up. There are also manipulations referred to as "transfer equivalents." Transfer equivalents include such operations as a change of end effectors and pipette attachment and removal. Assuming each move made by the robot consumes approximately 3 seconds, a transfer which involves eight moves will take 24 seconds. For estimating purposes, allowing 30 sec per transfer is convenient. It also allows some time margin for other locations that will appear in an actual program. Using these time guidelines and transfer definitions, the procedure outlined on the application worksheet can be viewed as a series of transfers or transfer equivalents. A conservative estimate of the robotic time can be calculated by totaling the number of transfers and dividing this value by two to yield the robotic time in minutes.

Determine the Non-Robotic Time

Each laboratory station may have operations to be performed which do not involve the robot, but which take significant time. Common examples are conditioning steps such as heating, shaking, evaporating and centrifugation as well as analytical measurements. These steps may take many minutes or even hours, and be multiples of the robotic manipulation time. These times do not set a limit on the sample output rate unless the resource involved is extremely expensive and cannot be processed simultaneously for multiple samples. The time required for analysis does set a limit on the sample output rate since most instruments can only analyze one sample at a time.

Calculate the Sample Output Rate

The sample output rate is the number of samples that can be processed per hour or day. This rate will be determined by the robotic manipulation time or the analysis time, whichever is greater.

Computer Station Capacity

The sample capacity of the laboratory work stations used in the non-robotic operations can be determined from the sample output rate and the non-robotic time. The station capacity is the non-robotic time divided by the sample output rate. This value reflects the number of samples which that station must handle simultaneously. There will be stages during the procedure when the station will not be completely filled. This will occur during the initialization and termination of a particular part of the procedure.

Input/Output Sample Rack Capacity

Real productivity happens with unattended and extended operation of an automated system. This means that human intervention should be minimized. The system should be set up to handle as many samples as possible between known times of operator servicing. The racks or sample holders must therefore be large enough to accommodate all samples that will be processed in this time. Capacity is defined as the intended hours of operation times sample output rate.

Laying Out the Bench Top

After completing the previous analysis steps, the actual bench layout becomes a task of placing the robot, modules, and racks in efficient locations. This is an optimization activity which relates the robot's manipulator capability to the task at hand.

Application Procedures in Solid Propellant Mixing Laboratory

The previous section entitled, "Selection and Implementation of Laboratory Automation," outlined the general methodology needed to develop an automation system while the previous section enumerated the practical design factors to be considered. This section provides a detailed procedural analysis for various applications identified for the Solid Propellant Mixing Laboratory including ingredient blending and drying, oxidizers, fuels and hazardous materials weighing, propellant mixing, casting and cleanup. Figure 6 illustrated a detailed flow chart of operational steps in a propellant mixing laboratory. The steps presently are performed by laboratory operators during these manual intensive operations.

The detailed study of these operations and the required steps are utilized in determining sample throughput, outlining the automated method in detail, determining sample output rate, laboratory layout and its capacity.

The step-by-step manual procedures for various operations are reviewed in the following sections. These procedures are accompanied with flowcharts to enhance understanding the specific steps in operations. The specific applications are derived from the Branch Operating Instruction 80-1 dated October 28, 1983 and KLM's site visits discussed earlier.

Procedure For Propellant Oxidizer Drying

*Location:* Bldg. 8473, Cell No. 5

*Protective Clothing Requirements:*

1. Flame retardant coveralls or lab coat.
2. Safety glasses or goggles.
3. Conductive shoes or leg stats.

*Instructions* (see Figure 7):

1. Pick up the desired amount of oxidizers from the storage bunker. Use covered paper cartons for transporting the material.

2. Label the material with manufacturer's lot number, date and time. Place this label on the aluminum tray to be used for drying.

3. Pour the oxidizer into the aluminum (or conductive) tray and spread out evenly.

4. Set or check the oven temperature and maintain at the proper temperature specified for the oxidizer, but do not exceed the safe temperature for the material involved. Set the oven temperature no more than 10 degrees F above control temp.

5. Place the tray in the oven and use only ovens identified for oxidizers.

CELL NO. 5

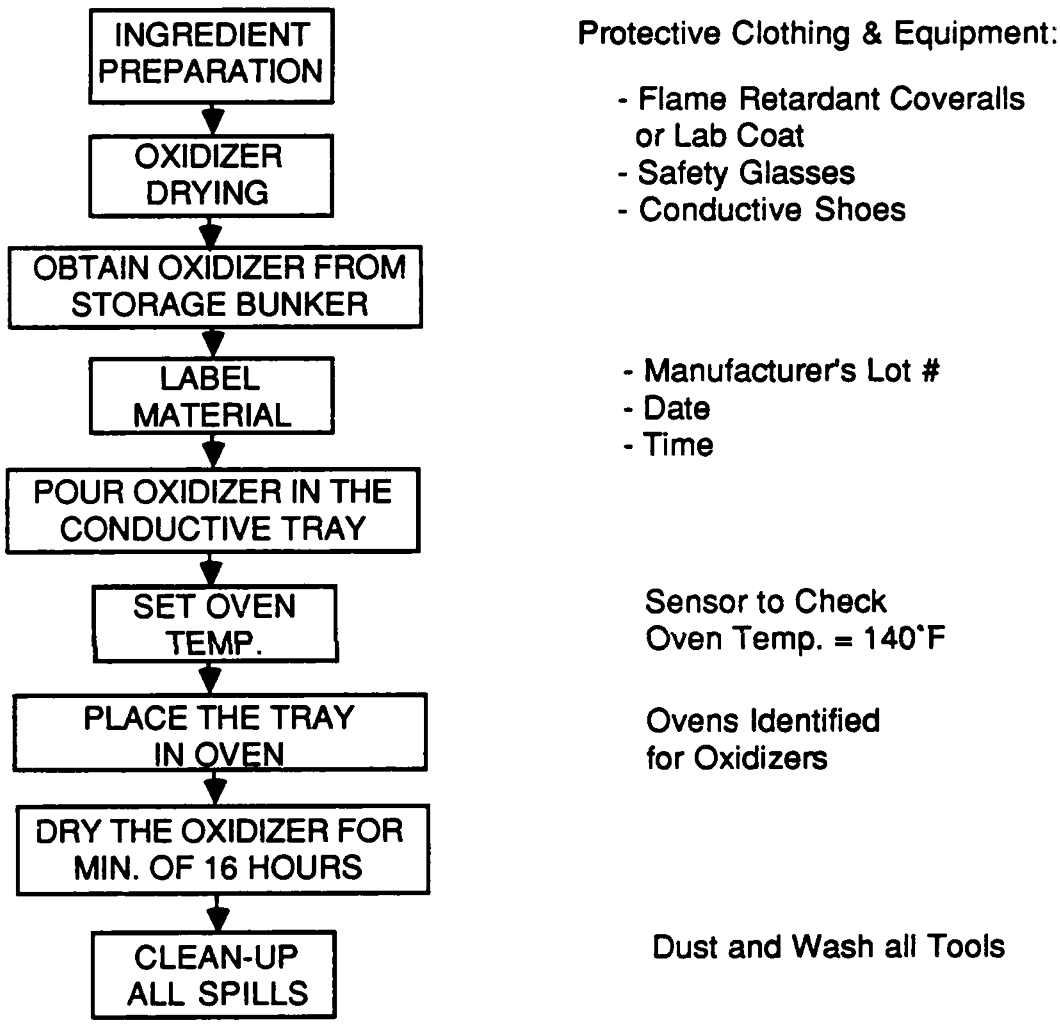



**FIGURE 7 OXIDIZER DRYING OPERATION**

6. Dry the oxidizer for a minimum of 16 hours before use.

7. The oven shall remain at 140 degrees F for ready use of the oxidizer.

8. Clean up all spills immediately. Use a dust broom first, then wash down with water.

Procedure For Propellant Oxidizer Blending

*Location:* Bldg. 8473, Cell No. 5

*Protective Clothing and Equipment Requirements:*

1. Flame retardant coveralls or lab coat.
2. Safety glasses or goggles.
3. Conductive shoes or leg stats.
4. Dust respirator.

*Instructions* (see Figure 8):

1. Check the interior of the blender for cleanliness.

2. Make sure the grounding cable is secure.

3. Charge the blender with material from oxidizer weighing. Blend 5 to 10 lbs. per batch or as required.

4. Fasten ports and check to see that gaskets are in place.

5. Check blender rotation path for clearance.

6. Check power cable, use 208 Vac-single phase only.

7. Check to see that the area is clear of personnel.

8. Start the motor from the control corridor and observe the blender operation from the viewing ports.

9. Blend for a minimum of 30 minutes.

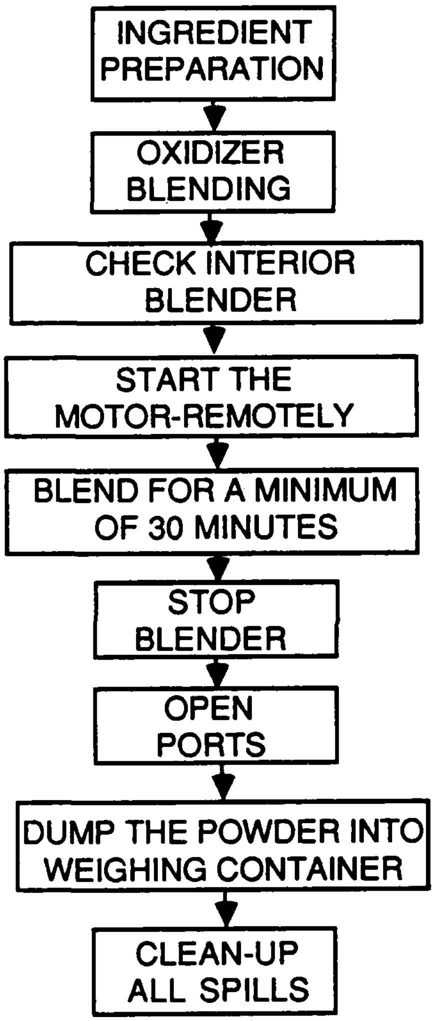
10. Do not enter the cell while the operation is in progress.

11. Stop, check results if required.

12. Open ports and carefully dump the powder into weighing container.

13. Thoroughly clean the cell and equipment at end of operation. Use a dust broom then follow with water.

CELL NO. 5




Protective Clothing & Equipment:

- Flame Retardant Coveralls or Lab Coat
- Safety Glasses
- Conductive Shoes
- Dust Respirator

Sensor:

- Check Ground Cable is Secure
- Check Gaskets to be in Place
- Check Blender Rotation Path for Clearance
- Check Power Cable, 208 VAC Single Phase

Dust and Wash all Tools

**FIGURE 8** **OXIDIZER BLENDING OPERATION**

Procedure for Propellant Oxidizer Weighing

*Location:* Cell No. 5

*Protective Clothing and Equipment Requirements:*

1. Flame Retardant coveralls or lab coat.
2. Safety glasses or goggles.
3. Conductive safety shoes or leg stats.

*Instructions* (see Figure 9):

1. Oxidizer weighing will be conducted in Cell 5 only.
2. Insure fuel and other combustables are removed from Cell 5.
3. Turn on the hood exhaust fan.
4. Obtain the material from an oven.
5. Check the ground on the balance.
6. Unlock the balance and turn on light source.
7. Weigh the amount specified on the Solid Propellant Processing Worksheet into the designated container.
8. Return excess to storage.
9. Clean up all spillage with a brush and turn off the hood.
10. Lock the balance and turn off the light source.

Procedure for Propellant Fuel Weighing

*Location:* Cell No. 7

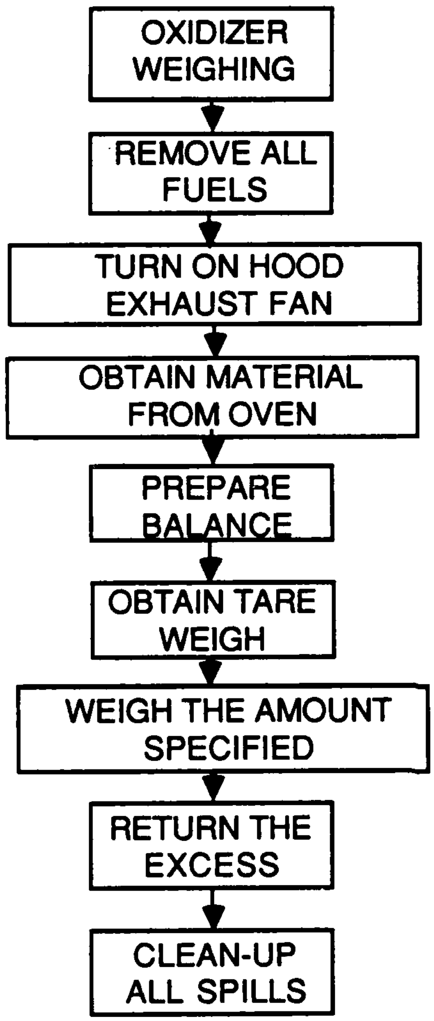
*Protective Clothing and Equipment Requirements:*

1. Flame retardant coveralls or lab coat.
2. Safety glasses or goggles.
3. Conductive safety shoes or leg stats.

*Instructions* (see Figure 10):

1. Fuel will be weighed in Cell 7 only.
2. Check the grounding cable on the balance.

CELL NO. 5




Protective Clothing & Equipment:

- Flame Retardant Coveralls or Lab Coat
- Safety Glasses
- Conductive Shoes

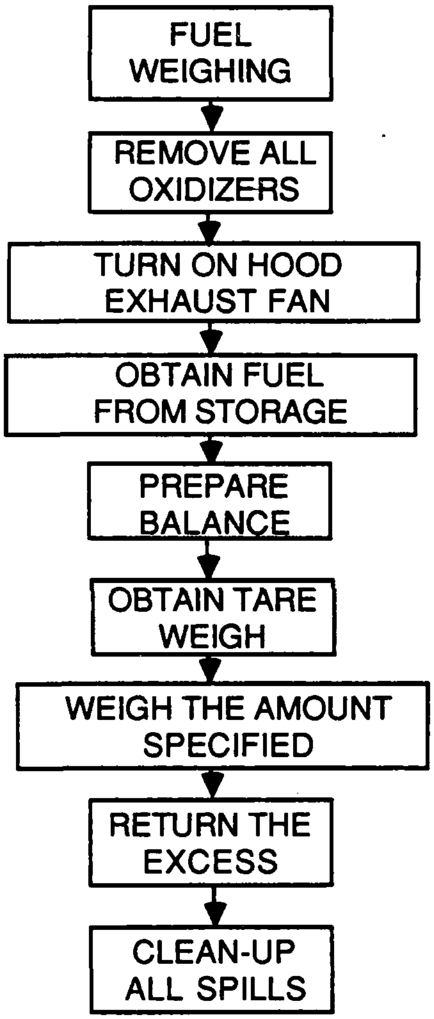
Sensor:

- Check Ground Cable is on Balance
- Turn on the Light
- Unlock Balance

- Brush any Spillage
- Lock Balance

**FIGURE 9** __OXIDIZER WEIGHING OPERATION__

CELL NO. 7




Protective Clothing & Equipment:

- Flame Retardant Coveralls or Lab Coat
- Safety Glasses
- Conductive Shoes

Sensor:

- Check Ground Cable is on Balance
- Turn on the Light
- Unlock Balance

- Brush any Spillage
- Lock Balance

**FIGURE 10 <u>FUEL WEIGHING OPERATION</u>**

3. Unlock balance and turn light source on.

4. Obtain fuel to be weighed from storage.

5. Weigh the amount specified on the Solid Propellant Processing Worksheet into the designated containers.

6. Return the excess to storage.

7. Clean up powder spillage with a brush; liquid spillage with the appropriate solvent.

8. Lock balance and turn off light source at the end of each day.

Procedure for Weighing Hazardous Liquids

*Location:* Cell No. 7

*Protective Clothing and Equipment Requirements:*

1. Flame retardant coveralls or lab coat.
2. Safety glasses or goggles or face shield and gloves.
3. Conductive shoes or leg stats.
4. Breathing equipment as required.

*Instructions* (see Figure 11):

1. Hazardous liquids will be weighed in Cell 7 only.

2. Insure all metal powders are removed from the immediate area.

3. Check the balance for a proper ground connection.

4. Obtain hazardous liquid to be weighed from storage.

5. Unlock balance and turn on light source.

6. Weigh the amount specified on the solid propellant processing worksheet into the designated container.

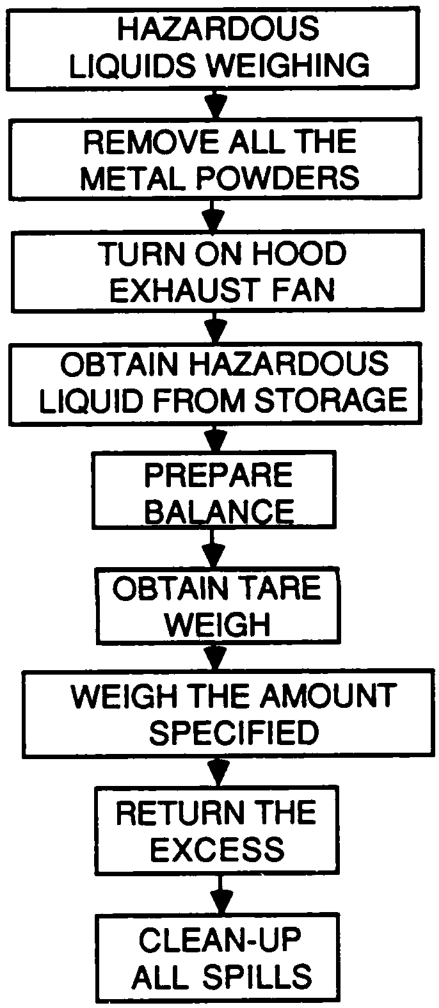
7. Be careful not to shake or drop containers of high energy binders.

8. Use plastic or glass (without ground glass stoppers) containers and non-metallic spatulas.

9. Return excess to storage.

10. Clean up liquid spillage with the appropriate solvent. The development engineer will supply the type of solvent to use for the hazardous liquid involved.

CELL NO. 7




Protective Clothing & Equipment:

- Flame Retardant Coveralls or Lab Coat
- Safety Glasses
- Conductive Shoes
- Breathing Equipment

Sensor

- Check Ground Cable is on Balance
- Unlock Balance

- Use Plastic or Glass Containers - Non Metalic

- Use Appropriate Solvent to Clean Any Liquid Spillage

**FIGURE 11** **<u>WEIGHING OPERATION</u>**

11. Notify the development engineer of any large spills.

12. Lock balance and turn off light source at the end of each day.

Procedure for Mixing and Casting Instructions

*Location:*

1. Cell No. 2, one gallon and two gallon mixers.
2. Cell No. 3, one pint and quarter pint mixers.
3. Cell No. 4, one gallon and one pint mixers.

*Protective Clothing and Equipment Requirements:*

1. Flame retardant coveralls or lab coat.
2. Conductive shoes or leg stats.
3. Eye protection (goggles or glasses).
4. Rubber gloves.
5. Breathing air mask (clean up) as required.

*Qualifications:*

1. No person may operate or be allowed to operate a mixer unless qualifed to do so, or be under the direct supervision of a qualifed person for training purposes.

2. There will be no exceptions to No. 1 above.

3. Qualification to operate the mixers must be demonstrated to engineer and foreman by:

   a. Demonstrating knowledge of hazardous materials and handling.
   b. Demonstrating proficiency in operation of the mixer and use of casting equipment in a safe manner.
   c. Demonstrating understanding of the solid propellant worksheet and accurate weighing of materials.
   d. Demonstrating knowledge of emergency instructions.
   e. Acknowledgement of the above by a signed and posted machinery use authorization list.

*Pre-Mix Instructions* (see Figure 12):

1. Prepare motor cases as required.

2. Check mixer:

   a. Insure that the mixer runs properly. Listen for unusual noises.
   b. Check the dump valve action.

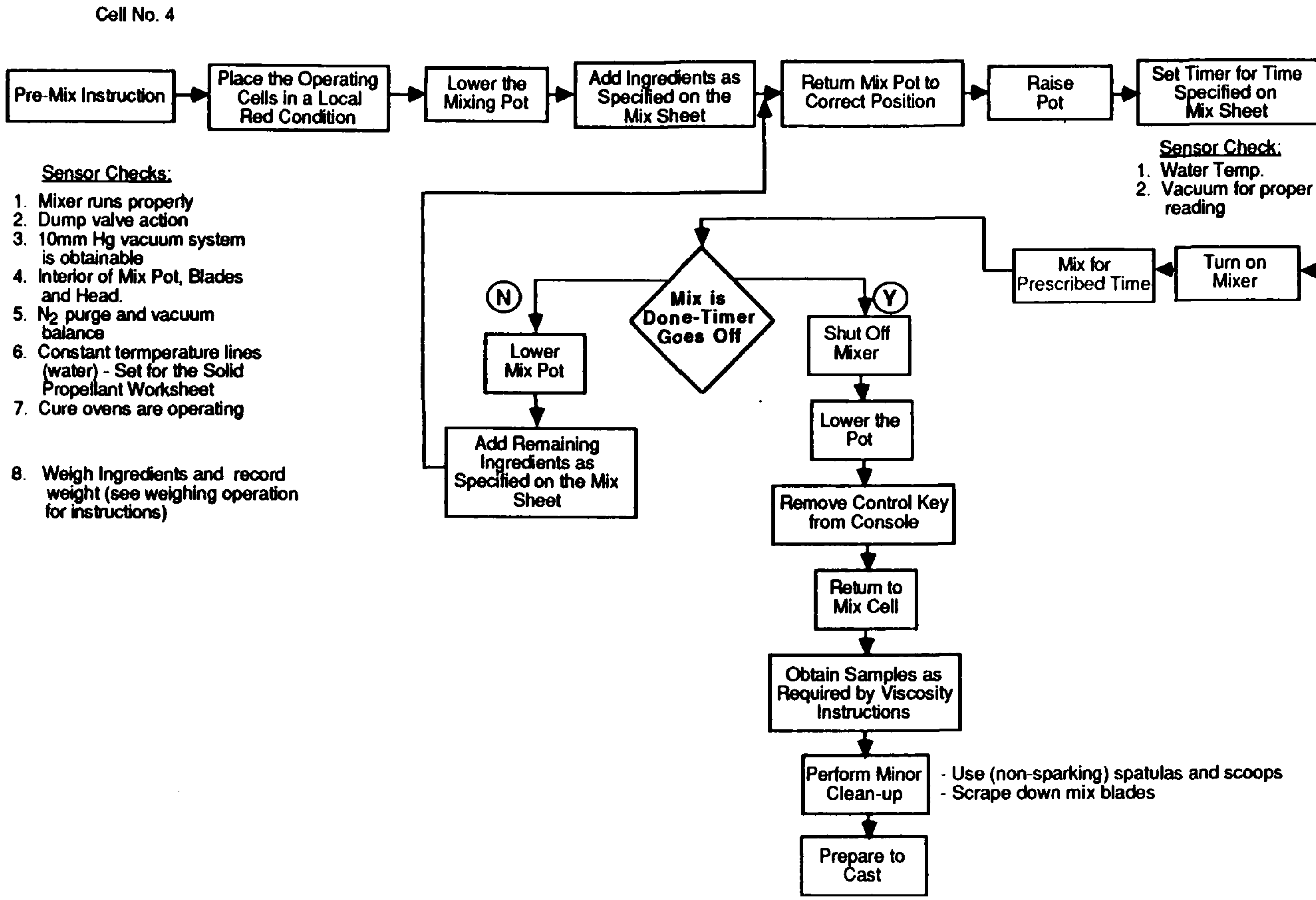



FIGURE 12 MIXING OPERATION

c. Check the vacuum system to insure that a pressure of 10 mm Mercury can be obtained.
d. Check interior of mixing pot, blades and head for cleanliness.
e. Check ground straps with Ohmmeter for a resistance of 0.005-1.0 Ohm.

3. Check nitrogen ($N_2$) purge and vacuum balance.

4. Attach constant temperature lines (for the water lines) and set to the temperature specified on the solid propellant worksheet.

