TECHNICAL REPORT NO. 11870 (LL-145)

# CYBERNETICALLY COUPLED RESEARCH VEHICLE
(An Interim Report)



January 1974

Contract No. DAAE07-72-C-0164

by
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Surface Mobility Division
and
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TACOM

MOBILITY SYSTEMS LABORATORY
U.S ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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ABSTRACT

This report describes the basic principles of operation and performance of the Cybernetically Coupled Research Vehicle.

This vehicle (consisting of two coupled M113 APC's) offers significant improvements in cross-country mobility, particularly in obstacle negotiation, and has demonstrated its potential as a research tool for exploration of the principles of controlling articulated vehicles with and without force feedback.

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# I. INTRODUCTION

As part of the Army's "New Initiatives Program", one of the missions of the Surface Mobility Division of the U. S. Army Tank-Automotive Command (TACOM) has been to conduct research in the area of cybernetic force feedback servo mechanisms to improve man-machine interaction and responsiveness and, thereby, to enhance the off-road mobility of existing or future Army vehicles. The Cybernetically Coupled Research Vehicle is part of that program.

Studies with the Jeep Train, the Polecat and other articulated vehicles have already demonstrated that coupling and/or articulation produces sufficient gains in mobility and allows the coupled units to negotiate certain terrain features which would be impassable to a single-frame vehicle. The improved performance comes from both the additional flexibility of the system and from the inter-vehicle assist.

Recently, studies with the Cobra have demonstrated that a significant additional improvement in coupled vehicle capabilities can be achieved by controlling pitch articulation. However, this increased capability imposes a difficult control and information processing problem on the driver. Consequently, an important part of this study was to employ existing knowledge of cybernetic feedback control in order to provide the driver with additional information which can make his driving task easier, thereby enhancing the performance of the man-vehicle system.

Two production M113 APC's were chosen as the basic vehicles for this study since they are readily available, reliable, and have an obviously apparent application. Using them could also demonstrate that it is possible to retrofit a special purpose system on existing hardware, and there would be available single-unit counterparts for direct comparison of performance.

The operational and performance specifications chosen for the proposed system were:

1. Climb vertical steps up to 5 foot high.

2. Cross trenches up to 10 feet wide.

3. Climb a 60% slope of 15 foot length with soil parameters of a coefficient of adhesion equal to c = 1 psi and an internal friction angle of $\phi = 25°$.

4. Pitch articulate $\pm 45°$; yaw $\pm 30°$.

5. Cross a 2-1/2 foot high obstacle at 2-1/2 mph.

6. Operate over various adverse terrains.

7. Be able to be controlled from either front or rear unit.

8. Be able to enter into, cross and exit from inland waterways.

To meet these requirements, a design was chosen which basically consists of connecting the two vehicles by means of a ball joint with roll, pitch and yaw freedom. Controlling this motion were two hydraulic cylinders (Figure 1).

## II. OBJECTIVES

The principle objectives of this program are:

1. To investigate the potential of a controlled articulation joint between two identical vehicles employing cybernetic feedback.

2. To compare the differences in mobility, especially obstacle crossing characteristics (including water obstacles), between the coupled vehicle system and the single vehicle.

On a longer term basis there are also the following objectives:

3. To use this test bed as a research tool in the study of articulated vehicle systems.

4. To provide input data to the theoretical analysis of such systems.