5. Insure that outside cell door is unlatched and not blocked (Cell 3 only).

6. Insure that the cure ovens are operating.

7. Weigh ingredients and record weights on the solid propellant worksheet.

8. Place the operating cells and the solids building in a local red condition.

9. No less than two qualified people must be present in solids building during mixing operations.

10. Place "No Admittance" signs across the rear of the active cells.

11. No personnel are allowed in the mixing cell while the mixer is running.

12. Set up casting equipment as directed by the solid propellant worksheet.

    a. Propellant molds must be scrubbed with solvent and dried before use to remove old propellant.
    b. Clean molds must be sprayed with mold release and heated in a curing oven before use.

*Mix Instructions* (See Figure 12):

1. Mix the propellant according to the processing steps detailed on the solid propellant worksheet.

    a. Before adding any ingredients, shut down mixer and remove vacuum as required. Remove key from console.

2. Use (non-sparking) spatulas and scoops when handling HMX or high energy (Class 1.1) propellant.

3. Cast propellant samples as indicated on the Solid Propellant Processing Worksheet.

    a. Lower the mixing pot and add ingredients as specified on the mix sheet.
    b. Return the mixing pot to correct position for raising, and return to remote control panel. Raise pot.

c. Set timer for time specified on mix sheet.
d. Check water temperature and vacuum for proper reading as required.
e. Turn on mixer, and mix for prescribed time as required on mix sheet.
f. When timer goes off, shut off mixer, lower the pot, remove control key from console, and return to mix cell.
g. Obtain samples as required by viscosity instructions.
h. Scrape down mix blades to remove all propellant.
i. Connect flush bottom valve to the propellant flow valve on the casting bell (see Figure 13).
j. Connect constant temperature hoses to the casting bell as required. Connect vacuum line and vacuum indicator to casting bell.
k. Hook $N_2$ line to vibrator if required.
l. Hand pressure follower into mix pot until the follower is fully seated, then close valve.
m. Check casting fixture pressure gauge for zero PSI.
n. Place pressure lid on the mix pot, and then secure with clamp.
o. Evacuate casting chamber and insure casting flow valve is in position. Then connect $N_2$ line to pressure lid.
p. Return to control panel and pressurize mix pot.
q. Open flush bottom valve, and return to mix cell to cast propellant.
r. Cast propellant as specified on mix sheet.
s. When through casting, remove vacuum from casting bell. Out propellant and bring to Cell 8 for mandrel insertion.
t. Disassemble casting equipment in reverse instruction.

*Clean Up Instructions* (see Figure 13):

1. Use spatulas and paper towels to clean and wipe the mixer pot, blades and head. Use an appropriate solvent to aid in cleaning if needed.

2. The casting valve and associated casting equipment must be scrubbed clean of propellant using the appropriate solvent indicated on the solid propellant worksheet.

3. Return the cleaned tools and casting equipment to the proper storage locations.

4. Insure that the mixer head and blow out ports are clean and free from accumulated propellant.

5. Insure that all metal threads are scrubbed free (with solvent) of propellant.

<u>Procedure for Propellant Curing</u>

*Location:* Cell Nos. 6 and 10

*Protective Clothing and Equipment Requirements:*

1. Flame retardant coveralls or lab coat.
2. Safety glasses or goggles.

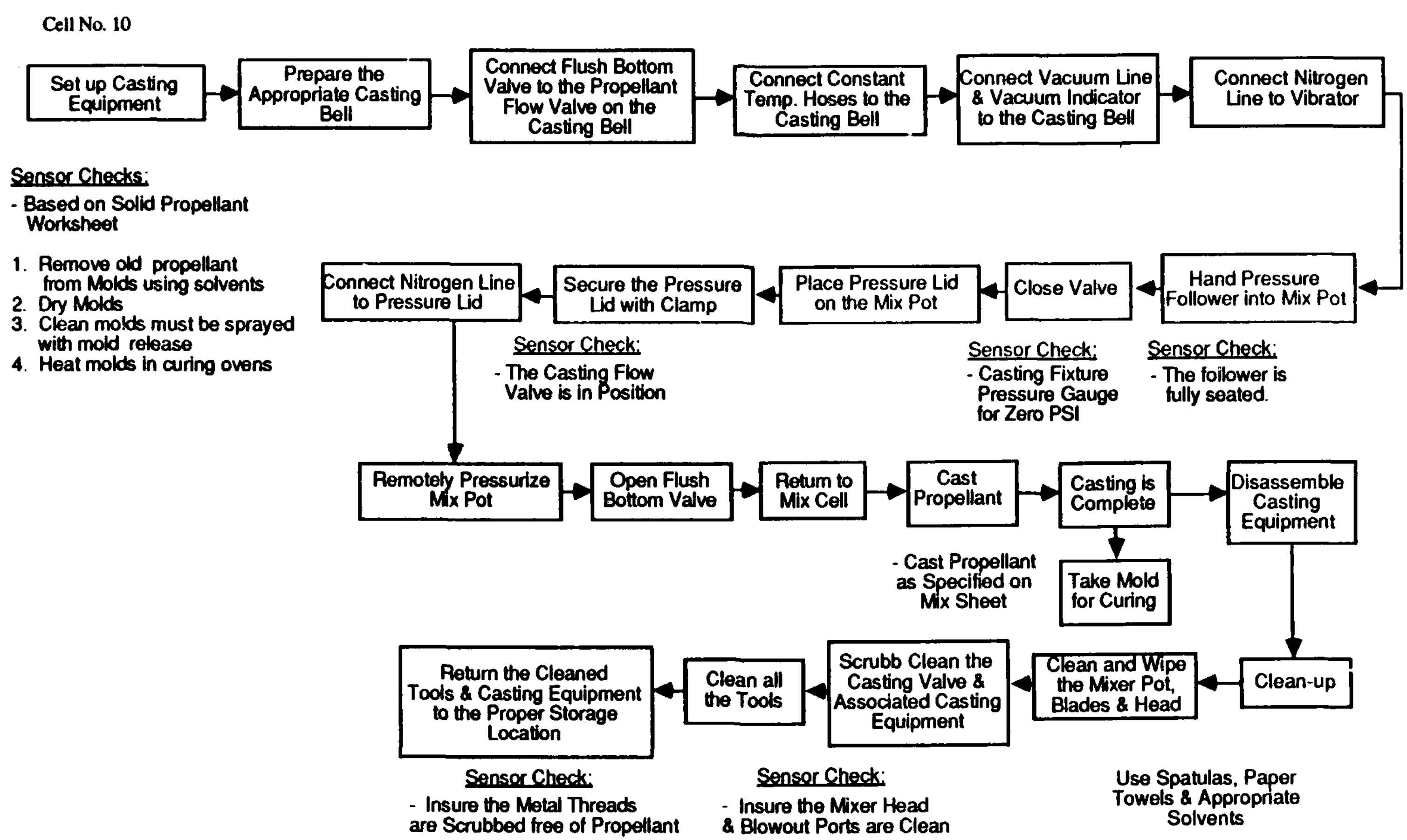



FIGURE 13 CASTING OPERATION

3. Conductive shoes or leg stats.
4. Gloves.

*Instructions* (see Figure 14):

1. Turn on the oven and set to the temperature on the solid propellant processing sheet.

2. Set oven temperature to no more than 10 degrees F above curing temperature.

3. Cure the required time or until propellant has cured enough to disassemble the mold.

4. After cure, remove the motors and allow them to cool before handling.

5. If the oven is to remain empty, turn it off.

6. Fixture disassembly will be accomplished in Cell No. 11.

7. If an oven-temperature shut off occurs in the oven, turn switch off and notify the development engineer.

"Islands of Automation" in a Solid Propellant Mixing Laboratory

To justify the capital outlay and minimize risk for robotic/automation implementation, the idea of "Islands of Automation" strategy will be utilized. This strategy will allow only one process (ingredients weighing, pre-batching and addition, propellant mixing, casting and clean-up) at a time to be fully implemented and allows the results to be monitored and reflected in the other islands. The key point is to consider necessary tools (hardware and software) required for successful integration between the automated process and the next operation. Table 10 presents potential robotic project applications and the state-of-the-art technology required for development and project implementation. This table is the result of a detailed study of project applications identified earlier and the available automated system capabilities.

Various solid propellant mixing applications including ingredient weighing, propellant mixing, casting and clean-up are potential processes to be implemented as "Islands of Automation." This section will explore these potential "Islands of Automation" and discuss the required instrumentation and hardware for each of the island layouts.

Each application is organized into five parts: (1) Process Description, (2) Process Consideration, (3) Basic Elements, (4) Justifications and (5) Current Technological Constraints. The first two parts deal with the generic process, and the next three parts deal with robotics/automation implications for the process.

*Process Description:* This section briefly describes the fundamental steps required for the specific laboratory process. The steps are presented in sequential order reflecting laboratory practice.

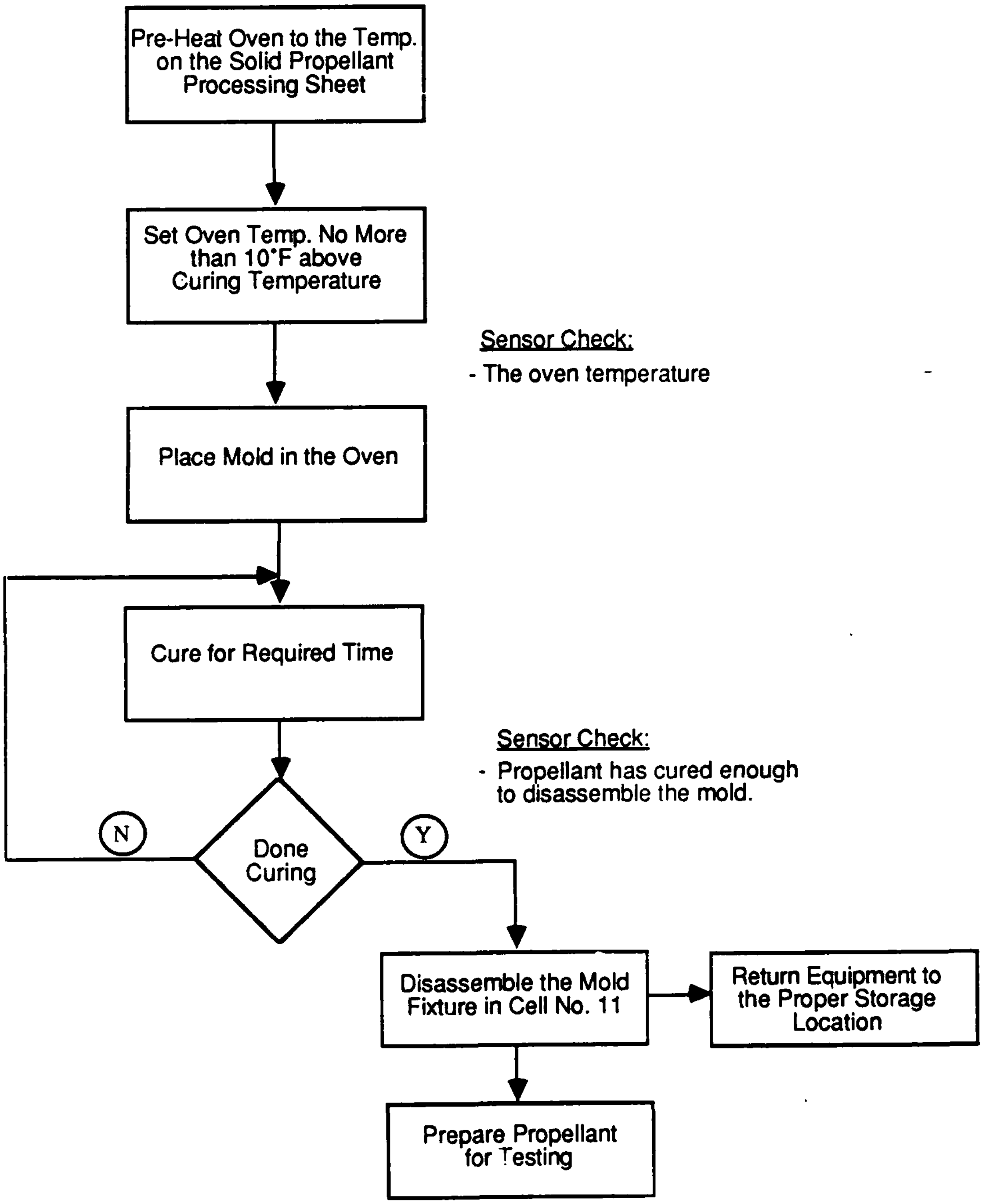



**FIGURE 14 CURING OPERATION**

## TABLE 10. TASK ALLOCATION MATRIX

| AUTOMATED SYSTEM CAPABILITY | PROJECT APPLICATIONS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Ingredient Blending | Ingredient Drying | Ingredient Weighing | Ingredient Mixing | Ingredient Addition | Viscosity Reading | Propellant Casting | Cleanup | Equipment Storage |
| Manipulator | X | X | X | X | X | X | | | X |
| Automtic Guided Vehicle | | | X | X | X | X | X | | X |
| Sensory Analysis | X | X | X | X | X | X | X | X | X |
| Data Handling | | | X | X | X | X | | | |
| Communications | X | X | X | X | X | X | X | X | X |
| Special Tooling | | | X | X | X | X | X | X | |
| Video Inspection | | | | X | X | | X | X | |
| Safety Alarms | | | X | X | X | | X | X | |

*Process Considerations:* This section points out aspects of the process that are either crucial to satisfactory performance of the task or that make performance of the task particularly difficult.

*Basic Elements:* This section describes the generic robotic/automation components that will be utilized in this particular application.

*Justifications:* This section points out the aspects of the application that tend to favor a robotic/automated system.

*Current Technological Constraints:* This section identifies, for each application, some of the limitations in current robotics/automation technology that might prevent penetration by robotics into the application.

Ingredient (Oxidizer, fuels, bonding and cure agents) Weighing Islands

*Process Description:* The fundamental steps required for the specific laboratory processes including weighing of oxidizers, fuels and hazardous materials were described in detail in earlier sections. In the case of weighing of bonding and cure agents, the processes are very similar to the oxidizers and fuels weighing except that a liquid dispensing equipment will be utilized.

*Process Considerations:* The only crucial aspect of these processes would be in weighing of certain hazardous materials and providing a static-free environment for handling of oxidizers and fuels. The required provisions including spark-free environment, explosion proof devices and static control equipment will all be taken into consideration.

Accurately calibrated liquid and solid dispensing equipments will be utilized to provide satisfactory performance of the task.

*Basic Elements:* The weighing "Islands" will include automatic solid and liquid dispensing systems, balances, robotic arms for sample manipulation, bar code readers for sample identification, sensory systems, power protection and safety equipment, linear track components, controllers, Laboratory Information Management Systems (LIMS) interface and Automatic Guided Vehicle (AGV) for sample transfer between Islands. Figures 15 through 17 illustrate conceptual "Islands of Automation" for ingredient weighing in Solid Propellant Mixing Laboratory.

*Justifications:* Based on the earlier discussion presented in the section entitled, "Identify Automation Application Candidates," and the analysis outlined in the previous section entitled, "Solid Propellant Mixing Laboratory Evaluation," the automation of the oxidizers, fuels, bonding and cure agents are justified. Due to undesirable operating conditions and handling of hazardous materials, the automation of such "Islands" are highly recommended. The automation will reduce personnel exposure to hazardous materials and fumes, provide cost and labor savings and reduce ingredient waste.

*Current Technological Constraints:* The necessary technology in various fields including manipulation, AGVS, sensory systems, data handling, communications,

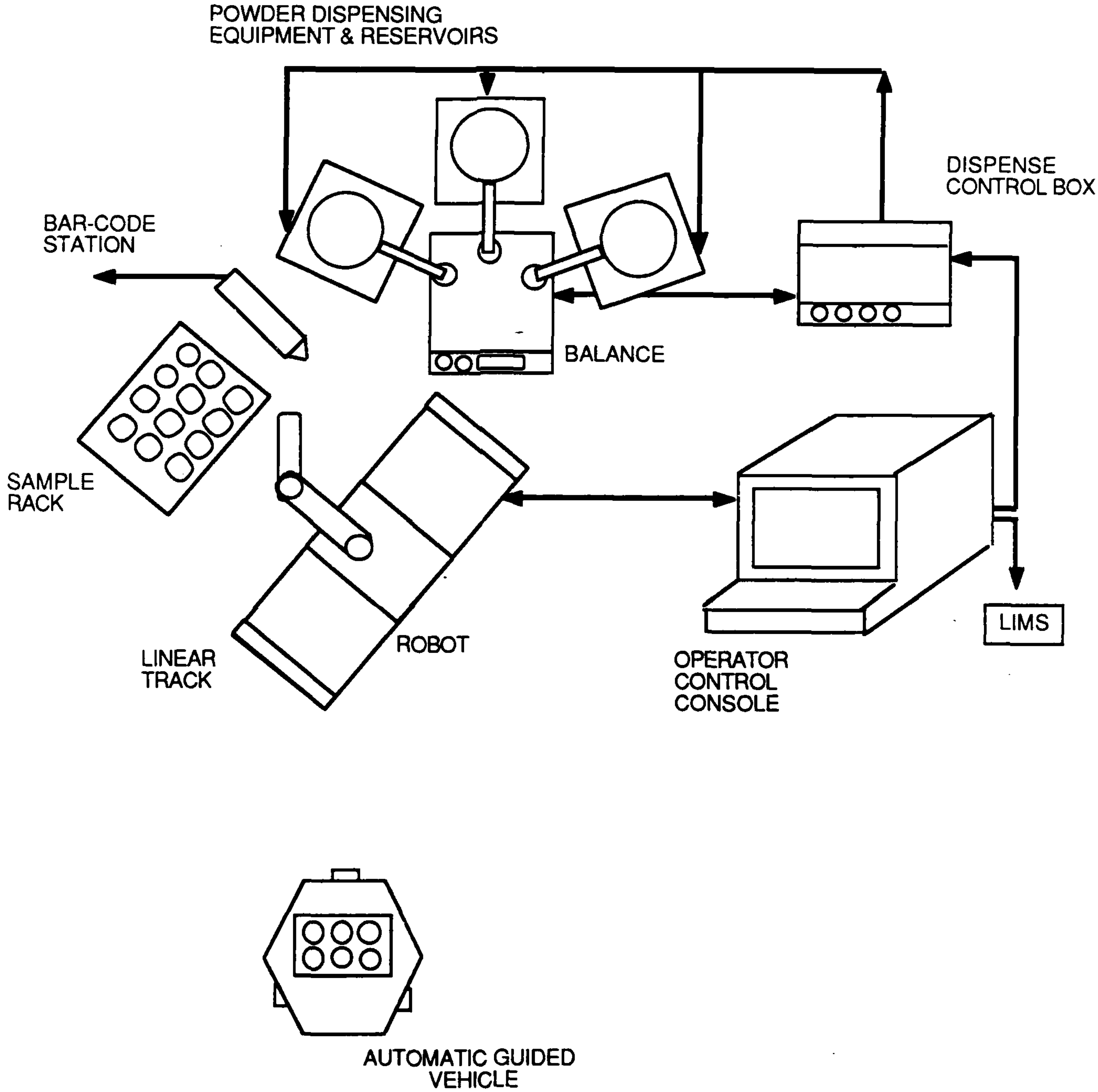



**FIGURE 15 OXIDIZER WEIGHING ISLAND CONCEPTUAL LAYOUT**

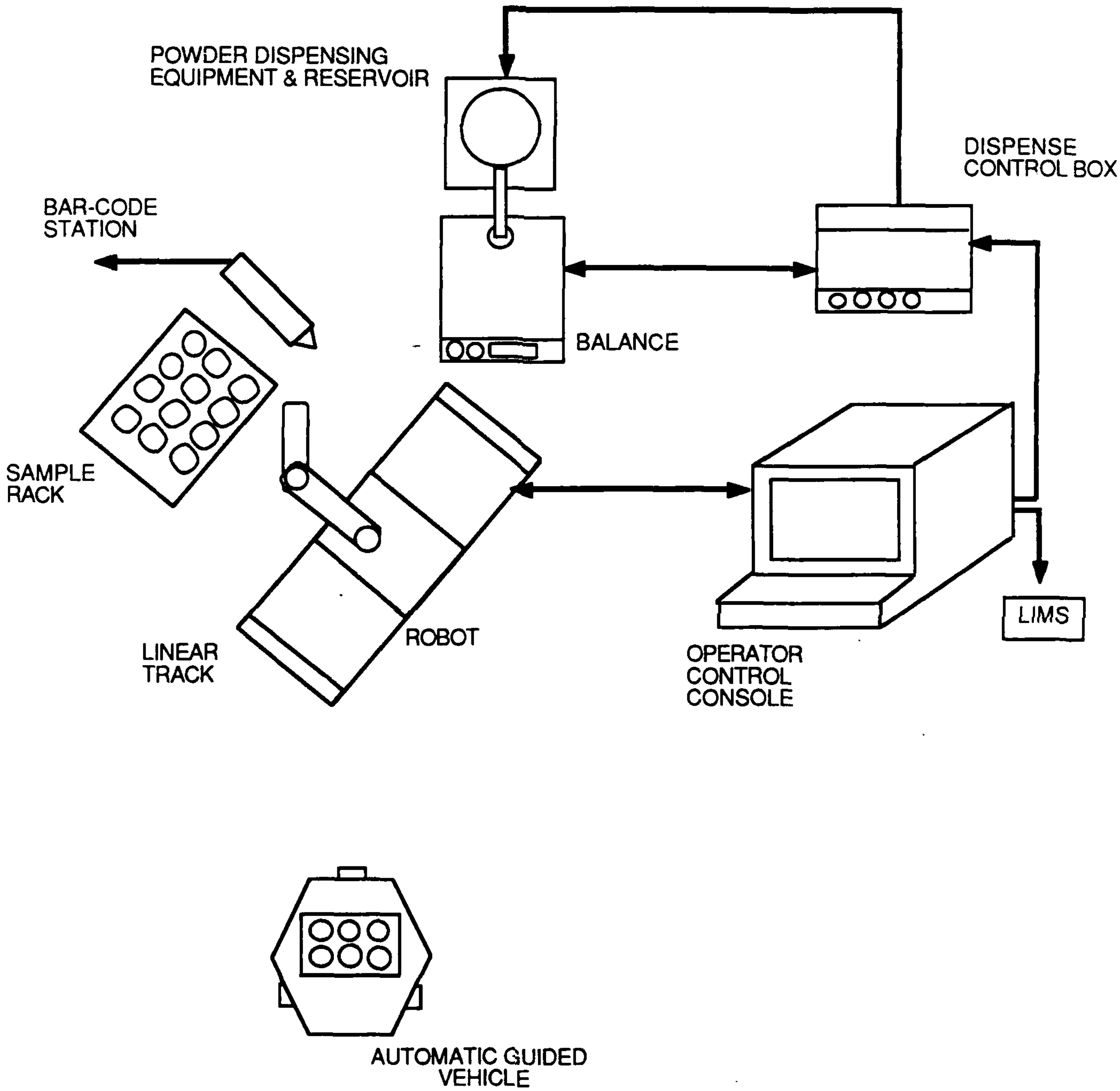



**FIGURE 16 FUEL WEIGHING ISLAND CONCEPTUAL LAYOUT**

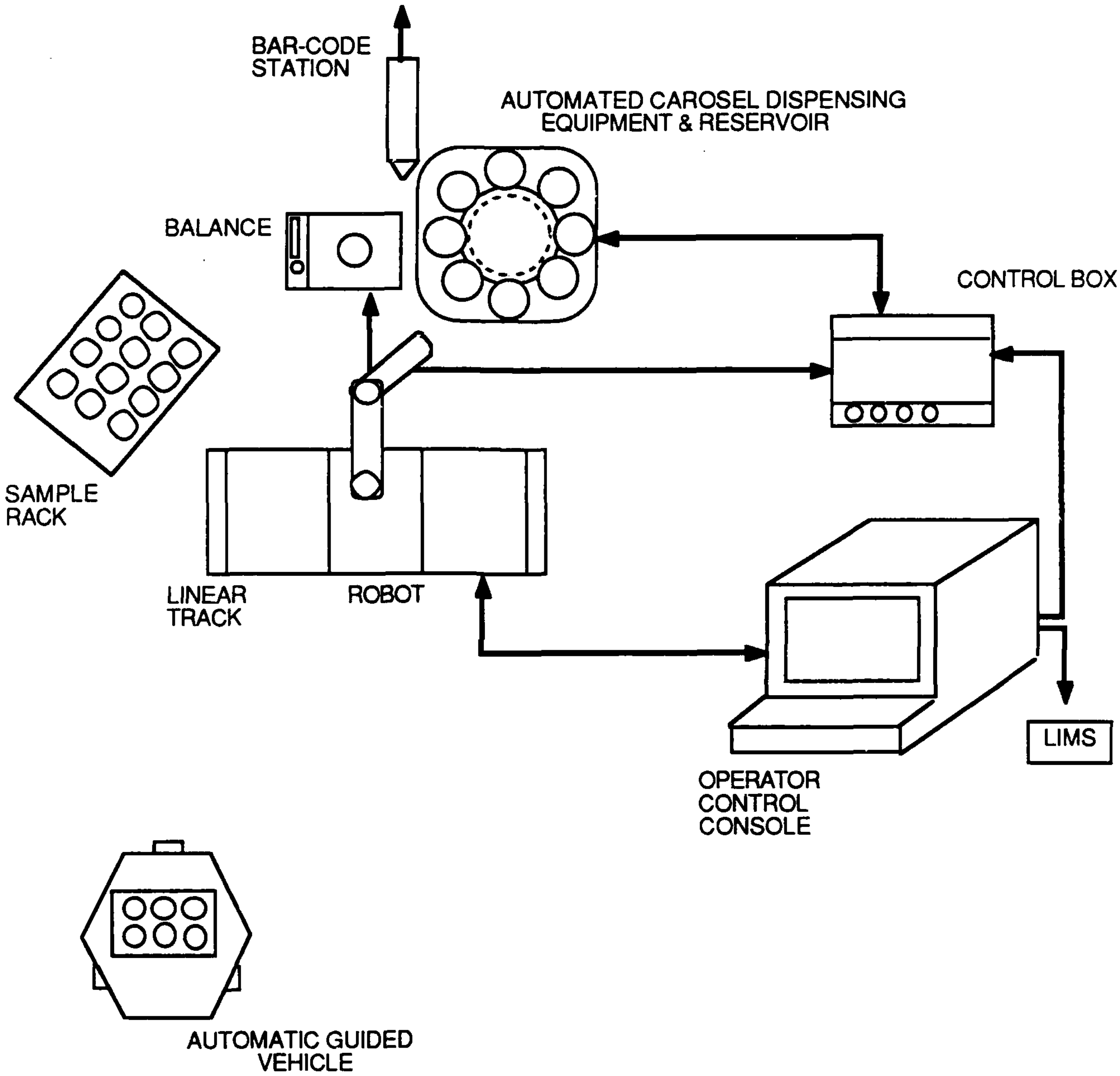



**FIGURE 17** **LIQUIDS (BONDING & CURE AGENTS) WEIGHING ISLAND CONCEPTUAL LAYOUT**

special tooling, video inspection and safety sytems are all available and exceed the requirements of such "Islands". All the devices are off-the-shelf items, however, a complete integrated "Island" does not exist. KLM will perform the engineering integration between the devices and provide the software to deliver a turnkey system.

Ingredient Addition and Propellant Mixing Island

*Process Description:* The fundamental steps required for the specific laboratory processes including ingredient addition and propellant mixing were described earlier in detail in the section entitled, "Procedure for Mixing and Casting Instructions." The description and the flowchart (Figure 12) provide a step-by-step procedure of the ingredient addition and mixing processes per instructions provided on the laboratory's Mix Sheet.

*Process Considerations:* The crucial aspect of this application is involved with over-heating of the mix batch, resulting in an explosion and fire. Mixing of very high viscous ingredients will be performed in several steps to monitor temperature of the batch on a regular basis. Appropriate sensory addition and modifications to the mixer will be required to accomodate for such problems.

Extensive software development will be performed to accommodate ingredient addition via robot manipulator. This will alleviate the labor intensive and risky task of ingredient addition of many steps throughout the mixing operation.

*Basic Elements*: The major components of this "Island" would be the mixer with extensive modifications to the mixing bowl, bowl hoist and addition of limit switches and torque protection sensors. Other necessary additions are linear slides and air cylinders to robotize the mixer. To implement ingredient addition, appropriate robotic manipulators mounted on linear tracks will be utilized.

Other devices such as sensory equipment and power protection devices will be utilized for safety purposes. Figure 18 illustrates the conceptual design of the "Mixing Islands ."

*Justifications:* Based on discussions presented in the previous section entitled, "Identify Automation Application Candidates," and calculated results given in the section entitled, "Justification Guidelines," the automation of ingredient addition and propellant mixing is justified. Due to a high level of impact to laboratory personnel pertaining to environmental conditions including mental strain, accident risk, laboratory safety and labor intensive operations, the applications tend to favor a robotic/automated system. In addition to reducing exposure of laboratory personnel to hazardous situations and carcinogens produced at the time of mixing, cost savings will be achieved by eliminating the need for protective clothing and equipment during mixing.

*Current Technological Constraints:* All devices utilized to automate this application are off-the-shelf items, and the technology to perform such project is available. However, the system integration and software development must be performed by system integrator to provide a turnkey system.

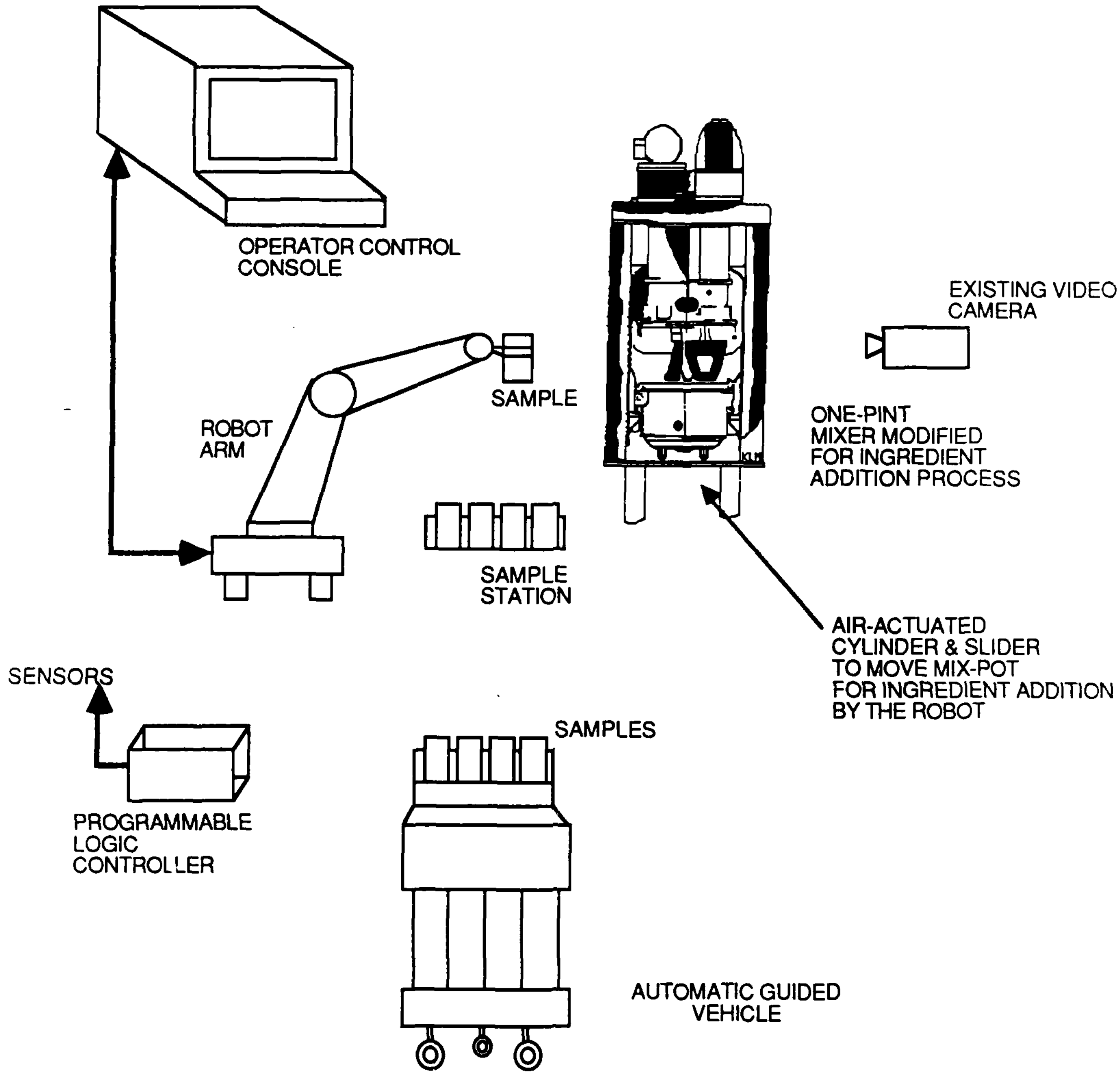



**FIGURE 18** **PROPELLANT MIXING ISLAND CONCEPTUAL LAYOUT**

Propellant Casting Island

*Process Description:* The step-by-step procedure pertaining to casting instructions was provided in detail in the previous section entitled, "Procedure for Mixing and Casting Instructions." Figure 13 presents a flowchart of casting operations describing the laborious application and the required sensory checks.

*Process Considerations:* The main consideration pertaining to this application is the present cumbersome design of the casting equipment including several valves, casting bell, pressure fall over, clamps, etc. The present equipment makes the performance of the task and subsequent cleanup particularly difficult. A better design will provide an easier and less tedious casting operation.

*Basic Elements:* The major component for this system is the redesigned new molds with self-contained vacuum assist suitable for casting process. This device will require some research and development which will be implemented in the Phase II work plan. The new system will replace or modify the existing casting equipment. It will utilize devices including solenoid valves, pumps, and actuators. Sensory devices, power protection and safety equipment will also be implemented. Figure 19 illustrates the conceptual "Casting Island".

*Justifications:* Operating conditions including mental strain, accident risk, safety, hazardous materials, carcinogen vapors, laborious and monotonous task, muscular strain provide satisfactory reasons to automate this process. The calculations provided in the previous section entitled, "Solid Propellant Mixing Laboratory Evaluation," emphasized the automation acceptance.

*Current Technological Constraints:* There are not any technological constraints for performing such an automation task. All the devices are off-the-shelf items; however, to design a successful and trouble-free casting system, certain amounts of research and development are required. The process of designing and engineering of such a system will be part of the Phase II work plan based on its importance and budget allocations.

Clean-up Island

*Process Description:* The step-by-step procedure pertaining to clean-up instructions was provided in detail earlier. The present clean-up operations consists of manual wiping of mixer pot, blades and the head. In addition, all the casting equipment and the tools need to be cleaned either by wiping or using appropriate solvents. Finally, all tools need to be stored at specified storage locations.

*Process Considerations:* The present cumbersome casting equipment introduces a degree of tediousness to the clean-up process. The modified or redesigned casting system will incorporate a washing and cleaning system with the appropriate solvents to thoroughly clean the equipment. The thorough clean-up of the mixing pot and blades in addition to the casting equipment is necessary to prevent any cross contamination of the batches.

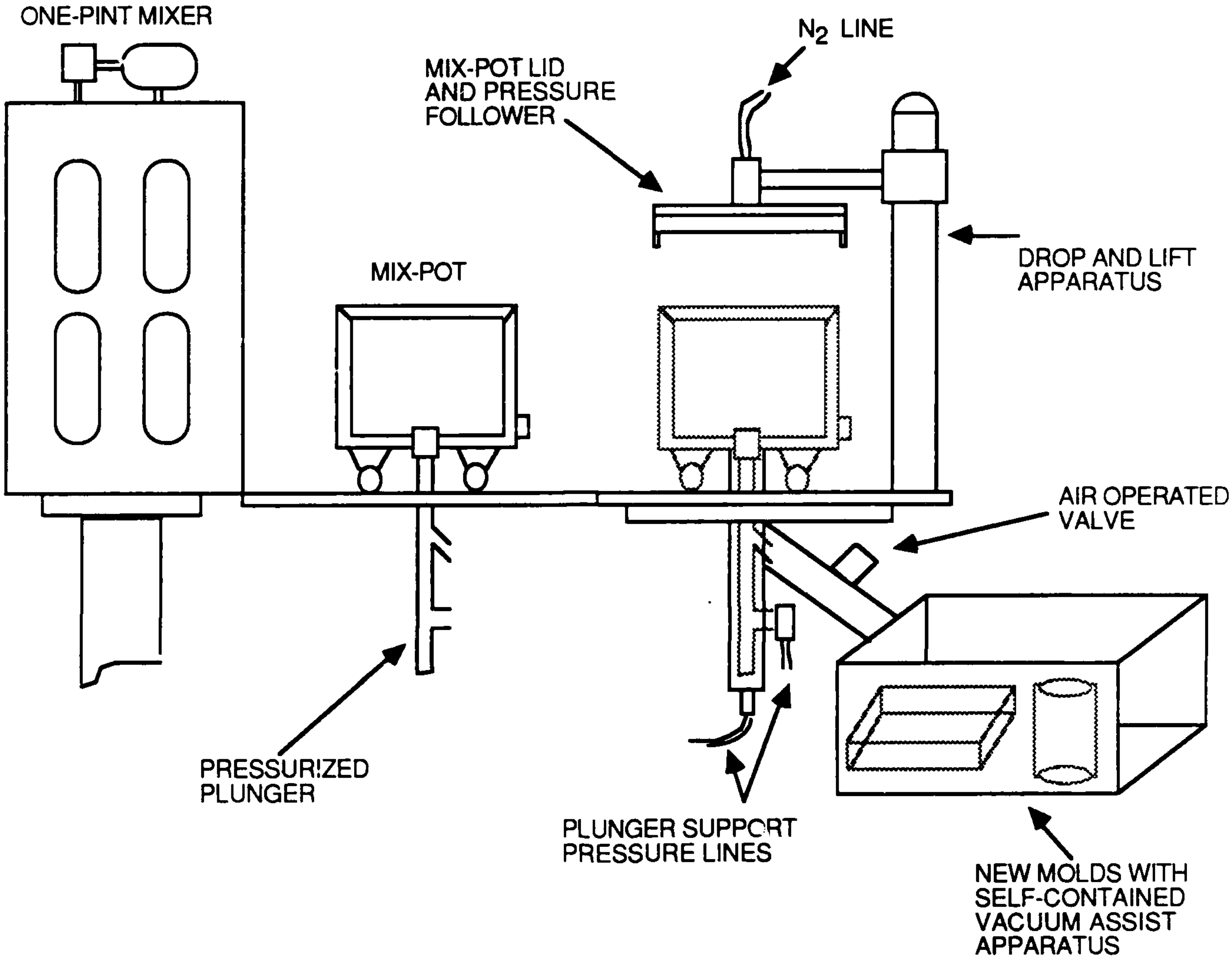



**FIGURE 19 PROPELLANT CASTING ISLAND CONCEPTUAL LAYOUT**

*Basic Elements:* The major component of this "Island" will be an automated cleaning interface which will include solenoid valves, pumps, actuators and controls. This will interface with the new/modified casting equipment to provide a complete flush through system. A vision system may be utilized to assure thorough clean-up of the blades. An ultrasonic rod may be utilized to provide necessary agitation for clean-up if experience indicates that a solvent and mixer blade operation is not adequate for clean-up. A solvent recovery system will be used with the system to minimize solvent disposal costs. Other necessary equipment are actuators, valves, sensors, programmable controllers and associated vacuum and solvent lines. Figure 20 illustrates the conceptual "Clean-up Island".

*Justifications:* Operating conditions including mental strain, accident risk, safety, hazardous materials, solvents, carcinogenic vapors, laborious and monotonous task, and muscular strain are satisfactory reasons to automate this process. The analyses provided earlier in the section entitled, "Solid Propellant Mixing Laboratory Evaluation," emphasized the benefits of automation. In addition, reduction in waste and protective clothing and equipment will provide cost savings.

*Current Technological Constraints:* There are not any technological constraints for performing such an automation task. All the devices are off-the-shelf items, however, to design a successful and trouble-free automated cleaning interface with a flush-through system, a certain amount of research and development is required. The process of designing and engineering of such a system will be part of the Phase II work plan based on its importance and budget allocations.

System Integration

Figure 21 illustrates the importance of the control function to interface the various described "Islands". The system integration required to automate each solid propellant mixing application will be developed by the system integrator. An automated set of procedures for the automation processes will be derived from earlier described processes to accommodate the robotic manipulator, automated dispensing equipment, automatic guided vehicles, etc. For each "Island of Automation" the required hardware will be interfaced and the appropriate software will be developed to complete Island integration. Finally, total integration of the system will be performed to link all the Islands and produce a complete automation system.

The conceptualized automation integration procedure in the solid propellant mixing laboratory will be as follows. A laboratory technician will download the mix-sheet instructions to various control modules at the Islands. At the Weighing Islands the robot manipulators will transfer sample beakers, when they are filled with the appropriate solid or liquid ingredients, to the platform stations. An automatic guided vehicle is then activated to transfer the sample beaker trays from platform stations to the Addition and Mixing Island. Based on the order of the program, the samples are added and mixed. At the completion of the mixing process, the new molds with self-contained vacuum assist casting apparatus and the automated cleaning interface will be utilized to effectively cast the propellant and clean the contaminated mixing and casting equipment.

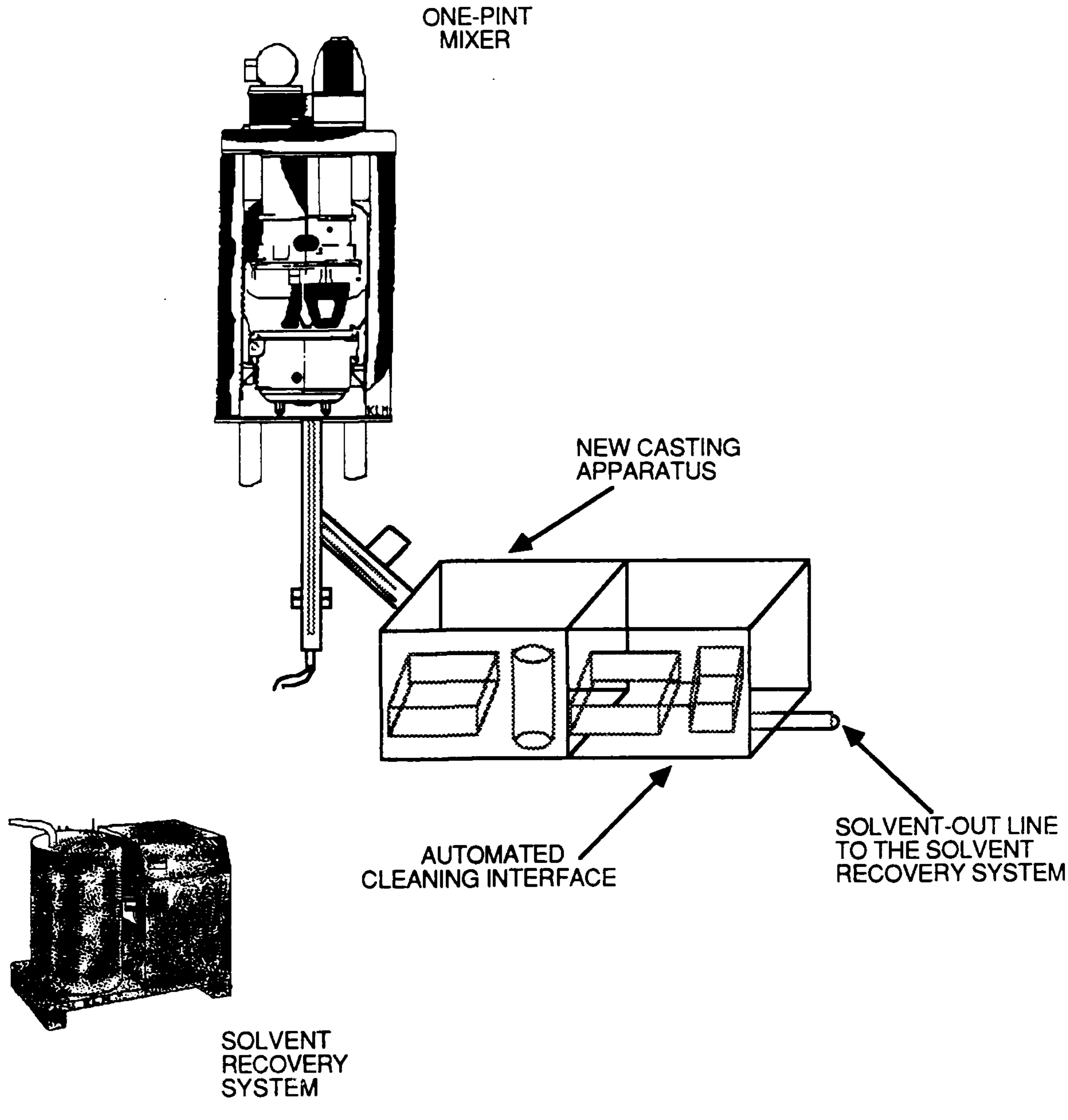



**FIGURE 20 PROPELLANT CLEAN-UP ISLAND CONCEPTUAL LAYOUT**

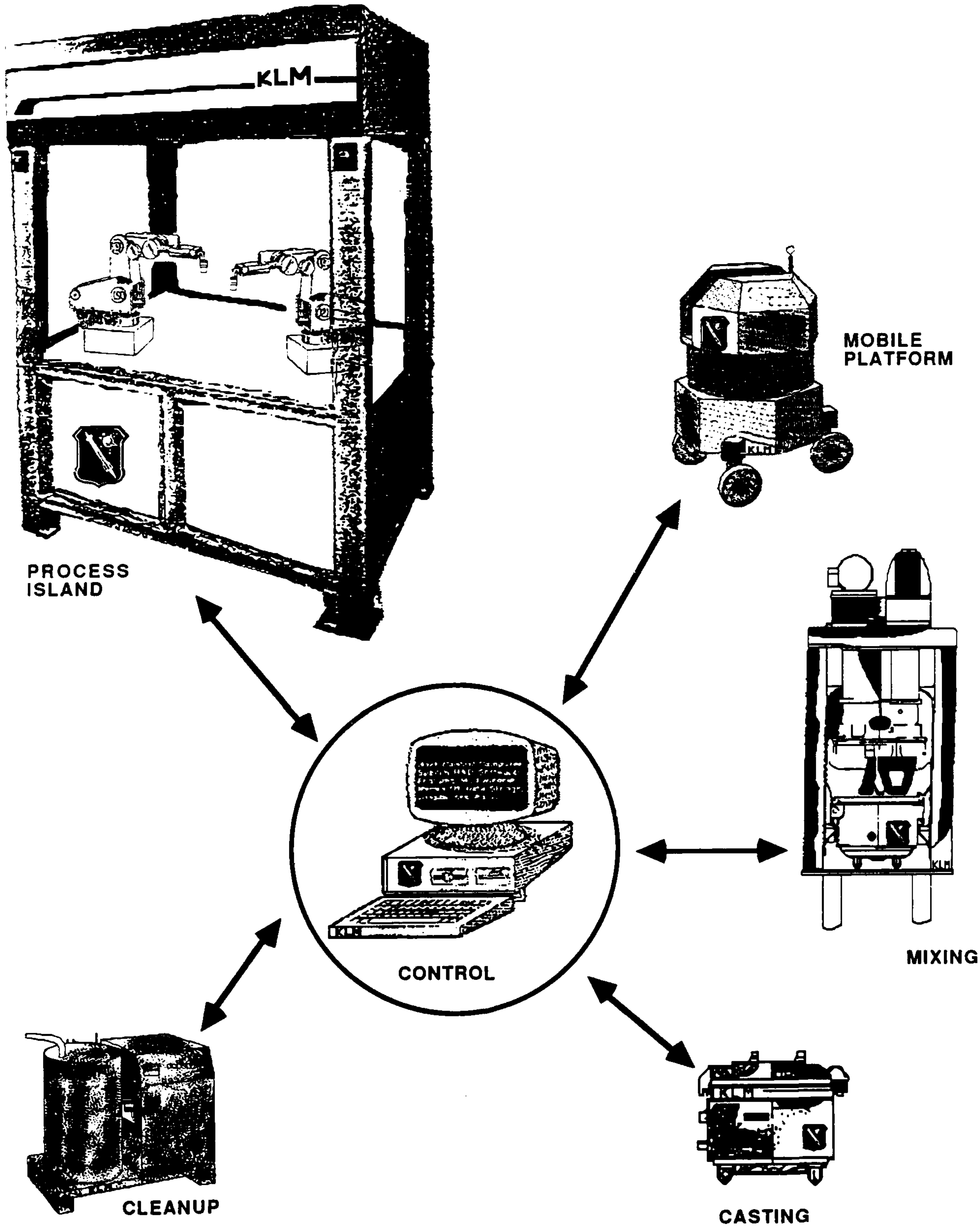



FIGURE 21 SYSTEM INTEGRATION

A detailed step-by-step automated procedure for each application will be developed based on the present manual procedures described earlier in the section entitled, "Application Procedures in Solid Propellant Mixing Laboratory." KLM would like to emphasize the fact that it understands all the required steps associated with the "Islands of Automation" and the necessary automated system capabilities (robotics, automatic guided vehicles, sensory equipment, data handling and LIMS, communication interfacing, special tooling design, testing, inspection and safety precautions). KLM has the knowledge and capabilities of developing the required software to accomplish this automation task. KLM does not anticipate any technological constraints in the implementation of such automation activities.

Assessment of Costs Associated with "Islands of Automation"

The purpose of this section is to develop the technical and economic analyses which would provide a detailed list of required devices with their associated costs and the necessary system engineering, design and software development cost estimates.

The cost analysis was performed for each of the "Islands of Automation" based on the identified hardware and the required manhour associated with system integration. The cost analysis is only an estimate and is provided for performance tradeoff analysis only. Tables 11 through 18 present a detailed cost analysis associated with required hardware and system engineering development for each "Island of Automation."

Phase II Demonstration Program

KLM proposes a Phase II Demonstration Program with the following technical objectives:

1. Design, fabricate, and factory test the selected "Islands of Automation" systems.

2. Perform facility engineering and interfacing, hardware and software integration and KLM site final testing of each "Island of Automation."

3. Install, start-up, train and optimize operation of the "Islands of Automation."

4. Support operations of the "Islands" over a period of time including all necessary performance evaluations.

5. Assure cost effective optimal design, manufacturing and operational features.

The technical activities taken to accomplish these objectives are listed in Table 19.

## TABLE 11. OXIDIZER WEIGHING ISLAND COST ESTIMATE

*HARDWARE*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 1 | 1 | Solid propellant controller | $ 4,500 | $ 4,500 |
| 2 | 6 | Solid dispensing equipment | 3,500 | 21,000 |
| 3 | 1 | Balance | 1,500 | 1,500 |
| 4 | 1 | Robot, robot controller and associated equipment | 20,000 | 20,000 |
| 5 | 1 lot | Sensory, power protection and safety equipment, linear track, barcode readers and other accessories | 13,000 | 13,000 |
| | | Subtotal Hardware | | $ 60,000 |

*PROFESSIONAL SERVICES*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 6 | 1 lot | Labor and overhead labor costs, direct transportation costs, other direct costs, G&A administrative expense, fee or profit | | $104,834 |
| | | Total Estimated Hardware and Software | | $164,834 |

## TABLE 12. FUEL WEIGHING ISLAND COST ESTIMATE

*HARDWARE*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 1 | 1 | Solid dispensing controller | $ 4,500 | $ 4,500 |
| 2 | 2 | Solid dispensing equipment (vibration system & reservoirs) | 3,500 | 7,000 |
| 3 | 1 | Balance | 1,500 | 1,500 |
| 4 | 1 | Robot, robot controller and associated equipment | 20,000 | 20,000 |
| 5 | 1 lot | Sensory, power protection and safety equipment, linear track, barcode readers and other accessories | 7,000 | 7,000 |
| | | Subtotal Hardware | | $ 40,000 |

*PROFESSIONAL SERVICES*

| | | | | |
|---|---|---|---|---|
| 6 | 1 lot | Labor and overhead labor costs, direct transportation costs, other direct costs, G&A administrative expense, fee or profit | | $ 61,156 |
| | | Total Estimated Hardware and Software | | $101,156 |

## TABLE 13

## CURE AGENTS, PLASTICIZERS, AND BONDER WEIGHING ISLAND COST ESTIMATE

*HARDWARE*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 1 | 1 | Liquid dispensing controller | $ 4,000 | $ 4,000 |
| 2 | 5 | Liquid dispensing devices (valves, pumps, reservoirs, etc.) | 3,500 | 17,500 |
| 3 | 1 | Balance | 1,500 | 1,500 |
| 4 | 1 | *Robot, robot controller and* associated equipment | 20,000 | 20,000 |
| 5 | 1 lot | Sensory, power protection and safety equipment, linear track, barcode readers and other accessories | 7,000 | 7,000 |
| | | Subtotal Hardware | | $ 50,000 |

*PROFESSIONAL SERVICES*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 6 | 1 lot | Labor and overhead labor costs, direct transportation costs, other direct costs, G&A administrative expense, fee or profit | | $120,473 |
| | | Total Estimated Hardware and Software | | $170,473 |

**TABLE 14. CASTING ISLAND COST ESTIMATE**

*HARDWARE*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 1 | 1 lot | New molds with self-contained vacuum assist suitable for casting process (solenoid valves, pumps, actuators, controls, etc.) | $ 30,000 | $ 30,000 |
| 2 | 1 lot | Sensory, power protection and safety equipment, appropriate tubing and other accessories | 7,000 | 7,000 |
| | | Subtotal Hardware | | $ 37,000 |

*PROFESSIONAL SERVICES*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 3 | 1 lot | Labor and overhead labor costs, direct transportation costs, other direct costs, G&A administrative expense, fee or profit | | $ 87,891 |
| | | Total Estimated Hardware and Software | | $124,891 |

## TABLE 15. MIXING ISLAND COST ESTIMATE

*HARDWARE*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 1 | 1 lot | Hardware modifications to mixer (mixing blades, bowl hoist, bowl, limit switches, torque protection, etc.) | $ 25,000 | $ 25,000 |
| 2 | 1 lot | Linear slides, air cylinders, power protection and safety equipment | 3,000 | 3,000 |
| | | Subtotal Hardware | | $ 28,000 |

*PROFESSIONAL SERVICES*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 3 | 1 lot | Labor and overhead labor costs, direct transportation costs, other direct costs, G&A administrative expense, fee or profit | | $ 61,729 |
| | | Total Estimated Hardware and Software | | $ 89,729 |

## TABLE 16. CLEANING ISLAND COST ESTIMATE

*HARDWARE*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 1 | 1 lot | Automated cleaning interface (solenoid valves, pumps, actuators, controls, etc.) | $ 15,000 | $ 15,000 |
| 2 | 1 | Solvent recovery system | 10,000 | 10,000 |
| 3 | 1 lot | Sensory, safety equipment, appropriate tubing and other accessories | 5,000 | 5,000 |
| | | Subtotal Hardware | | $ 30,000 |

*PROFESSIONAL SERVICES*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 4 | 1 lot | Labor and overhead labor costs, direct transportation costs, other direct costs, G&A administrative expense, fee or profit | | $ 73,205 |
| | | Total Estimated Hardware and Software | | $103,205 |

## TABLE 17. INGREDIENT ADDITION COST ESTIMATE

*HARDWARE*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 1 | 1 lot | Landing robot with controller, appropriate end-effectors, robot sleeve and linear track | $ 35,000 | $ 35,000 |
| 2 | 1 lot | Sensory, power protection and safety equipment, sample stations barcode readers and other accessories | 3,500 | 3,500 |
| | | Subtotal Hardware | | $ 38,500 |

*PROFESSIONAL SERVICES*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 3 | 1 lot | Labor and overhead labor costs, direct transportation costs, other direct costs, G&A administrative expense, fee or profit | | $ 66,715 |
| | | Total Estimated Hardware and Software | | $105,215 |

## TABLE 18. OTHER REQUIRED HARDWARE

*HARDWARE*

| Item | Quanitity | Description | Unit Price | Price |
|---|---|---|---|---|
| 1 | 1 | Multi-tasking computer system with mass-storage, networking and printing capability | $ 25,000 | $ 25,000 |
| 2 | 1 | Data acquisition and analysis system with simulation capability | 8,000 | 8,000 |
| 3 | 1 | Automatic guided vehicle (mobile platform, ultrasonic collision avoidance and lift turret) | 76,000 | 76,000 |
| | | Subtotal Hardware | | $109,000 |
| *PROFESSIONAL SERVICES* | | | | |
| 4 | 1 lot | Labor and overhead labor costs, direct transportation costs, other direct costs, G&A administrative expense, fee or profit | | $102,347 |
| | | Total Estimated Hardware and Software | | $211,347 |

## TABLE 19. PHASE II TECHNICAL ACTIVITIES

1. Program Initiation
2. Engineering, Procurement(s) and Vendor Selection(s)
3. Equipment Fabrication
4. Facility and Interface Engineering
5. Integration and Testing at KLM Site
6. Training and Maintenance Documentation Preparation
7. Equipment Packaging and Shipping
8. Equipment Installation
9. Operational Testing
    - Start-up
    - Optimization
    - Demonstration and Performance Evaluation
10. On-Site Training
11. Final System Integration
12. Final System Documentation

## PHASE I PROJECT SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Earlier in this report, the background of the proposed laboratory automation project was identified. The subsequent sections introduced the technology of laboratory robotics, a methdology to evaluate the use of such technology as well as detailed analysis and conceptual design for the automation of the Solid Propellant Mixing Laboratory at Edwards Air Force Base. The purpose of this section is to review the Phase I project activities and establish recommendations for the proposed Phase II project.

Review of Technical Objectives

Successful robotic programs in a research and development laboratory environment have one, single underlying characteristic: special attention is paid to the organizational structure, operational environment and history, and real needs within the setting under study. Without this critical component, acceptable, recommended courses of action and successful fielding of robotic solutions are undermined. The KLM methodology utilized 'o meet the requirements of the Phase I study emphasized this fact. Additionally, the successful implementation of robotic hardware and software requires a carefully structured series of tasks which examine, in detail:

- The operational requirements of a system designed to satisfy specific R&D objectives.
- The development of an implementation and integration strategy for creating the optimal relationship between researcher and the automation system.
- A firm basis for establishing economic and non-economic costs and capabilities (value).
- Appropriate equipment testing and evaluation to increase the likelihood for a successful program.

The proposed evaluation and implementation program for the automation of the Solid Propellant Mixing Laboratory is structured into two distinct phases:

- Phase I: Mission Analysis and Establishment of Performance Requirements
- Phase II: Development, Test and System Performance Evaluation and In-Service Test Demonstration and System Performance Evaluation

Each phase consists of distinct tasks which are logically structured to ensure that the objectives of each phases will be met.

The technical objectives of this development program are to:

a) Establish the feasibility of a general purpose robotic-based laboratory automation system that could handle a vast array of laboratory propellant development applications in a Solid Propellant Mixing Laboratory.

  Response: The Phase I analysis and design activities established the feasibility of utilizing robotic-based "islands of automation" to fully support the Solid Propellant Mixing Laboratory operations discussed in the previous section entitled, "Application Procedures in Solid Propellant Mixing Laboratory," with the conceptual design presented in the sections entitled, "Island of Automation in a Solid Propellant Mixing Laboratory" and "System Integration."

b) Develop a multiphase program which will be designed to realistically analyze various laboratory operations necessary in a Solid Propellant Mixing Laboratory and potentially applicable for automation and/or robotic modifications (e.g., ingredient weighing and prebatching, ingredient addition, propellant casting, etc.).

  Response: Phase I has developed the feasibility of automating various propellant laboratory procedures. Further, the conceptual design of the robotic laboratory work stations will be fully engineered and implemented in Phase II of this project.

c) Implementation of Laboratory Information Management System (LIMS) in Solid Propellant Mixing Laboratory environment.

  Response: The role of LIMS is an integral part of KLM's design for the automated Solid Propellant Mixing Laboratory and will be utilized to integrate the use of "islands of automation", laboratory instruments, user interfaces, etc.

d) Study of various existing equipment in Solid Propellant Mixing Laboratory and if necessary propose certain modifications for system enhancement, time and labor savings and increased safety and productivity.

  Response: This objective has been implemented in the proposed design and will center around the one-pint mixer. Particular changes involve the addition of propellant ingredients to the mixer, modification to allow automated propellant casting and cleanup.

The feasibility analysis activities of this program represent the first major task prior to defining the detailed performance requirements for the technology being assessed. The first phase of the program examined, in detail, the candidate mission and general performance requirements for robotic or automated equipment. The

Phase I major activities used to implement the above are discussed in the next sections. The following items identify the major feasibility issues addressed in Phase I:

1) Can the robotic devices and/or automated equipment operate and perform useful tasks in solid propellant mixing laboratories?

2) Can various processes such as ingredient weighing and prebatching, monitoring of relevant mix parameters, propellant casting and clean-up be automated and robotized?

3) By automating, would the element of risk to the personnel involved in handling explosive and hazardous materials be eliminated?

4) Can LIMS be implemented in Solid Propellant Mixing Laboratories to save time, labor and improve safety and productivity?

5) Would automation be cost effective?

These questions need to be addressed within the context of specific operational steps which should be considered for automation including ingredient weighing and prebatching, ingredient addition, on-line monitoring of relevant mix parameters, propellant casting, clean-up, testing and within certain performance boundary conditions, such as, time constraints, accuracy, speed and cost. The results presented in the section entitled, "Automation Opportunities in a Solid Propellant Mixing Laboratory," clearly answer all the above questions in the positive.

Once the feasibility has been established within the context of particular applications and performance constraints, detailed applications and performance parameters can be established to better define the specific design requirements of the fielded research equipment. This phase of the program forms the foundation for the development test and evaluation programs of Phase II which will be designed to examine the performance of prototype equipment. It should be noted that the flexibility required will result in versatile hardware, and result in general purpose interfaces and application software that will be readily configurable to handle a wide range of laboratory activities.

Phase I Work Plan

The primary objective of the Phase I study was to conduct an analysis which identified specific requirements to which laboratory robotic and automation technology must comply as well as system requirements for each application. These areas represent those activities currently required to support on-going research and development efforts within the Solid Propellant Mixing Laboratory.

The Phase I requirements analysis tasks were structured to: identify specific tasks; define environmental, safety and performance parameters inherent in the research environment and required of the equipment, respectively; and complete a general cost/capability evaluation. These tasks identified potential automating processes occuring in Solid Propellant Mixing Laboratory including:

- Ingredient weighing and prebatching
- Ingredient addition
- On-line monitoring of relevant mix parameters
- Propellant casting
- Clean-up
- Testing

The major activities of Phase I were broken into the following tasks:

1. Define Research Area Requirements
2. Identify Research Robotic and Automation Activities
3. Establish Laboratorial Performance Parameters
4. Conduct Cost/Performance Trade-off Analysis
5. Identify Laboratory Hardening/Safety Requirements
6. Develop Phase II Implementation Plan
7. Project Documentation

The result of each of these is reviewed below.

Task 1: Define Research Areas Requirements

Response: KLM consulted with responsible solid propellant mixing laboratory personnel at various facilities including the Edwards AFB and commercial firms including Morton Thiokol and Aerojet to identify design requirements for analyses of laboratory applications.

KLM's activities are reflected in the section entitled, "Automation Opportunities in a Solid Propellant Mixing Laboratory," of this report and address applications of automation and robotics in each of the identified propellant laboratory processes.

In particular, KLM considered items such as:

a) Solid Propellant Mixing Laboratory equipment and facilities
b) Sensor data acquisition (optical, proximity, and others)
c) Robot configuration and end-of-arm tooling
d) Laboratory Information Management System integration

KLM did extensive analysis, into not only the procedures and practices in the laboratory, but also into the background of the technology used within the propellant laboratory. This included the mixers, mixing expertise of the personnel as well as unique physio-chemical characterstics of the fuels, oxidizers and other propellant ingredients.

In particular, previous sections of this report entitled, "Propellant Casting Island" and "Clean-up Island," identify the technical areas which will require additional analysis in Phase II.

Task 2: Identify Research Robotic and Automation Activities

a) Ingredient weighing and prebatching
b) Ingredient addition
c) On-line monitoring of relevant mix parameters
d) Propellant casting
e) Clean-up
f) Testing
g) Existing equipment modification
h) Labor intensive and hazardous operations

The survey of present and proposed robotic applications provided the foundation for Task 2 and assisted in:

a) Specify potential robotics or remote technology applications associated with research activities.

b) Specify locations associated with each task.

c) Define environmental and performance parameters inherent in the research environment and required equipment.

d) Identify the equipment field - hardening requirements.

Response: As indicated earlier, two visits and several telephone communications with the laboratory personnel were used to provide the application specification established in the section entitled, "Application Procedures in Solid Propellant Mixing Laboratory." The resultant "island of automation" and environmental design factors were addressed in the section entitled, "Islands of Automation in a Solid Propellant Mixing Laboratory."

Task 3: Establish Laboratorial Performance Parameters

This task examined each of the major parameters identified below to assess the design impact of hardware options on the proposed propellant laboratory robotic applications identified in Task 2. The major engineering consideration included the following as applicable:

a) Robot Specifications

- Configurations
- End-of-arm tooling
- Reach (horizontal, vertical)
- Speed, accuracy and repeatability

b) Physical Sensor Parameters

- Physical properties

- Collection medium
- Frequency, deviation and rate of sampling, etc.

c) Laboratory Information Management Systems (LIMS)

- Sample tracking
- Long-term data storage
- Trend analysis

d) Laboratory Equipment

- Reliability and maintainability
- Accessibility
- Potential modifications
- Safety precautions

e) Robot Transport

- Slider mechanisms
- Linear tracks
- Gantry configuration

f) Environmental Constraints

- Available space
- Temperature
- Humidity
- Air quality
- Explosions
- Sparks
- Solvents
- Other

<u>Response</u>: The resultant performance specifications are included in the previous section entitled, "Islands of Automation in a Solid Propellant Mixing Laboratory." In many cases, several alternatives are still available which will only be resolved in the detailed engineering tasks of Phase II.

Task 4: <u>Conduct Cost/Performance Tradeoff Analysis</u>

Initial cost/tradeoff information was generated during Task 4. The result of this approach was:

1) The development of a Task Identification Matrix.

2) An assessment of potential capability and general cost associated with a capability.

3) An immediate indication of the state of the art for development vs. commercialized hardware.

An equipment performance criteria was used to determine the feasibility of specific capabilities. A profile is established which evaluates various equipment alternatives and their ability to satisfy particular requirements. Finally, an assessment of costs and benefits associated with the selection of particular robotic configuration is made.

Response: The results of these analyses are provided both in the methodology utilized and discussed earlier as well as the conceptual design given in the section entitled, "Application Procedures in Solid Propellant Mixing Laboratory." The Task Identification Matrix is given in Table 10. The assessment of costs associated with each specific "Island of Automation" was previously provided.

Task 5: Identify Laboratory Hardening/Safety Requirements

For the final configuration of the Solid Propellant Mixing Laboratory robotic system, KLM will identify the potential field hardening requirements to support types of laboratory research; these will include areas such as:

a) Robotic devices (manipulator and/or end-effectors
b) Physical sensors (contact and/or noncontact)
c) Robot transport (linear and/or circular track)
d) Electronics (controllers and/or device interfaces)

Response: The preliminary design results given in the sections entitled, "Application Procedures in Solid Propellant Mixing Laboratory" and "Islands of Automation in a Solid Propellant Mixing Laboratory," reflect the results of this effort. It should be noted that the final aspect of this task will not be implemented until the procurement phase of the Phase II program.

Task 6: Develop Phase II Implementation Plan

Response: Based upon the previous tasks, KLM developed a comprehensive Phase II plan to develop, test and enter production of the desired low-cost laboratory robotic system. An overview was given in the section entitled, "Phase II Demonstration Program," while the details of it are reflected in KLM's Phase II proposal.

Task 7: Project Documentation

Response: This report provides Phase I project documentation.

## Summary and Conclusions

KLM Technologies has successfully completed its Phase I project to investigate the use of automation/robotics technology as a valuable technique to reduce hazards to personnel and cost savings in a solid propellant mixing laboratory.

Based on KLM's intensive research, it is apparent that the technology to automate such laboratories is available. KLM's knowledge of system integration combined with manufacturer's devices would provide unique and cost effective systems.

To justify the capital outlay and minimize risk for robotic/automation implementation, KLM Technologies has considered the implementations of "Islands of Automation" strategy. This strategy would allow only one process (ingredient weighing, addition and prebatching, propellant mixing, casting and clean-up) at a time to be automated and allows the results to be monitored. The important key point would be to consider necessary tools (hardware and software) required for successful integration between the automated process and the next operation.

KLM believes that ingredient weighing, propellant mixing, casting and clean-up are potential processes to be implemented as "Islands of Automation." Consequently, application software would be written to allow the islands to communicate. This software would be in place to move the information back and forth.

However, the budgetary limitations imposed on Phase II does not allow all the Islands to be automated during Phase II plant implementation. KLM would select certain appropriate applications based on their importance, cost effectiveness and minimal need to reduce laboratory modifications. KLM suggests the following order of automation of applications including oxidizer, fuels and bonding agents weighing, mixing, casting, cleaning, ingredient addition, AGV integration and total system integration.

## Recommendations

Based upon the successful feasiblity study of automating the Solid Propellant Mixing Laboratory at Edwards Air Force Base and the development of an integrated system design to implement the feasibility study, it is recommended that the Phase II program previously outlined be funded for implementation in 1988.

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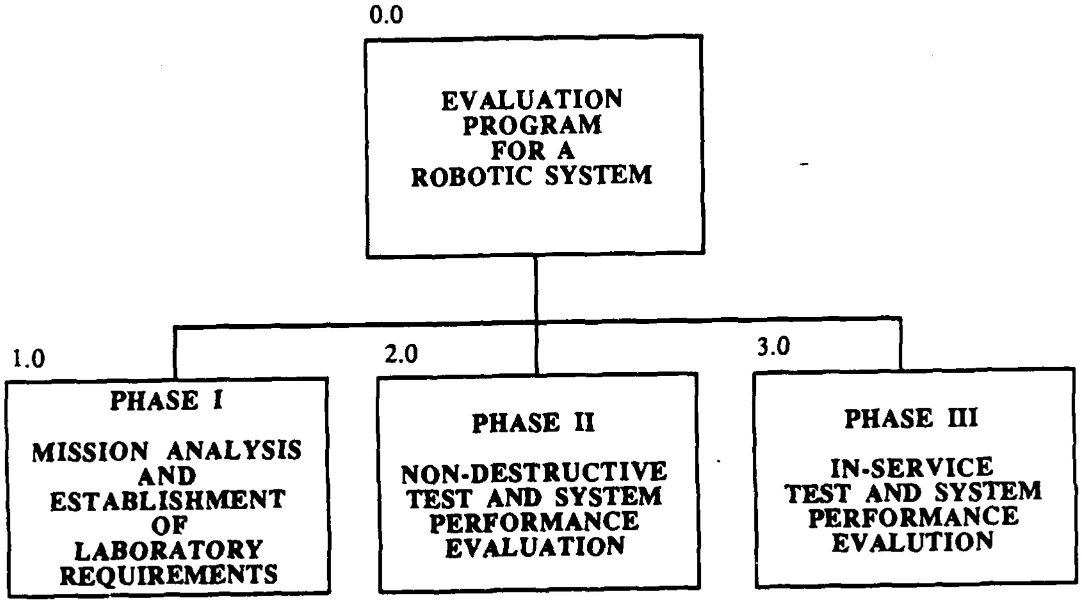
# APPENDIX A

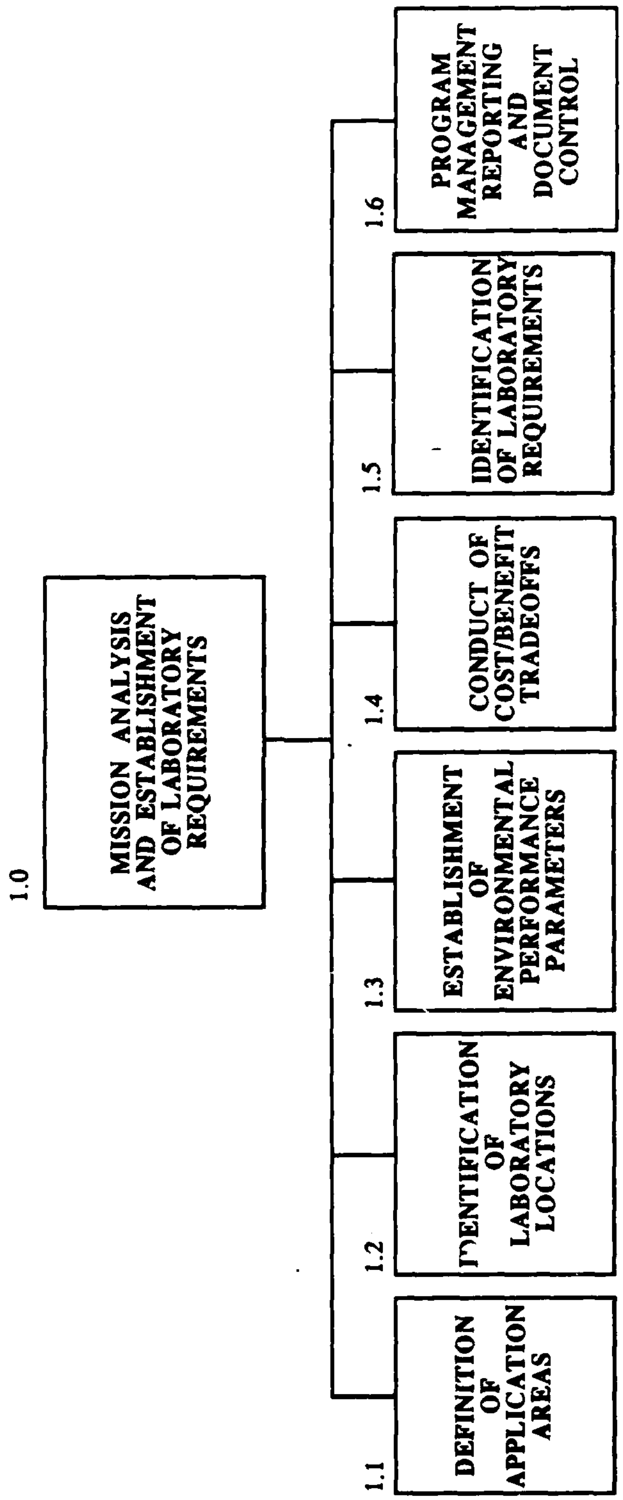
## General Methodology for Study

- WORK BREAKDOWN STRUCTURE FOR THE APPLICATION OF ROBOTIC TECHNOLOGY TO THE LABORATORY ENVIRONMENT
- HIGHLIGHTED TEST PLAN ELEMENTS
- EXAMPLE OF TYPICAL ROBOTIC DEVICE EVALUATION CRITERIA

WORK BREAKDOWN STRUCTURE FOR THE APPLICATION OF ROBOTIC TECHNOLOGY TO THE LABORATORY ENVIRONMENT




**WORK BREAKDOWN STRUCTURE**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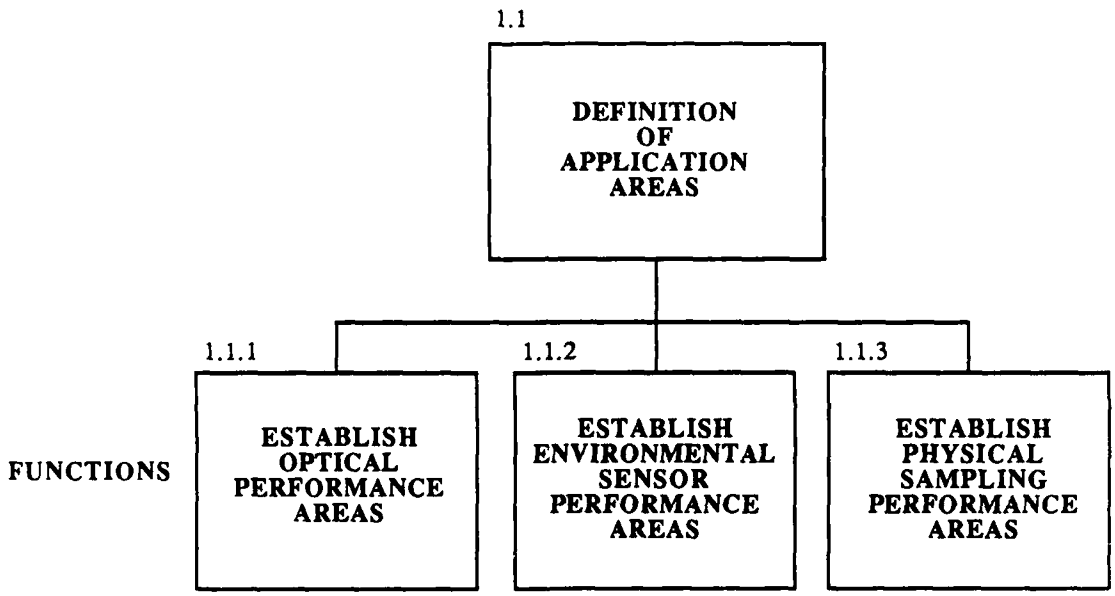
1.2
IDENTIFICATION OF LABORATORY LOCATIONS
1.3
ESTABLISHMENT OF ENVIRONMENTAL PERFORMANCE PARAMETERS
1.4
CONDUCT OF COST/BENEFIT TRADEOFFS
1.5
IDENTIFICATION OF LABORATORY REQUIREMENTS
1.6
PROGRAM MANAGEMENT REPORTING AND DOCUMENT CONTROL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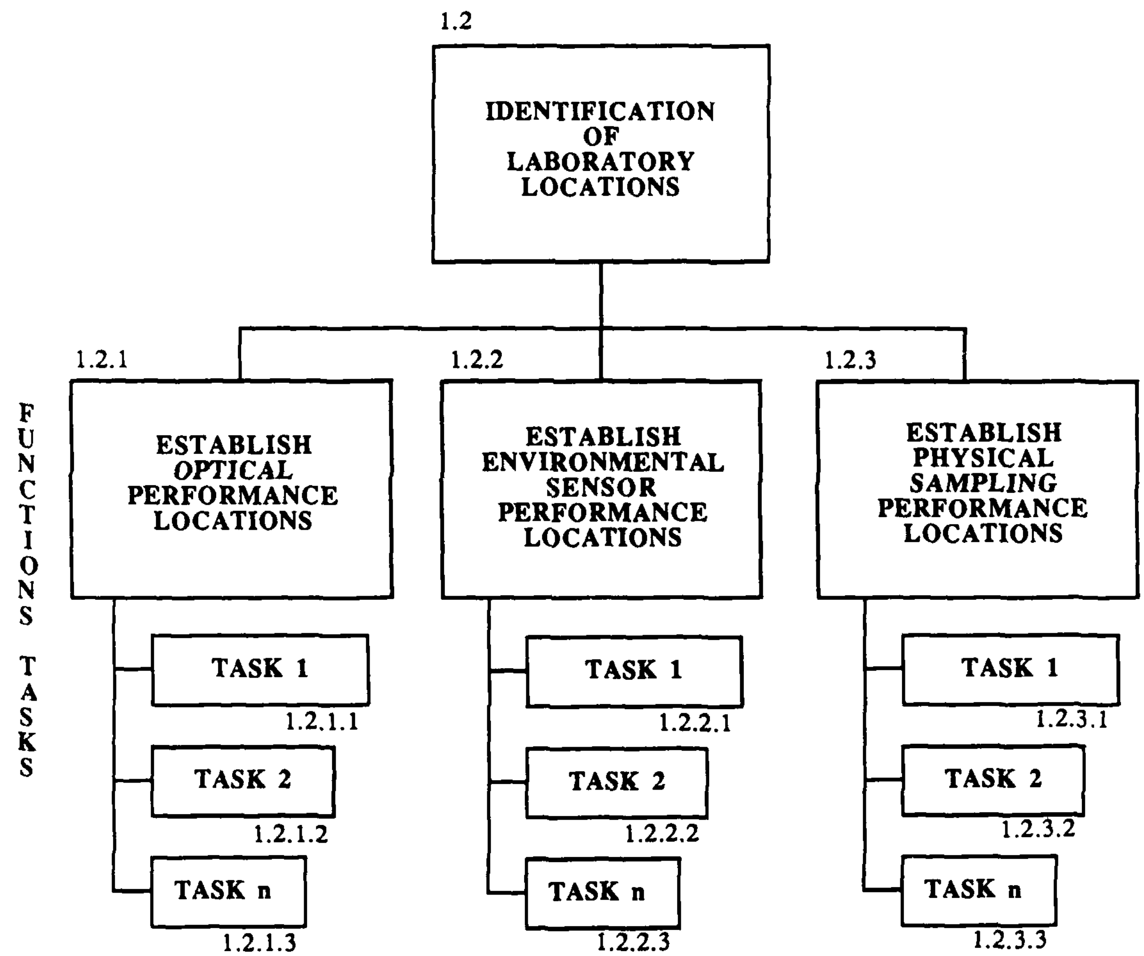
ESTABLISH PHYSICAL SAMPLING PERFORMANCE AREAS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ESTABLISH ENVIRONMENTAL SENSOR PERFORMANCE LOCATIONS
1.2.3
ESTABLISH PHYSICAL *SAMPLING* PERFORMANCE LOCATIONS
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TASK 2
1.2.1.2
TASK n
1.2.1.3
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TASK 2
1.2.2.2
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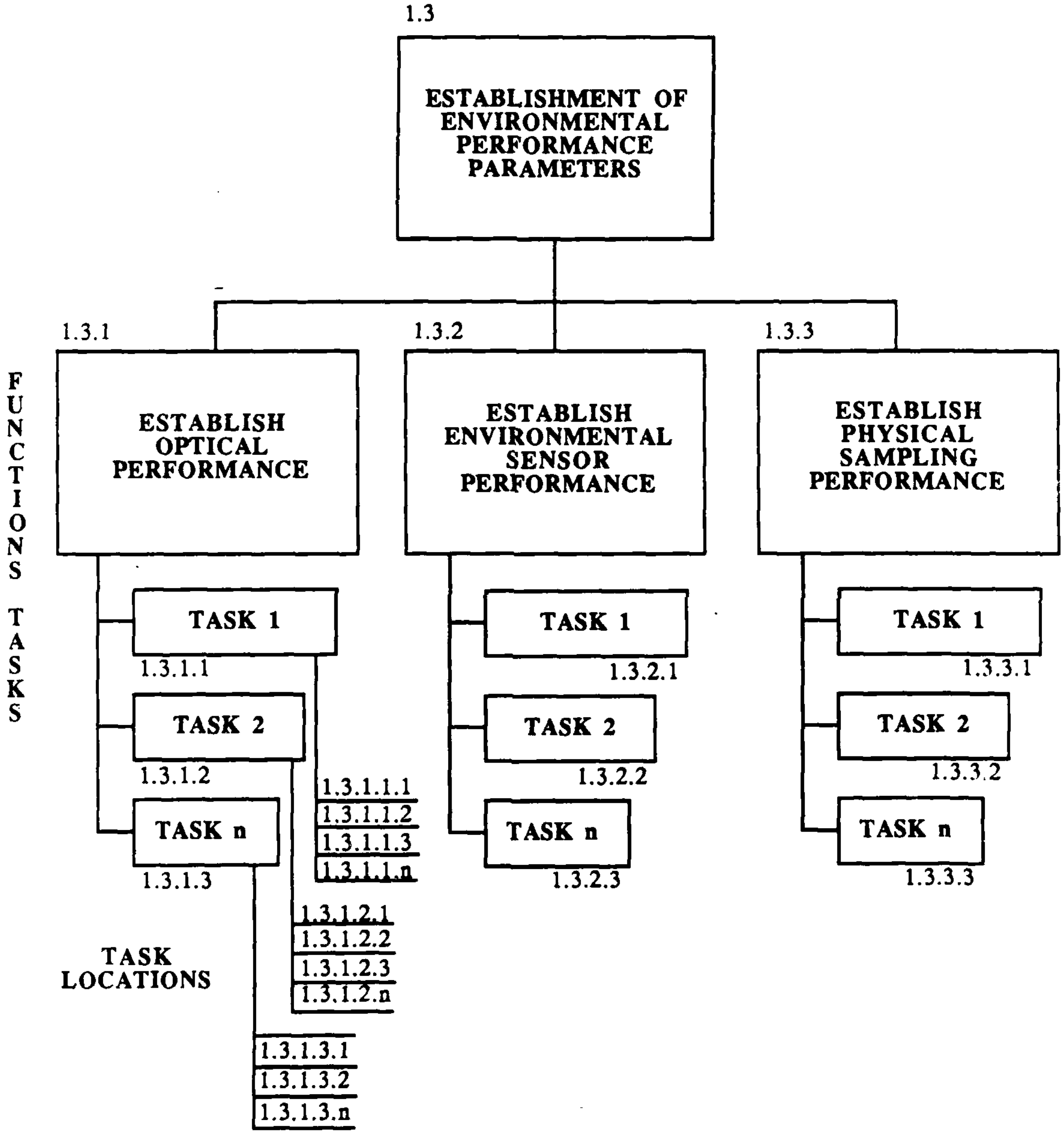
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1.3.3
ESTABLISH PHYSICAL SAMPLING PERFORMANCE
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TASK 2
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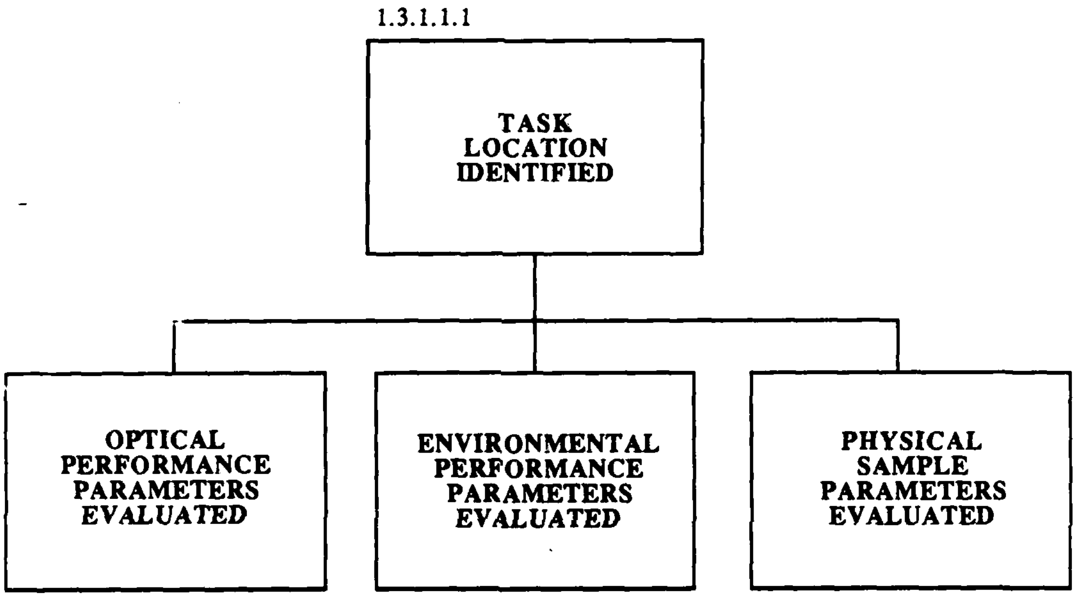
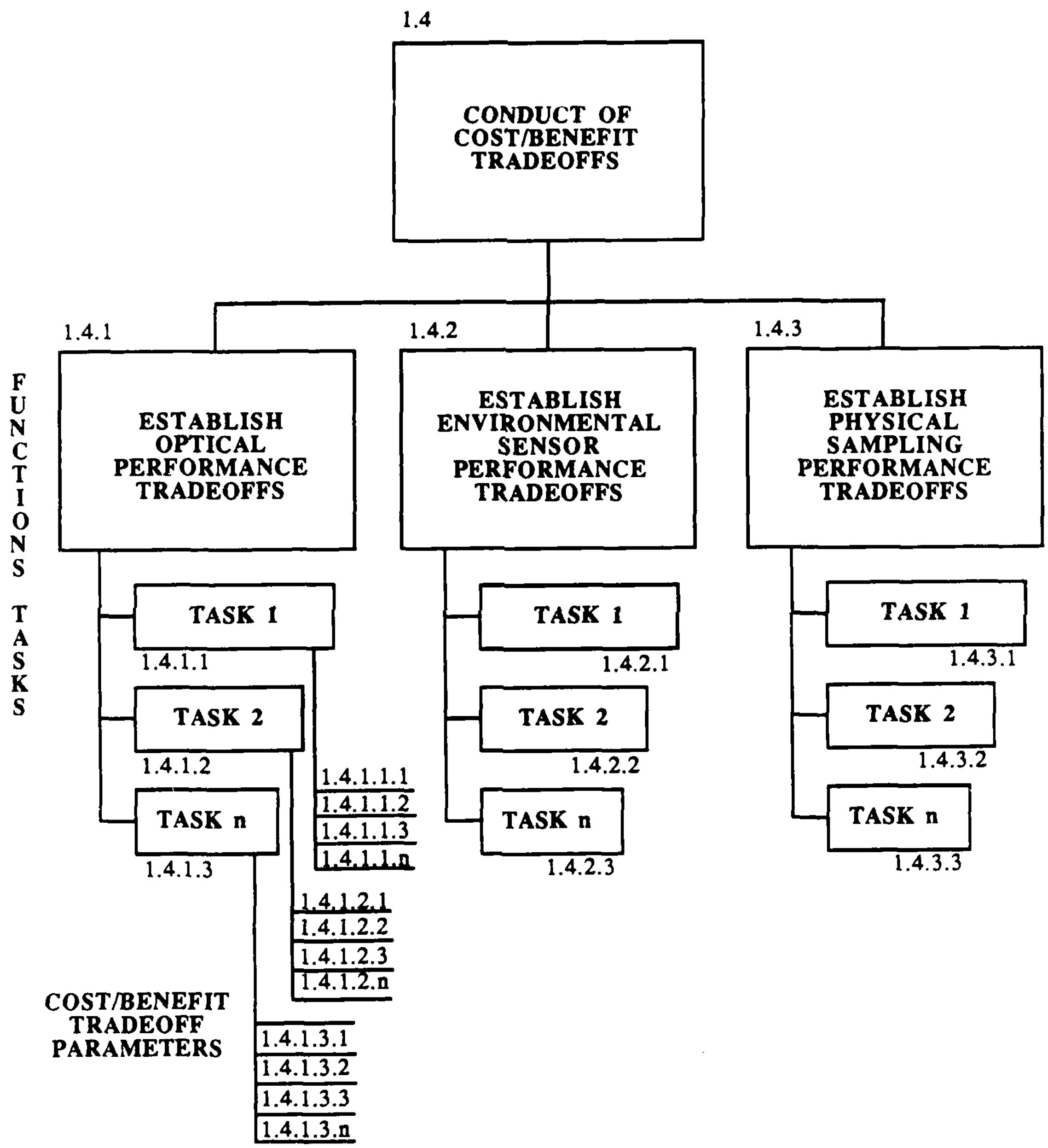



- Accessibility
- Movement accuracy
- Time to access
- On-station time
- Egress
- Light level
- Lens-to-object distance
- Resolution
- Power Requirement
- Telemetry rate
- Interference
- Barriers

- Accessibility
- Movement accuracy
- Time to access
- On-station time
- Egress
- Temp, moisture level ranges
- Cumulative dosage
- Sampling position
- Power requirements
- Telemetry rate
- Interference
- Barriers

- Accessibility
- Movement accuracy
- Time to access
- On-station time
- Egress
- Chemical & physical properties of material
- Collection medium
- Frequency, deviation and volume rate of sampling
- Power requirements
- Telemetry rate
- Interference
- Barriers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TASK 2
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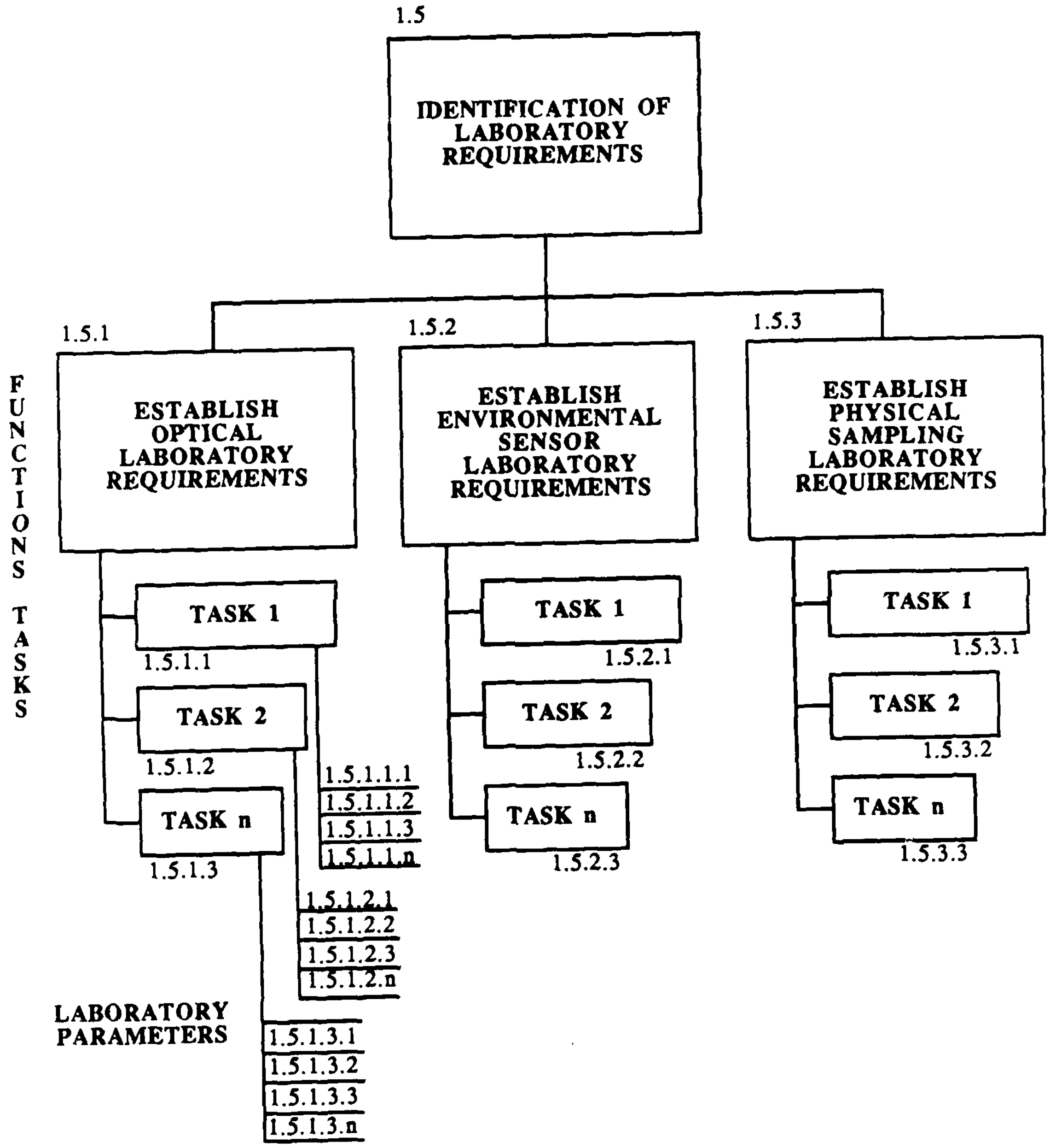
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FUNCTIONS
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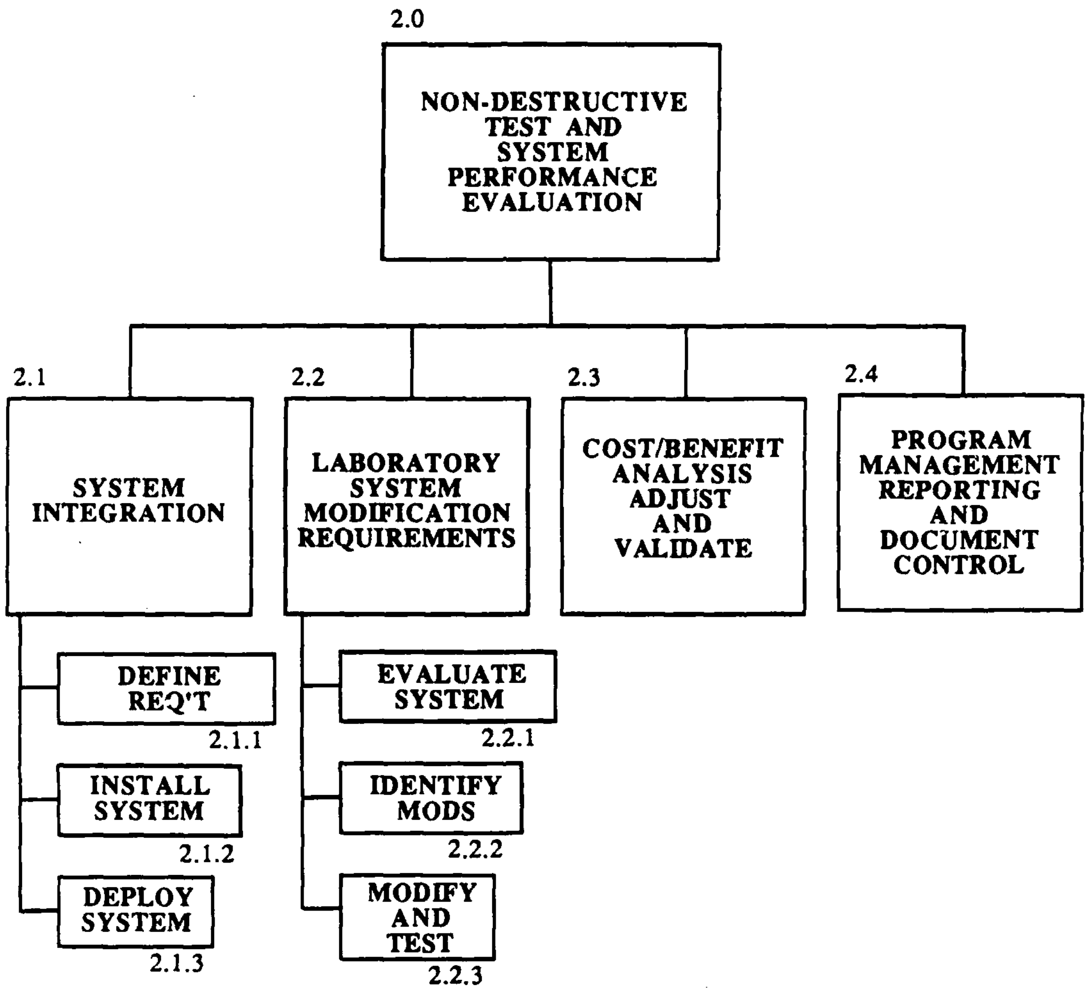
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2.4
PROGRAM MANAGEMENT REPORTING AND DOCUMENT CONTROL
DEFINE REQ'T
2.1.1
INSTALL SYSTEM
2.1.2
DEPLOY SYSTEM
2.1.3
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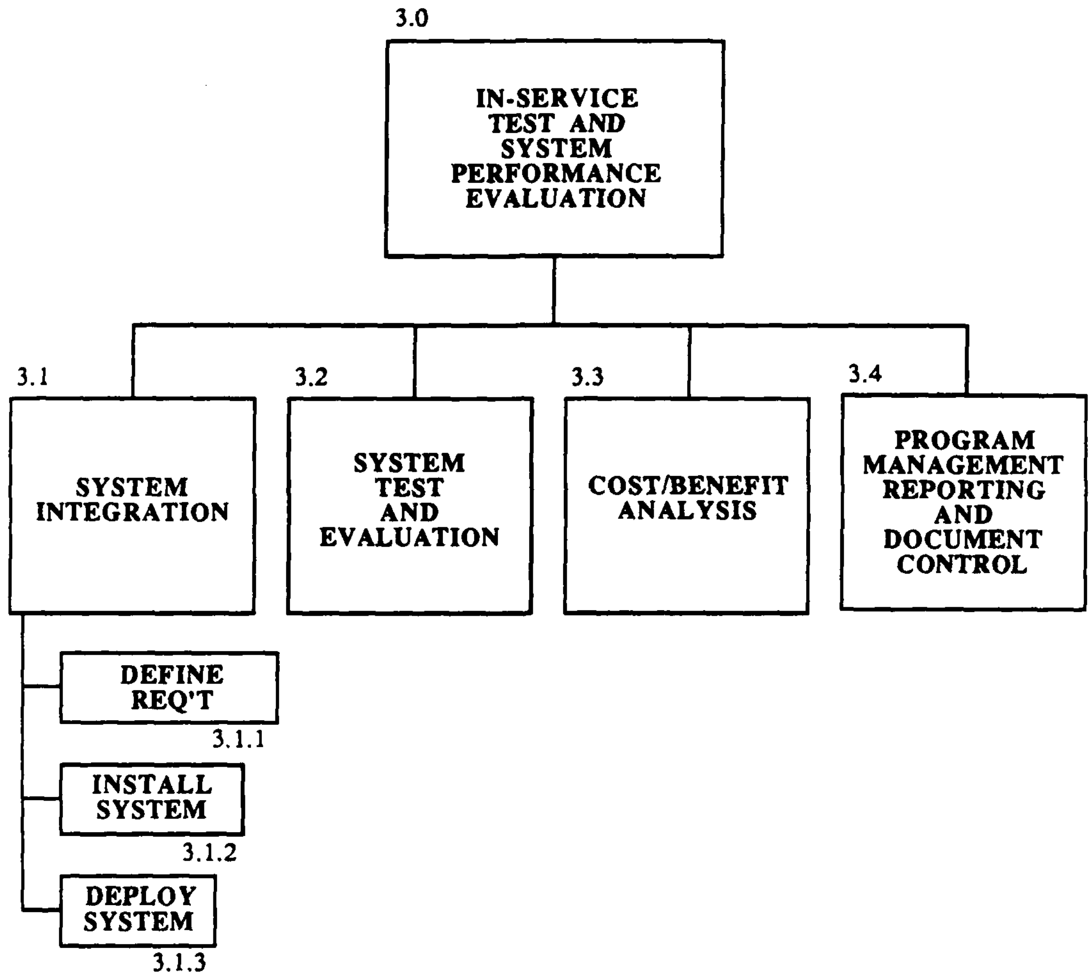
2.2.1
IDENTIFY MODS
2.2.2
MODIFY AND TEST
2.2.3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SYSTEM TEST AND EVALUATION
3.3
COST/BENEFIT ANALYSIS
3.4
PROGRAM MANAGEMENT REPORTING AND DOCUMENT CONTROL
DEFINE REQ'T
3.1.1
INSTALL SYSTEM
3.1.2
DEPLOY SYSTEM
3.1.3

# HIGHLIGHTED TEST PLAN ELEMENTS

# HIGHLIGHTED TEST PLAN ELEMENTS

Mission Identification

A number of mission objectives and specific tasks have been identified as performance requirements for the System. The purpose of Phases II and III is to evaluate the capabilities of the System to satisfy these performance requirements. However, a number of factors will limit the project's effective evaluation of all performance capabilities.

First, the testing center has a number of existing plant mock-ups which will allow the System to exercise several of its capabilities. It is planned to construct additional special mock-ups where appropriate ones do not exist. However, not all design features of the System can be examined in a non-destructive environment. This is especially true where it is required to evaluate the interaction of a number of performance capabilities simultaneously.

Second, the objective of Phase II is to ensure that specific subsystems can operate effectively prior to a total integrated test. Consequently, attention will be focused on ensuring that realistic and comprehensive evaluation procedures are developed for each subsystem. These tests will be conducted within the context of the specific missions and tasks identified earlier. Under these circumstances, however, the attention will be focused on the performance of the electronics rather than the ability of the total system to successfully perform a series of tasks, although this will be included as a measure of its performance capabilities. Procedures for the subsystem and integrated system tasks will be completed for each mission and will address, to the extent possible, the missions and tasks originally identified.

System Installation

Due to the extent of initially testing individual subsystems, there is no need to develop installation procedures similar to those expected in an operational reactor site. Most of the installation requirements for Phase II will, by necessity, reflect the needs of the particular test rather than that ultimately required by an operational system. For example, special installation hardware and cabling will be required for performing communication tests. Data acquisition equipment will be configured for the purposes of system evaluation rather than for its operation. Each procedure will describe the equipment requirements as well as the installation requirements. In addition, the procedure for installing the remote transmitter/receivers as well as the control/display console will be developed prior to the integrated system test.

Personnel Training Requirements

Due to the emphasis on subsystem testing, there will be minimal emphasis on operator/maintainer training. The testing which will occur during Phase II will, however, provide an opportunity for establishing the actual training needs of the operator/maintainer during Phase III.

Each test procedure will provide for the identification of training requirements associated with the task to be performed. This will be accomplished with the use of a Task Analysis which will identify the task objectives and methods for the operator/maintainer to accomplish each task activity. Task Analysis data will be collected throughout the testing program and will be used to generate an operations and maintenance manual. These manuals will be employed during the Phase III testing.

## EXAMPLE OF TYPICAL ROBOTIC DEVICE EVALUATION CRITERIA

## EXAMPLE OF TYPICAL ROBOTIC DEVICE EVALUATION CRITERIA

ROBOTIC DEVICE EVALUATION CRITERIA

The successful deployment of the System is dependent upon a number of factors including those associated with the System's operation as well as its maintenance and repair. The following paragraphs discuss three major evaluation factors which will have a strong influence on the success of the System's mission and its acceptability by the user community: efficiency of operation, man-machine interface and the System's total cost (e.g., maintenance, training, storage). The evaluation criteria cited in the following will be further expanded into an evaluation procedure that can be used during the integrated test and evaluation Phases II and III.

Efficiency of Operation

The efficiency with which the System can be operated depends on a number of factors including those associated with its actual operation as well as its design, construction and maintenance. A rating scale will be developed during Phase II testing and a methodology will be established to accurately assess the System's performance. The following list of variables summarizes the major evaluation categories which will be used to assess total efficiency:

- Design and Construction, including:
  - Materials
  - Workmanship
  - Interchangeability of parts
  - Electromagnetic interference and compatability
- Safety
- Installation
- Storage
- Power Allocation
- Cabling
- Operational Readiness
- Reliability
- Maintainability
- Test Provisions

- Environmental Performance, including:
  - Temperature
  - Humidity
  - Shock and vibration
  - Lighting

- Logistics, including:
  - Maintenance support
  - Parts supply
  - Electrical power
  - Personnel and training
  - QA program
  - Acceptance testing program
  - Transportability
  - Shipping

- Software and Data Base Management, including:
  - Data Base design
  - Data preparation and entry
  - Software design
  - Memory capacity
  - Software tests

Although there are a number of performance variables which can be used to evaluate the System's performance, the aforementioned factors are considered to be the most critical.

Man-Machine Interface

*In a robotic system, the operator plays a major role in* handling, operation, maintenance and repair. It is important to note that the "man-in-the-loop" design of the System might potentially create problems of operator fatigue, especially during prolonged operational periods. Consequently, its design must reflect appropriate human factors engineering principles to reduce operator error and improve system performance. The following variables have been selected as evaluation factors to be used during the test and evaluation phases:

- Visual display design
- Auditory display designs
- Control design
- Labeling
- Anthropometry
- Workspace requirements
- Maintainability
- Personal safety
- User-software interface

Appropriate design features of the equipment will be compared against the previously cited evaluation factors with the use of human factors engineering guidelines. Display evaluation factors include, for example, readability, information density, contrast and scale markings. Additional detailed evaluation guidelines will be provided for all variables.

# APPENDIX B

## Overview of Industrial/Laboratory Robotics Technology

## Introduction

There is some confusion over the exact definition of an industrial/laboratory robot. In order to understand what a robot is, in this context, it is useful to review the various categories of automation. Automation ranges in degree from simply the use of powered or nonpowered tools to the complete control of a task by a computer-aided system utilizing high storage memories, sensory devices, and periodic changes in software programming. Between these extremes fall the categories of "hard automation" and "flexible automation".

In hard automation, a task is performed by a tool which has been set up using mechanical limits and adjustments so that no human control is required during operations. Hard automation is typically dedicated to one application throughout the life of the tool or system. The primary disadvantage of hard automation is the difficulty of justifying the investment in dedicated equipment for a batch operation, in which changeovers may be required such as a laboratory environment. An additional drawback is the need for human assistance in loading and unloading the tool. The automated laboratory instruments are examples of hard automation since they are dedicated to only one type of analytical activity or measurement.

The alternative to hard automation until recently was to increase the direct labor content of a task. Flexible automation was developed as a means of increasing the range of tasks that can be performed and also to improve the changeover capability of manufacturing/laboratory tools. In flexible automation, a tool is pre-programmed by a human as in hard automation. In this case, however, the workpiece can be manipulated so that a greater number of tasks can be performed in each cycle. In addition, a changeover to another job can typically be accomplished by reprogramming rather than by reworking or replacing the equipment. Machinery and instrumentation can therefore be more productively used throughout its useful life.

Laboratory robots can be classified as a type of flexible automation. The Robot Institute of America (RIA) defines a robot as a "reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motion for the performance of a variety of tasks." The RIA definition of industrial robots is the best one to be presented to date. The first three words in the definition are essential to understanding the basic concept of a robot:

- "Reprogrammable" - A robot is controlled by a programmable controller with memory, such as a microprocessor. The controller is programmed to command the robot arm and gripper to repeat a specified series of movements, such as moving a liquid sample through a titration operation. If the robot is to be used in a different operation, an entirely new sequence of movements can be created by reprogramming the controller.

- "Multifunctional" - An industrial robot is much more flexible than hard automation in that it can perform a wide variety of tasks. During a single cycle of movement, for example, a robot can load an instrument with a sample, unload the previous sample and transport it for another laboratory operation. It is therefore a general purpose device rather than a dedicated machine.

- "Manipulator" - An industrial robot differs from other forms of automation in its ability to move an object through space while at the same time reorienting its position. It is this ability to manipulate objects that leads to the inevitable comparisons between robots and human arms and hands. This is also the capability which allows robots to perform many tasks that previously could only be performed by human workers.

Robots can thus be thought of as machines that fill the gap between the specialized capabilities normally associated with hard automation and the extreme flexibility of human labor. Basically, a robot is a device with a single arm for manipulating tools or samples through a programmed sequence of motions through space. What differentiates a robot from other types of automation is its ability to perform a sequence of several different, repetitive motions without the need for human involvement. Because of this unique capability to perform several different tasks, robots are used in a variety of industrial and laboratory applications where the task can be performed in a more safe and effective manner by robots than by human workers.

Appendix C contains an extensive listing of technical robotic terms which are utilized to describe the technology.

## Basic Robot Components

Although robots are available in a wide variety of configurations all robots consist of three basic elements: (1) a manipulator, (2) a controller and (3) a power supply. The manipulator (and its support stand) is the basic mechanical element of the robots and is responsible for performing the work. The controller is the robot's brain and is responsible for directing the movement of the manipulator. The power supply is the energy source for the manipulator.

### Manipulator

The most fundamental objective of a robot is to move an object through three-dimensional space. This motion is mechanically accomplished by the manipulator. The manipulator consists of a mechanical "arm" and a "wrist" both of which are mounted on a support stand. A mounting surface is provided on the end of the wrist for attaching the tool (called an "end effector") with which the robot performs its jobs. Typically, the end effector is in the form of a gripper device for grasping and manipulating a part.

### Mechanical Configurations

There are several ways in which a manipulator can be constructed in order to move a part through space. As with the human arm, motion is achieved through a series of mechanical linkages and joints. The basic configuration of the mechanical arm is best described in terms of its coordinate system. There are currently four different coordinate systems being used to move a part from point "A" to point "B". The simplest is the rectangular, or cartesian coordinate system as illustrated in Figure B-1. In this system, all motion is translational; i.e., straight along one of three perpendicular axes. This type of motion is the easiest to control and is often used in the "pick and place" type of robot, which is used for such applications as transporting samples from one point to another.

Robot arm configurations based upon rotational motion about several axes, although being more difficult to control, are preferred in most currently available robots because of the simpler design requirements as well as the greater range within which such robots can work. Three rotational systems are in use today: cylindrical. spherical, and jointed-arm spherical (see Figures B-2, B-3 and B-4).

The importance of each of these configurations to a potential user is determined by the "work envelope" within which the robot end effector is capable of working. A robot work envelope is analogous to a human work envelope defined by industrial engineers. Robot manufacturers will normally include drawings of work envelopes for each robot model along with dimensions. It is important to understand how the manufacturer defines the work envelope; typically, the work envelope includes the region of space which can be reached by a particular point on the wrist of the manipulator, not the tip of the end effector. This is because the end effector is generally a custom designed item provided by the user, and so its dimensions cannot be predicted by the manufacturer. In planning for the placement of equipment near the laboratory robot and for the safety of workers, the robot purchaser must take into account the additional reach that will be provided by the end effector when attached to the wrist of the manipulator.

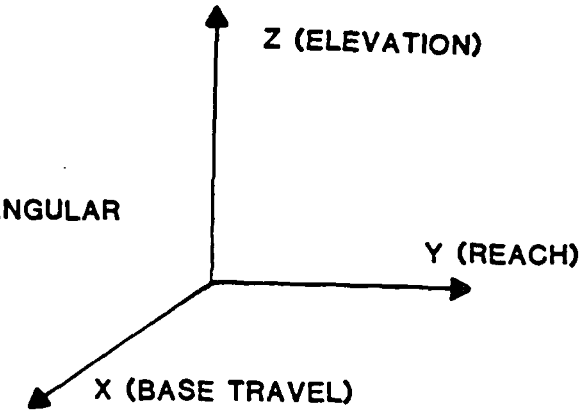
Typical work envelope shapes for each of the basic rotational coordinate systems are shown in Figure B-5. A cylindrical coordinate robot has a work envelope in the shape of a portion of a cylinder. It consists of a horizontal arm attached to a vertical column, which is mounted on a rotating base. Motion is a combination of translational and rotational movements. The horizontal arm moves radially in and out while moving up and down on the column. Both pieces rotate about the base.

The spherical coordinate robot is similar to a tank turret. A boom arm extends and retracts, pivots in a vertical plane and rotates about a vertical axis to trace the outline of a sphere.

The jointed-arm coordinate robot has a manipulator that most closely resembles a human arm. Two arm members are connected to each other, and one arm is connected to a base. The arms are connected by "elbow" and "shoulder" joints to provide three rotational motions. When the wrist is connected to the lower arm an additional three "degrees of freedom" are provided. The wrist axes allow "roll" (rotation in a plane perpendicular to the end of the arm) "pitch" (vertical rotation around the end of the arm) and "yaw" (horizontal rotation around the end of the arm). The resulting motion at the end of the wrist traces an irregular shape that roughly approximates a sphere.

COORDINATE SYSTEM

RECTANGULAR




TYPICAL ROBOT DESIGN

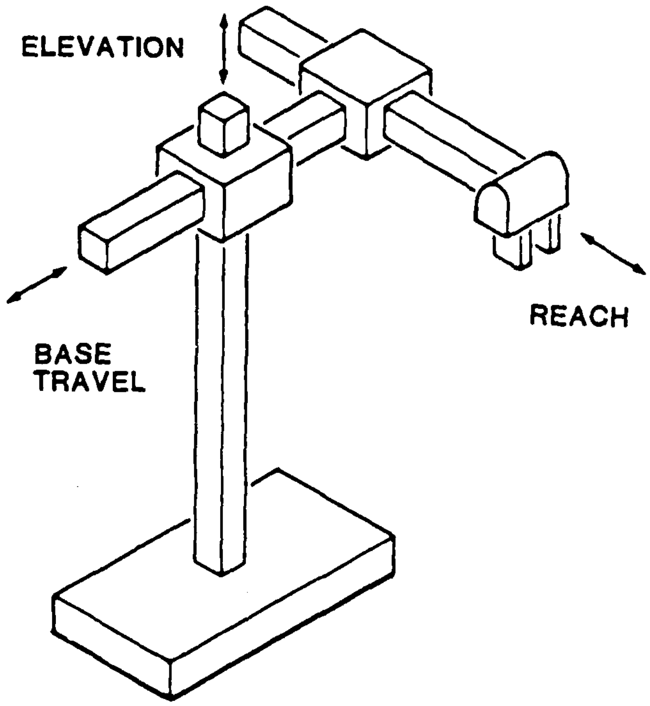
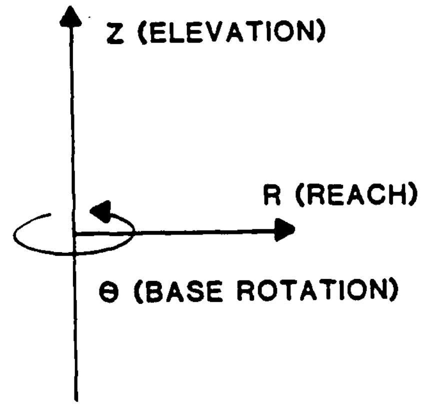



**FIGURE B -1[7] ROBOT CONFIGURATIONS: RECTANGULAR**

COORDINATE SYSTEM

CYLINDRICAL




TYPICAL ROBOT DESIGN

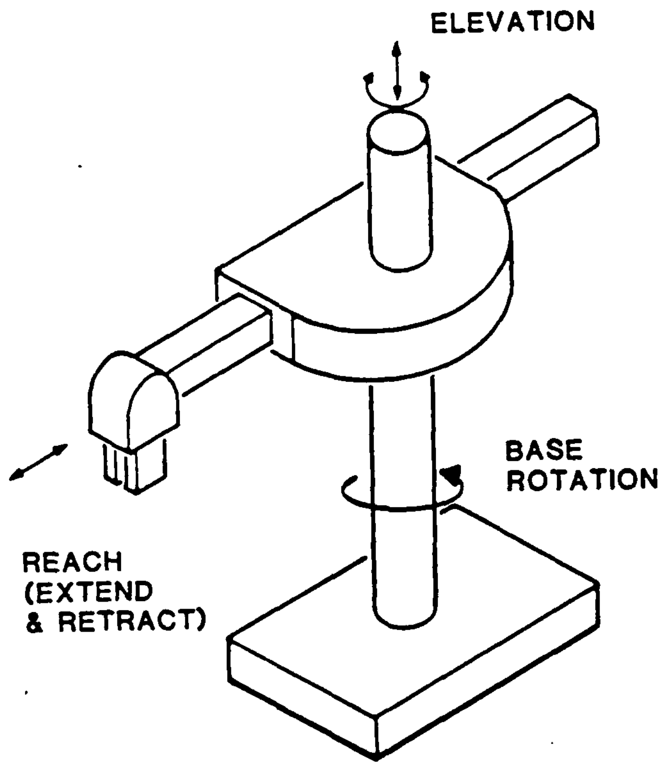
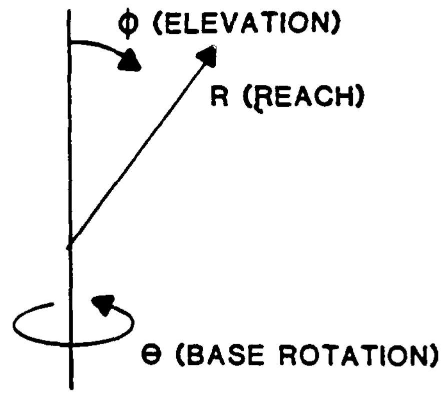



FIGURE B-2[7] ROBOT CONFIGURATIONS: CYLINDRICAL

COORDINATE SYSTEM

SPHERICAL




TYPICAL ROBOT DESIGN

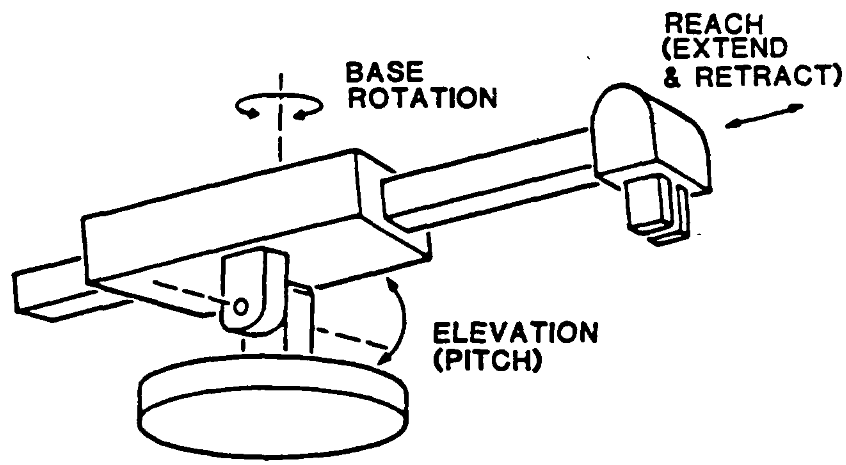
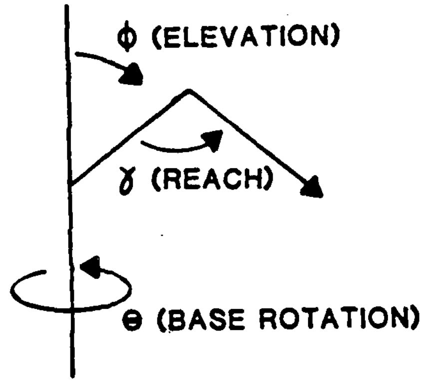



FIGURE B-3[7] ROBOT CONFIGURATIONS: SPHERICAL

COORDINATE
SYSTEM

JOINTED




TYPICAL
ROBOT
DESIGN

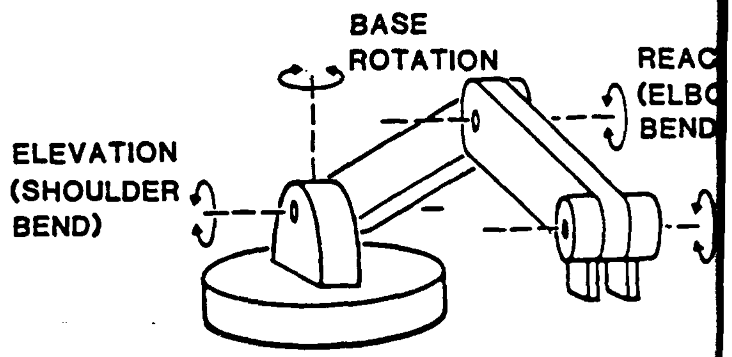



FIGURE B-47 <u>ROBOT CONFIGURATIONS: JOINTED ARM</u>

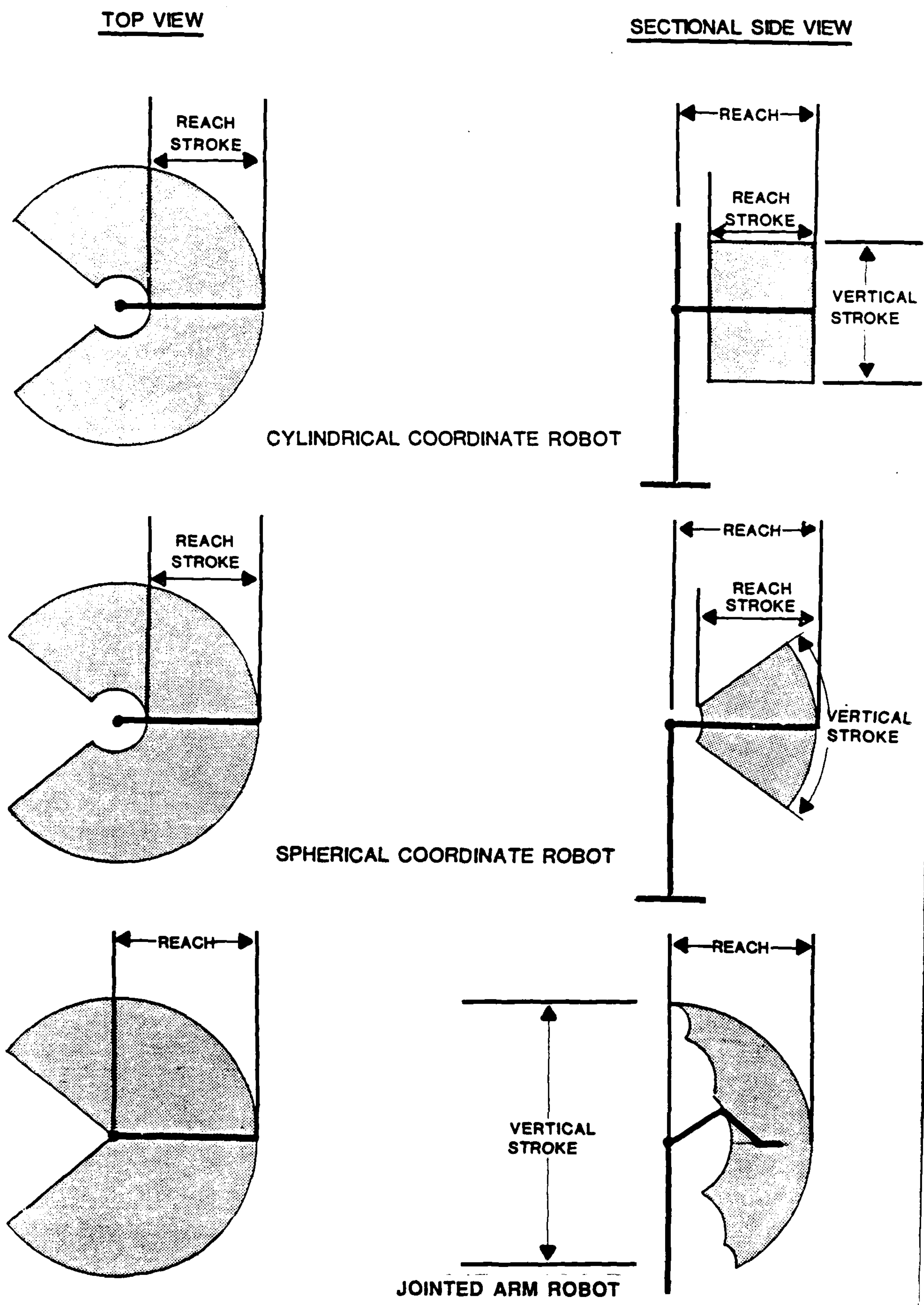



FIGURE B-5[7] ROBOT WORK ENVELOPES

Typical robots in industrial applications have five or six degrees of freedom. A seventh degree of freedom can be achieved by mounting the robot on a movable track (on the floor or overhead) and an eighth is achieved if the track allows motion of the robot in two directions. In summary, a typical six degrees of freedom robot has three axes of motion provided by the arm and an additional three axes provided by the wrist.

Manipulator Arm Operation

The manipulator arm is basically a series of mechanical linkages and joints that move in a specified sequence. The function of the arm is to bring the end effector to a specified point in space. This motion is accomplished by one of three types of drive systems: hydraulic, electric or pneumatic. The arm mechanisms are driven by several actuators which may be pneumatic or hydraulic cyclinders, hydraulic rotary actuators, or electric motors. These actuators either drive the links directly, or they indirectly drive them through gears, chains or ball screws. In the case of hydraulic or pneumatic drives, valves mounted on the manipulator control the flow of air or oil to the actuators.

Hydraulically driven robots have the advantage of mechanical simplicity, strength and high speed. Electrically actuated robots (typical of laboratory robots), most of which are driven by DC servo motors, are generally not as fast or as strong as hydraulic robots, but they tend to be more accurate and can repeat sequences of operations with higher precision. Also, since no hydraulic power unit is required, they save floor space. Pneumatically driven robots are generally used for small "pick and place" type of operations.

In addition to actuators, each link of the manipulator arm has a feedback device which keeps the controller informed of its position. The type of feedback mechanism used can range from a simple limit switch actuated by the manipulator arm to various position measuring devices, such as encoders, resolvers, potentiometers, or tachometers. The type used depends upon several factors, such as the type of movement or the desired resolution. These feedback devices are the internal sensors used by the robot controller to gather information by which to generate signals to move the end effector through space.

End Effectors

An end effector is installed on the mounting surface of the wrist. This is the tooling used to perform the robot's task. The term end effector refers to a gripper (e.g., used to grasp a sample), a tool held by a gripper, or a tool mounted directly on the wrist. An end effector is typically used for one of three basic operations: (1) grasping and manipulating a workpiece; (2) performing manufacturing operations, such as drilling, spraying, or welding; and (3) sensing the position or shape of an item. Most end effectors are designed for a specific application and are provided by the user. However, an increasing number of standard gripper designs are being offered by manufacturers.

A tremendous variety of gripper and tool designs can be used on robots. Grippers are used either to manipulate parts or to hold tools that perform manufacturing operations. Many grippers contain their own actuators to allow relatively complex manipulation and positioning of objects. Although grippers are normally custom designed, three basic categories are currently in use: mechanical, magnetic, or vacuum (using suction cups). Mechanical grippers hold an object by exerting pressure on the part (friction) or by gently placing solid material around the object to physically constrain it from moving. The types of mechanical linkages used include jaw grippers and finger grippers. Jaw type grippers contact the object by bringing two flat surfaces together, either in parallel or at an angle. Finger type mechanical grippers include two-fingered, three-fingered, or multi-fingered devices.

Vacuum and magnetic grippers use attraction as the means of securing an object. Vacuum, or suction cup grippers are especially useful in applications where flat pieces of material must be moved, such as sheet glass. For grasping irregularly shaped objects, magnets or suction cups are normally attached in arrays on specially shaped mountings.

A small sample of the many types of grippers used today is illustrated in Figure B-6. In designing end effectors, it is important to take into account the weight of the tool or gripper and its effect on the load carrying capacity of the manipulator arm. Secondly, the size and shape of the end effector must be considered in determining the ability of the manipulator to maneuver around equipment or other obstacles.

Controller

The controller control unit is the "brain of the robot". The basic function of the controller is to direct the motion of the *manipulator and end effector* so that it is both positioned and oriented correctly in space over time. The controller stores the required sequence of motions of the manipulator arm and end effector in a memory. When requested by an operator, it directs the manipulator through the programmed sequence of motions. At the same time, it interacts with the manipulator and other machines connected with the robot through a series of feedback devices to insure that the correct motions are being followed.

A variety of robot controllers are available. Robot control can be accomplished through the use of a stepping drum programmer, a pneumatic logic sequencer, a diode matrix board, an electronic sequencer, a microprocessor, or a minicomputer. The controller may be integrated into the manipulator arm or it may be a separate unit.

Motion of the manipulator is controlled through the various control and position monitoring feedback devices located on the arm links. The controller continually monitors position, orientation, speed, and acceleration of the end effector and directs it through its operating cycle.

Categories of Robot Control

There are several ways in which robots can be classified including the type of coordinate systems upon which the mechanical configurations are based, the type of applications for which the robots are used, or the general level of sophistication of the technology. The most commonly employed, and technically correct approach to

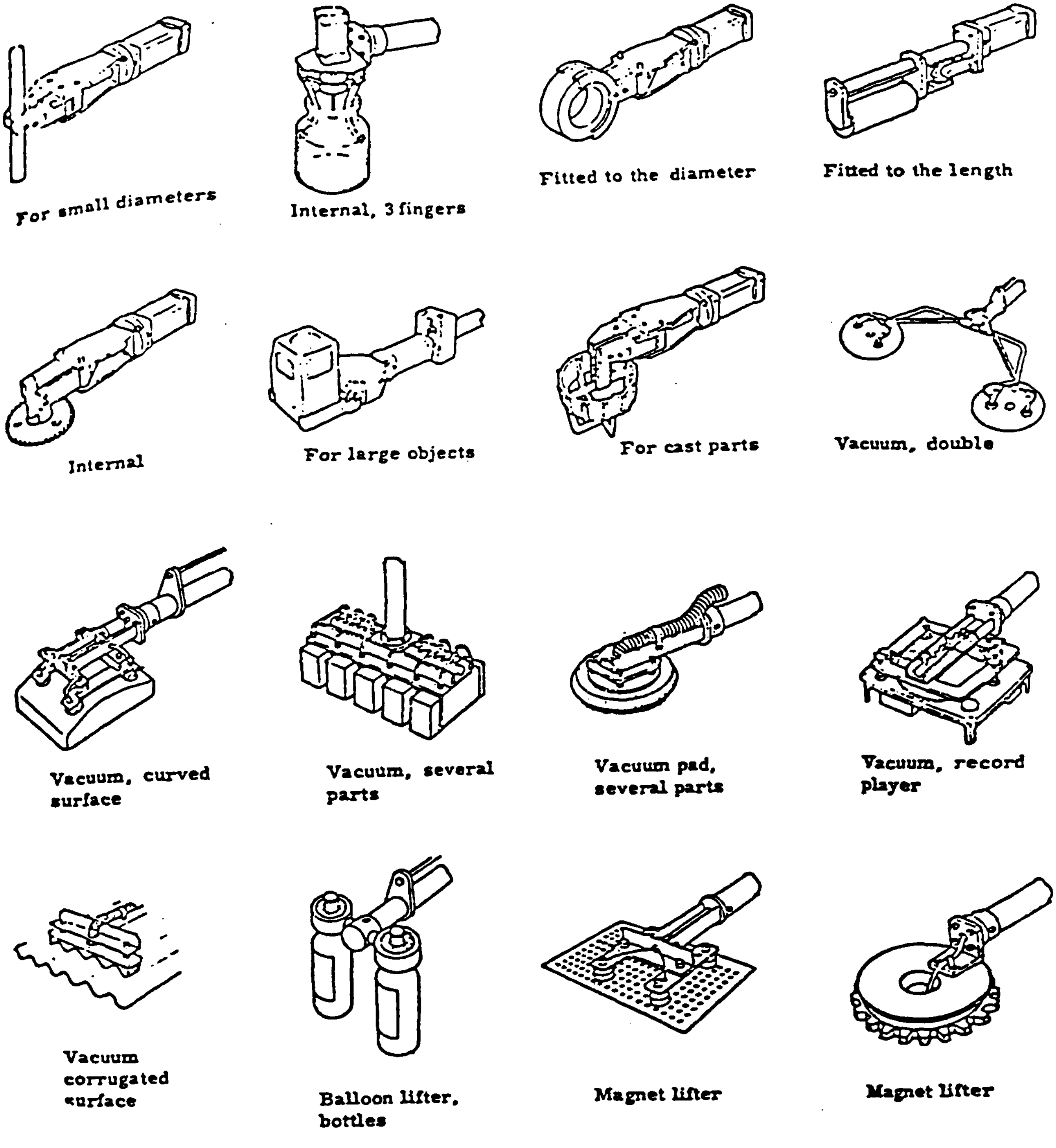



FIGURE B-6[7] SAMPLE ROBOT GRIPPERS

classifying robots is according to the type of control used to direct its motions (Figure B-7).

- Non-servo robots, often referred to as "pick and place", "limited sequence", or "end point" robots, rely on an open loop system for control, in which robot motion is controlled by mechanical stops. These robots move on each axis between two positions (end points) only, although it is possible in some cases to activate intermediate stops on certain axes. The mechanical stops are adjustable so that the movement can vary according to the task to be performed. Although non-servo robots provide relatively high speed operation, a high degree of reliability and a high degree of accuracy when sequences are repeated, they are limited to performing relatively simple tasks, such as transporting parts from one area to another. Typical non-servo robots available in the U.S. include Auto-Place, Seiko, Prab and Mobot.

- Point-to-point servo robots are controlled by a closed loop servo system, in which the position of a robot axis is measured by feedback devices and compared with a predetermined point stored in the controller's memory. If there is a difference, the controller will command a servo on the axis to energize an actuator which then moves the axis to the correct postion. The feedback devices then send new position data back to the controller, and further position corrections are then made as required. Servo robots are capable of executing smooth motions with controlled speeds and accelerations. The point-to-point servo robot is one that is controlled with a servo, but moves in a series of steps from one point to another. The controller can stop each axis at one of any number of points along its axis rather than at only two points, as in the case of non-servo robots. Thus, the manipulative capability of these robots is greatly enhanced. Controllers for these robots include electronic sequencers, mini-computers, microprocessors and solid state electronic memory devices. Point-to-point servo robots are represented by some of the largest robots available. The great majority of robots in use today fall into this category. They are used in a wide variety of applications including material handling, machinery, assembly and others. Typical robots available in the U.S. in this category include ASEA, Cincinnati Milacron, Unimate, Armax and several others.

- Continuous path servo robots differ from point-to-point servo robots since the entire path followed by each axis is programmed on a constant time base during teaching which means that every motion programmed into the robot will be recorded and played back in exactly the same way. In the case of a point-to-point servo robot, only the end points for each motion are stored in memory, while the particular path that will be followed in arriving at each point is not. The continuous path servo robot follows a smooth continuous motion. Because of the large number of positions stored in memory, a greater memory capacity is required for continuous than for point-to-point robots. Continuous robots are generally smaller and can achieve higher end-of-arm speeds than point-

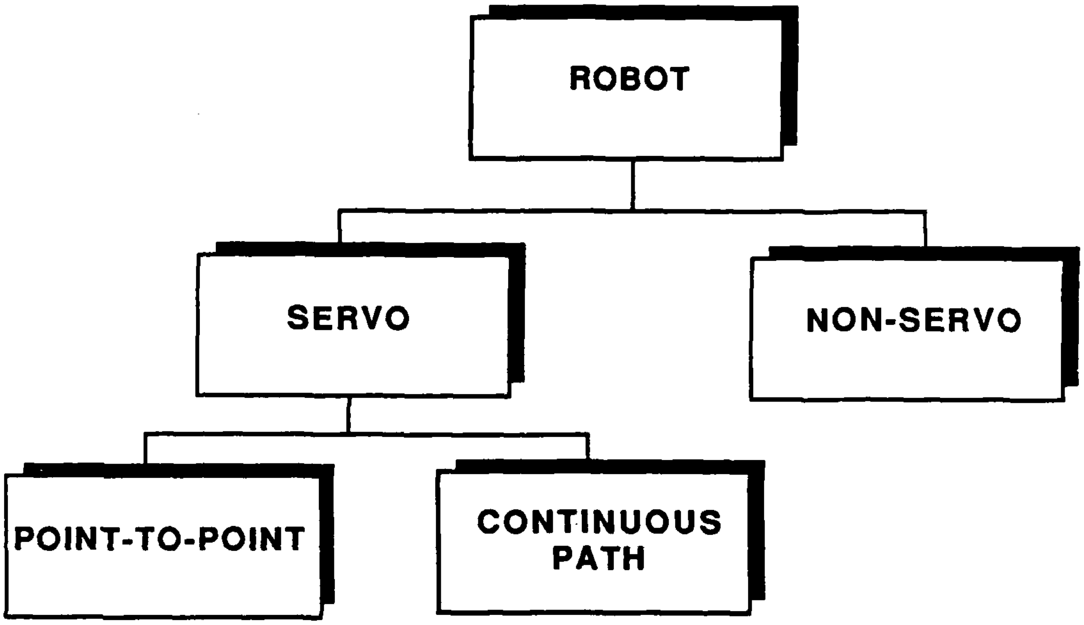



FIGURE B-7 ROBOT CONTROL MODE CLASSIFICATION to-point robots. They are typically used in operations where the particular path followed by the end effector is of special importance, such as in spray painting, polishing, arc welding and other spraying operations. Typical continuous path servo robots available in the U.S. include Cybotech, Nordson, Binks DeVilbiss/Trallfa and Thermwood.

To summarize, non-servo robots are controlled by directing each axis to move between two end points by utilizing an open loop (non-feedback) system. Servo robots use feedback devices on the axes of the manipulator to measure and control the position of the axis at any point within its range. Point-to-point servo robots are programmed to move from one point to another, with a large number of steps possible within a cycle while continuous path servo robots move along a specified precisely determined path with a smooth, continuous motion.

Programming

In order for the controller to be able to direct the motions of the manipulator, the operator must first tell the controller what to do. The process of programming the controller is referred to as "teaching" the robot. There are three basic approaches that can be used to program an industrial robot:

- Manual - Typically used for programming non-servo robots, manual programming is generally associated with controllers that have mechanical, pneumatic, or electrical memories. In this approach, the robot is programmed by physically presetting mechanical devices such as the cams on a rotating stepping drum, setting limit switches on the axes, arranging wires, or fitting air tubes. This approach is feasible for less sophisticated robots that move through only a few steps in their operating cycles.

- Leadthrough - In the case of more sophisticated robots using electronic memories in the controllers, the robot can be "taught" by leading it through the operating sequence by means of a control console or hand-held control box (teach pendant). The robot manipulator is led through each step, and the motion is recorded in memory at the end of each movement. This approach is typically used for programming point-to-point servo robots.

- Walkthrough - Typically used for programming continuous path robots, this approach requires the programmer to manually move the manipulator through a complete operating cycle. These motions are then recorded in memory exactly as they were performed by the operator. This approach requires little knowledge of robotics by the operator, but it requires a great deal of skill in performing the operation which is being taught to the robot. Spray painting and welding are two good examples of operations in which walkthrough programming is used.

- Off-Line Programming - Similar to the type of programming used for part programming in numerical control machining operations, off-line programming involves the development of a program on a computer using a higher level programming language. The program is then entered into the robot controller's memory. In this way, the amount of robot downtime is reduced during teaching. The disadvantage of this approach is that it is difficult to write programs that take into account the positioning in space of the manipulator relative to separate objects in its vicinity. However, it is expected that off-line programming, which is currently used in less than 10 percent of robot applications, will increase significantly in usage in the future.

Memory

The robot's memory or data storage is an integral component of the controller. It stores the programs and then gives commands to the robot through the controller. The type of memory used is important, since it determines the way in which commands are stored. Memory devices can be as simple as mechanical step sequencers such as rotating drums. There may also be pneumatic devices such as patch boards or diode matrices, or more sophisticated electronic memories, such as microprocessor devices (ROM, RAM, magnetic tapes or floppy discs). Generally, the degree of sophistication of the memory is consistent with that of the controller and with that of the robot itself.

Interfacing

Most robots need to interact with other devices, or parts from outside of its immediate environment. For example, a robot cannot transfer a sample until an input signal has been received by the robot that the sample has arrived at the initial position. Once the robot has successfully transferred the sample to the end position it must move clear of the end position and signal that the next sample can be sent to the initial position. Input and output signals can be provided in several ways, such as electrical, pneumatic, or electronic signals. It is in the area of interfacing that external sensing capabilities can play a role. Tactile (touch) sensors, proximity detectors, force feedback devices and vision sensors can all be used in applications in which the robot requires data on the location or position of a part.

Note that these external sensors are differentiated from the internal sensors, or feedback devices, which allow servo robot controllers to interface with the robot manipulators. External sensors, which allow the robot controller to interface with equipment and parts from the outside, represent the highest level of robotics technology currently available. They also represent one of the major areas of future developmental activity in the robotics field.

Sensors

Sensors are not necessary in fixed automation, where every position of an object must be known. In robotics however, motions are much more complex, and so the expense of redesigning tooling to insure precise positioning would be high. The alternative to precise tooling for insuring correct positioning is the use of sensors that can detect certain characteristics of objects through some form of interaction with them. A sensor is simply a feedback device that allows the robot to make changes in its motions based upon information about its external environment.

The two basic categories of sensors currently available are contact and noncontact. Contact (or tactile) sensors are used to measure force, torque, or to simply detect the existence of an object through touching. Force and torque sensors produce signals upon coming into contact with an object that measure the magnitude of the contact forces. Touch sensors produce signals that indicate the presence of an object, but not the magnitude of a force. Therefore, they tend to be lighter and more sensitive to small forces than force on torque sensors. Contact sensors can be used in such applications as sample placing, assembly operations, packaging, collision avoidance, and machining operations. A variety of transducers are used for force sensors, such as strain gauges, magnetic, or piezoelectric transducers. Ideally, a force sensor should measure all three components of force as well as all three components of torque. At the present time, the capabilities of commercially available contact sensors are rather limited. More developmental work is required before force or touch sensors become widely used.

Noncontact sensors are used to determine the characteristics of an object (location, shape, etc.) without coming into direct contact with the object. Three basic types of noncontact sensors are available:

- Proximity sensors - This type of noncontact sensor determines when one object is close to another object. Close is normally defined as a distance ranging from several inches to a few millimeters. Proximity sensors normally do not measure the actual distance, but simply detect the presence of the objects. Commercially available proximity sensors are based upon optical or infrared light detection, magnetic field detection, ultrasound detection, or electrostatic detection.

- Range sensors - A range sensor can be used to measure the distance from the sensor to an object. This can be accomplished using television cameras that measure the distance through triangulation. Another approach is the use of a laser interferometric gauge, which is precise, but expensive, difficult to use and sensitive to environmental conditions. Another relatively new approach is the use of an acoustic range finder based upon the sonar principle. In general, very few commercially available range sensors exist.

- Vision sensors - The most potentially useful type of sensor is that based upon visual feedback. The use of visual sensors can greatly reduce the need for specialized jigs and fixtures, and it can ease part tolerances. Vision sensors can be used to recognize parts and to measure characteristics of the parts. Standard television cameras are often interfaced with computers for part recognition. The difficulty is in translating the information received from the sensor into useful information for the robot. Many research organizations are conducting extensive amounts of research on the problem of developing a low cost, effective visual sensor. The primary applications of visual sensors are to recognize and identify a part by studying its shape, to determine the orientation of a part and to measure the specific position of an object so that the manipulator arm can move to it. Within the next five years, low cost effective vision sensors should be widely available.

Power Supply

The third basic component of an industrial robot (the other two are the manipulator and the controller) is the source of energy that drives the manipulator's actuators. The type of power supply required is generally a function of the type of actuators used in the manipulator arm axes. The power system of a robot must be considered in choosing a type of robot since the performance and capabilities of each type vary according to the type of application being considered. Electrically powered robots tend to run quieter than others and their motors can be enclosed and protected from dirty environments. Pneumatically powered robots are generally used in light duty applications requiring fast operation. Hydraulically powered robots tend to be stronger than others. They are also more accurate, since hydraulic fluid is not compressible.

The power supply for electrically driven robots simply functions to regulate the incoming electricity. Pneumatically powered robots usually receive power from a remote compressor which may also supply power to other machines. In the case of hydraulic robots, a hydraulic power system can be either an integral part of the manipulator or a separate unit.

## Robot Performance Characteristics

The previous sections described the basic physical structure of an industrial robot and the types of applications in which it is used. The purpose of those sections was to tell what a robot is and what it does. In this section, the parameters by which the performance of a robot is measured are reviewed. These characteristics represent some of the more important considerations that a system integrator needs to study when deciding on what type of robot to select for a particular application.

In general, a robot must satisfy three basic requirements. First, it must be flexible. By definition, a robot is not a dedicated machine, but rather offers the advantage of being "multifunctional", as discussed earlier. Therefore, a robot should be capable of being used in several operations. Secondly, an industrial robot must be reliable. The advantage of high utilization because of a high degree of flexibility will be lost if the robot is out of service often for maintenance or repairs. Reliability means a relatively low requirement for maintenance, dependable operation requiring few repairs, and the ability to function satisfactorily in a hostile operating environment (e.g., high temperatures or corrosion). Finally, a robot must be easily programmed. Since a robot can be used for many different tasks, it is likely to require constant reprogramming to change its operating cycle. Because programming causes a certain amount of downtime, it is essential that a minimum amount of time be devoted to this activity. This is one reason that the use of off-line programming is likely to increase in the future.

In addition to these basic general requirements, there are several specific performance characteristics that should be understood and analyzed when considering the purchase of a robot.

- Positioning accuracy - This is a measurement of the ability of the manipulator to position the end effector (tool or gripper) at a specified point ordered by the controller. Accuracy is specified as a range (e.g., ±0.020") around a target point within which the end effector center is expected to position itself upon receiving a command (Figure B-8). Accuracy is a meaningful measurement only in the case of computer controlled systems where the control system has to calculate a position and then command the manipulator to move there. In the case of a "tape recorder" mode, in which the control system simply records positions during teaching, and then plays them back during operation, accuracy is not a consideration. In the case of a spray painting (continuous path) robot using a walkthrough teach program, for example, once the initial sequence is programmed, the important consideration is whether the manipulator can reach the same position again. This is known as repeatability. Most manufacturers and users are more concerned about this measurement which specifies how well the manipulator is able to reach a specified position over and over again (Figure B-8). A repeatability of ±0.010", for example, means that once a certain position has been reached by the end effector, it can be assumed that during the next cycle the end effector will reach a position that is within 0.010" of the original position.

- Reliability (Uptime) - The reliability of a robot is normally specified as the percentage of time during which the robot can be expected to be operating normally (i.e., not out of service for maintenance or repairs). In general, reliability for industrial robots is very good, with typical estimates of 96-98% uptime claimed by robot manufacturers. In most cases, robot users have found that these estimates are correct.

- Mean time before failure - This is a measure of the estimated number of hours that a robot is expected to operate until it encounters its first failure requiring downtime. Most manufacturers claim a time of between 200 and 800 hours for their robots, with some estimates ranging as high as 2,000 hours. This will increase as the technology matures.

- Payload capacity - The amount of weight that an industrial robot can carry during operation is an important consideration in determining the size of robot required. The payload capacity is the maximum weight that can be carried by a robot at low speed (given as a percentage of maximum speed), and at normal operating speed. These numbers typically range from just one or two pounds up to well over 2,000 pounds.

- End of arm speed - This is a difficult measurement to accurately define, because of the variations in arm movements positioning, and load being

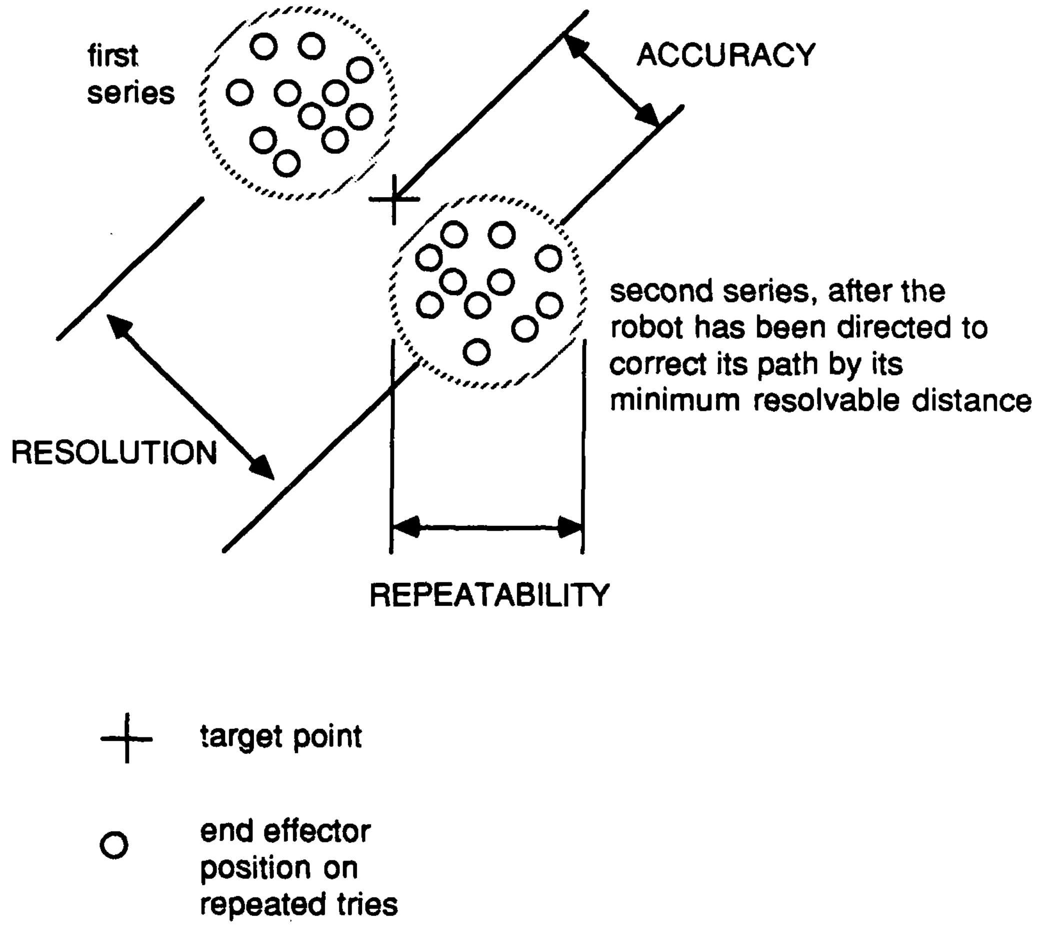



**FIGURE B-8** **<u>ACCURACY, REPEATABILITY and RESOLUTION</u>**

carried. However, it is useful to compare the speeds with which robots can move an object from one point to another and back again. Typical speeds of current robots are in the range of 30-60 inches per second; non-servo robots tend to be somewhat faster than servo robots.

- Memory Capacity - The memory capacity of a servo robot controller is an important feature since it determines the length and complexity of the operating cycle which can be performed. Non-servo robots do not possess a memory as it is normally defined. Memory capacity is defined by the number of steps or motions which can be performed during one operating cycle. Most commercially available robots offer up to several hundred steps (or "points") in storage capacity. In this way, the motion of a point-to-point robot can be programmed so precisely that the movement of the manipulator arm looks like that of a continuous robot.

The taxonomy of a generic robot discussed in this section is summarized in Figure B-9.

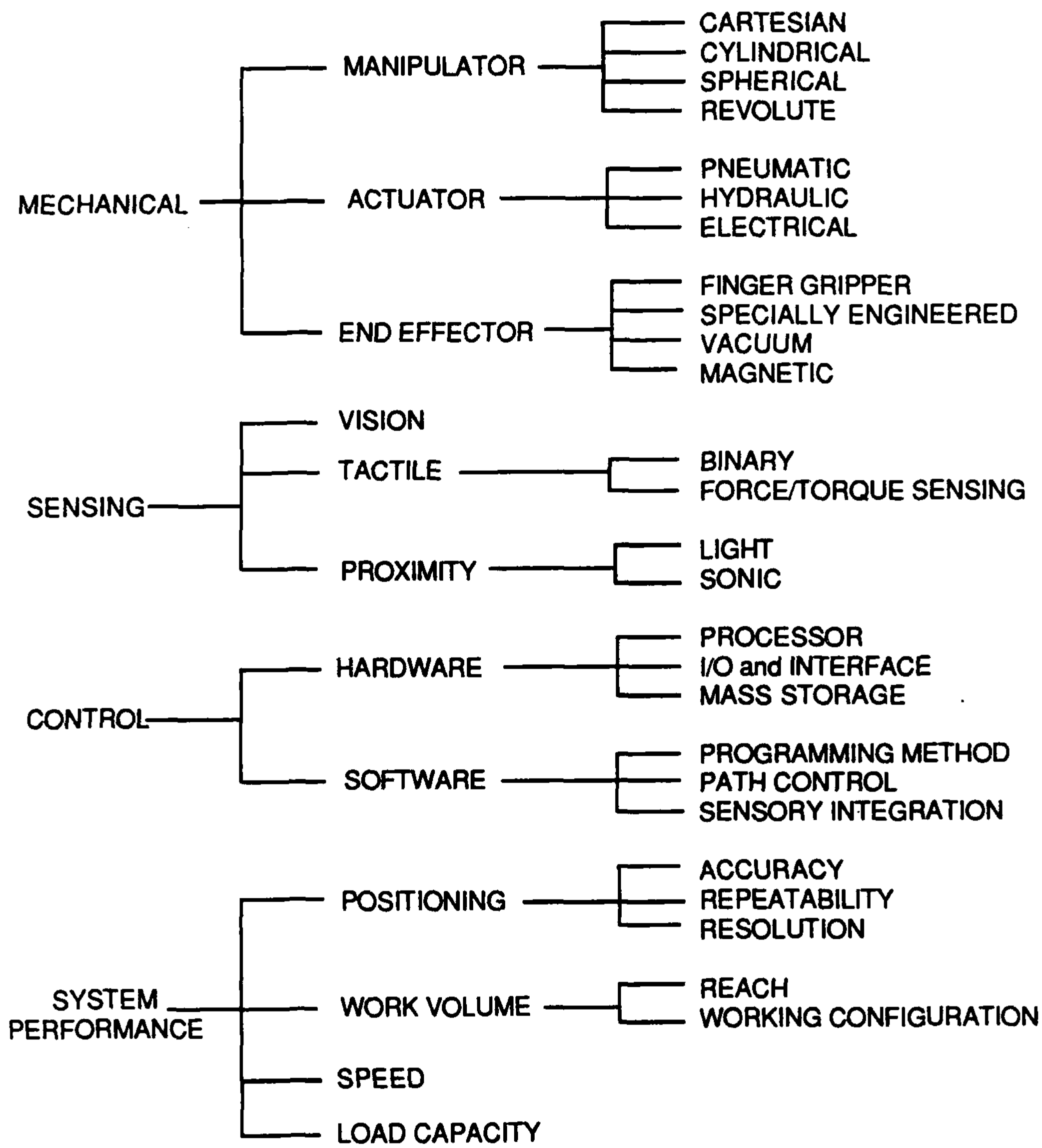



**FIGURE B-9** **TAXONOMY OF A GENERIC INDUSTRIAL ROBOT**

# APPENDIX C

## Selected Glossary of Robotics Terms

ACCURACY - The ability of the manipulator to position the end effector (tool or gripper)at a specified point in space upon receiving a command by the controller.

ACTUATOR - transducer that converts electrical, hydraulic, or pneumatic energy to cause motion of the robot.

ARM - An interconnected series of mechanical links and joints that support and move the end effector through space.

ARTIFICIAL INTELLIGENCE - The ability of a machine to perform certain complex functions normally associated with human intelligence such as judgement, pattern recognition, understanding, learning, planning and problem solving.

BASE - The platform which supports the manipulator arm.

CLOSED LOOP CONTROL - Robot control which uses a feedback loop to measure and compare actual system performance with desired performance, and then makes adjustments accordingly.

COMPUTER-AIDED DESIGN (CAD) - The use of a computer to assist in the design of a product or manufacturing system.

CONTACT SENSOR - A device that detects the presence of an object or measures the amount of force or torque applied by the object through physical contact with it.

CONTINUOUS PATH MOTION - A type of robot motion in which the entire path followed by the manipulator arm is programmed on a constant time base during teaching. so that every point along the path of motion is recorded for future playback.

CONTROLLER - The robot brain, which directs the motion of the end effector so that it is both positioned and oriented correctly in space over time.

CYCLE - One complete sequence of robot motions from the start of one operation to the start of another.

CYLINDRICAL COORDINATE ROBOT - A robot whose manipulator arm moves along a cyclindrical coordinate system so that the work envelope forms the outline of a cylinder.

DEGREES OF FREEDOM - The number of independent ways in which the end effector can move, defined by the number of rotational or translational axes through which motion can be achieved.

END EFFECTOR - The tool or gripper which is attached to the mounting surface of the manipulator wrist in order to perform the robot's task.

EXTERNAL SENSOR - A feedback device for detecting locations, orientations, forces, or shapes of objects outside of the robot's immediate environment.

FLEXIBILITY - The ability of a robot to perform a variety of different tasks.

FORCE SENSOR - A device that detect and measures the magnitude of the force exerted by an object upon contacting it.

GRIPPER - The hand of the manipulator which is used by the robot to grasp objects.

HARD AUTOMATION - Automated machinery that is fixed, or dedicated to one particular manufacturing task throughout its life.

HIERARCHICAL CONTROL - A control technique in which the processes are arranged in a hierarchy according to priority.

HYDRAULIC MOTOR - An actuator which converts forces from high pressure hydraulic fluid into mechanical shaft rotation.

INTERFACE - A boundary between the robot and machines, transfer lines or parts outside of its immediate environment. The robot must communicate with these items through input/output signals provided by sensors.

INTERLOCK - A safety device which prevents the robot from operating further until some condition has been satisfied.

INTERNAL SENSOR - A feedback device in the manipulator arm which provides data to the controller on the position of the arm.

JOINTED ARM ROBOT - A robot whose arm consists of two links connected by "elbow" and "shoulder" joints to provide three rotational motions. This robot most closely resembles the human arm.

LEADTHROUGH PROGRAMMING - A means of teaching a robot by leading it through the operating sequence with a control console or a hand-held control box.

LIMIT SWITCH - An electrical switch that is actuated when the limit of a certain motion is reached and the actuator causing the motion is deactivated.

PITCH - Rotation of the end effector in a vertical plane around the end of the manipulator arm.

POINT-TO-POINT MOTION - A type of robot motion in which a limited number of points along a path of motion is specified by the controllers and the robot moves from point to point rather than in a continuous, smooth path.

PROGRAMMABLE - A feature of a robot that allows it to be instructed to perform a sequence of steps and then to perform this sequence in a repetitive manner. It can then be reprogrammed to perform a different sequence of steps, if desired.

PROXIMITY SENSOR - A noncontact sensor which determines when one object is close to another.

RECTANGULAR COORDINATE ROBOT - A robot whose manipulator arm moves in linear motions along a set of cartesian, or rectangular axes. The work envelope forms the outline of a three dimensional rectangular figure.

RELIABILITY - The percentage of time during which the robot can be expected to be in normal operation (i.e., not out of service for repairs or maintenance). This is also known as the uptime of the robot.

REPEATABILITY - The ability of the manipulator arm to position the end effector at a particular location within a specified distance from its position during the previous cycle.

ROBOT - A reprogrammable multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motion for the performance of a variety of tasks.

ROLL - Rotation of the end effector in a plane perpendicular to the end of the manipulator arm.

ROTATIONAL MOTION - A degree of freedom that defines motion of rotation about an axis.

SENSOR - A feedback device which can detect certain characteristics of objects through some form of interaction with them.

SERVO CONTROL - The control of a robot through the use of a closed loop servo system, in which the position of a robot axis is measured by feedback devices and compared with a predetermined point stored in the controller's memory.

SHOULDER - The manipulator arm link joint that is attached to the base.

SPEED - The maximum speed at which the end of the manipulator arm can move at a certain load.

SPHERICAL COORDINATE ROBOT - A robot whose manipulator arm moves along a spherical coordinate system (radial motion plus two angles), so that the work envelope forms the outline of a sphere.

TACTILE SENSOR - A sensor that detects the presence of an object or measures force or torque through contact with the object.

TEACHING - The process of programming a robot to perform a desired sequence of tasks.

TOUCH SENSOR - A sensor that detects the presence of an object by coming into contact with it.

TRANSLATIONAL MOTION - Movement of a robot arm along one of three axes without rotation.

VISION SENSOR - A sensor that identifies the shape, location, orientation, or dimensions of an object through visual feedback such as a television camera.

WALKTHROUGH PROGRAMMING - A method of programming a robot by physically moving the manipulator arm through a complete operating cycle. This is typically used for continuous path robots.

WORK ENVELOPE - The three dimensional space that defines the entire range of points which can be reached by the end effector.

WRIST - The manipulator arm joint to which an end effector is attached.

YAW - Rotation of the end effector in a horizontal plane around the end of the manipulator arm.

# APPENDIX D

## List of Manufacturers/Vendors

## Computer Controlled Dispensers

| Company Name | Product Name | Location |
|---|---|---|
| PA Technology | High Accuracy, Computer Controlled Dispensers (Custom Engineered Systems) | Highstown, NJ |
| Chem Mix | Meter Mix Dispense Assembly | Medford, MA |
| Tridak | Designer & Manufacturer of Standard and Custom Dispensing Equipment | Brookfield, CT |
| Max Machinery, Inc. | Design and Manufacture Liquid Metering, Mixing and Dispensing Equipment | Healdsburg, CA |
| Glenmarc Manufacturing, Inc. | Design and Manufacture Liquid Metering, Mixing and Dispensing Equipment | Northbrook, IL |
| K-Tron Corporation | Design and Manufacture Liquid & Solid Dispensing Equipment with Advanced Controls | Pitman, NJ |
| Hierath & Adrews Corp. | Net Weight Powder Filling Systems | Wheat Ridge, CO |

## Laboratory Automation

| Company Name | Product Name | Location |
|---|---|---|
| Radian Corporation | Sam™ (Sample and Analysis Management) LIMS | Austin, TX |
| Intellution | The FIX™, Process Management and Control Software | Westwood, MA |
| Perkin Elmer | LIMS 2000, Database for Tracking Sample Flow through a Laboratory | Norwalk, CT |
| Trivector | STAR Lab, Powerful Laboratory Management Software | West Chester, PA |
| Strawberry Tree Computer | Laboratory & Industrial Data Acquisition & Control Products for PC and Apple Macintosh | Sunnyvale, CA |
| Solartron Instruments | IMPULSE, Data Acquisition Package | Elmsford, NY |
| Beckman | Computer Automated Laboratory System (CALS) | Waldwick, NJ |
| CyberResearch | Data Acquisition & Instrumentation for IBM PC, XT, or AT | New Haven, CT |
| Rebus Development Corp. | Parameter Manager Plus™ (pmPLUS™) Technical Spreadsheet complete data and acquisition analysis solution | San Jose, CA |
| ACRO Systems | Data Acquisition & Control Instruments (ACRO 900 Series) | Beverly, MA |
| National Instruments | LabView (Laboratory Vertual Instrument Engineering Workbench) | Austin, TX |
| Seagull Scientific Systems | The non-contact Bar-Code Reader Reader Package | Sacramento, CA |

## General

| Company Name | Product Name | Location |
|---|---|---|
| Brookfield Engineering Laboratories, Inc. | Viscometers (Dial Reading and DigitalDisplay) | Stoughton, MA |
| ELGAR | Elgar's FailSafe Software-The Intelligent Power Protection System | San Diego, CA |
| Haake Buchler Instruments | Haake Viscometers | Saddle Brook, NJ |
| Charleswater | Static Control Equipment (Conductive Floor Finish, Table/ Floor Mat, etc.) | Glendale, CA |
| Mettler | Balances | Hightstown, NJ |
| Sartorius | Balances | Westbury, NY |
| OHAUS | Balances | Florham Park, NJ |
| Baker Perkins | Vertical Mixers | Houston, TX |
| Blue M | Constant Temperature Controlled Equipment Ovens | Blue Island, IL |
| Hotpack Corp. | Ovens | Philadelphia, PA |
| Heat Systems Ultrasonics | Ultrasonic Cleaning Devices | Farmingdale, NY |
| Mettler Electronics Corp. | Ultrasonic Cleaners | Anaheim, CA |
| Sonics & Materials, Inc. | High Intensity Ultrasonic Processor | Danbury, CT |
| Finnish Engineering Co. | Solvent Distillation System and Recovery | Erie, PA |
| Chugai International Corp. | "Computer" CCD Cameras for Machine Vision and Robotics | Torrance, CA |
| Tomita Co., Ltd. | Robotic Components-End Effectors | Bedford, MA |
| Recora Company | Switchmat-Units for Efficient, Safe Equipment Operation | St. Charles, IL |

## General Cont'd

| Company Name | Product Name | Location |
|---|---|---|
| Ross Operating Valve Co. | Air Control Products | Troy, MI |
| Fabco-Air, Inc. | Valves and Cylinders | Gainesville, FL |
| Anorad Corporation | A Complete Positioning Company | Hauppauge, NY |

## Laboratory Robotic Systems

| Company Name | Product Name | Location |
|---|---|---|
| Zymark Corporation | Zymate System - A Unique Laboratory Automation System | Hopkinton, MA |
| Perkin-Elmer | MasterLab System for Automated Sample Preparation | Norwalk, CT |
| Precision Robots, Inc. | PRI Autobench 3000 | Woburn, MA |
| Adept Technology, Inc. | The Adept One™ and Adept Two™ Robot Systems; the Adept Vision™ Systems. | San Jose, CA |
| CRSPLUS, Inc. | Small Laboratory Robot System | Ontario, Canada |
| Microbot, Inc. | Alpha II, Programmable Robot for Laboratory Automation | Mountain View, CA |

**Automated Guided Vehicles**

| Company Name | Product Name | Location |
|---|---|---|
| Litton Automated Vehicle Systems | The Litton Series 500 Automated Guided Vehicles | San Diego, CA |
| United States Robots | The GV-30 Mobile Conveyor System | Carlsbad, CA |
| Eaton-Kenway | OPTRAC Automatic Guided Transfer | Salt Lake City, UT |
| EDCOM, Inc. | Motormouse I, Automated Guided Vehicle | Manchester, NJ |
| Cybermation | The K2A Mobile Platform | Roanoke, VA |
| Apogee Robotics | The Automatic Guided Vehicle System(AGV) - ORBITOR | Fort Collins, CO |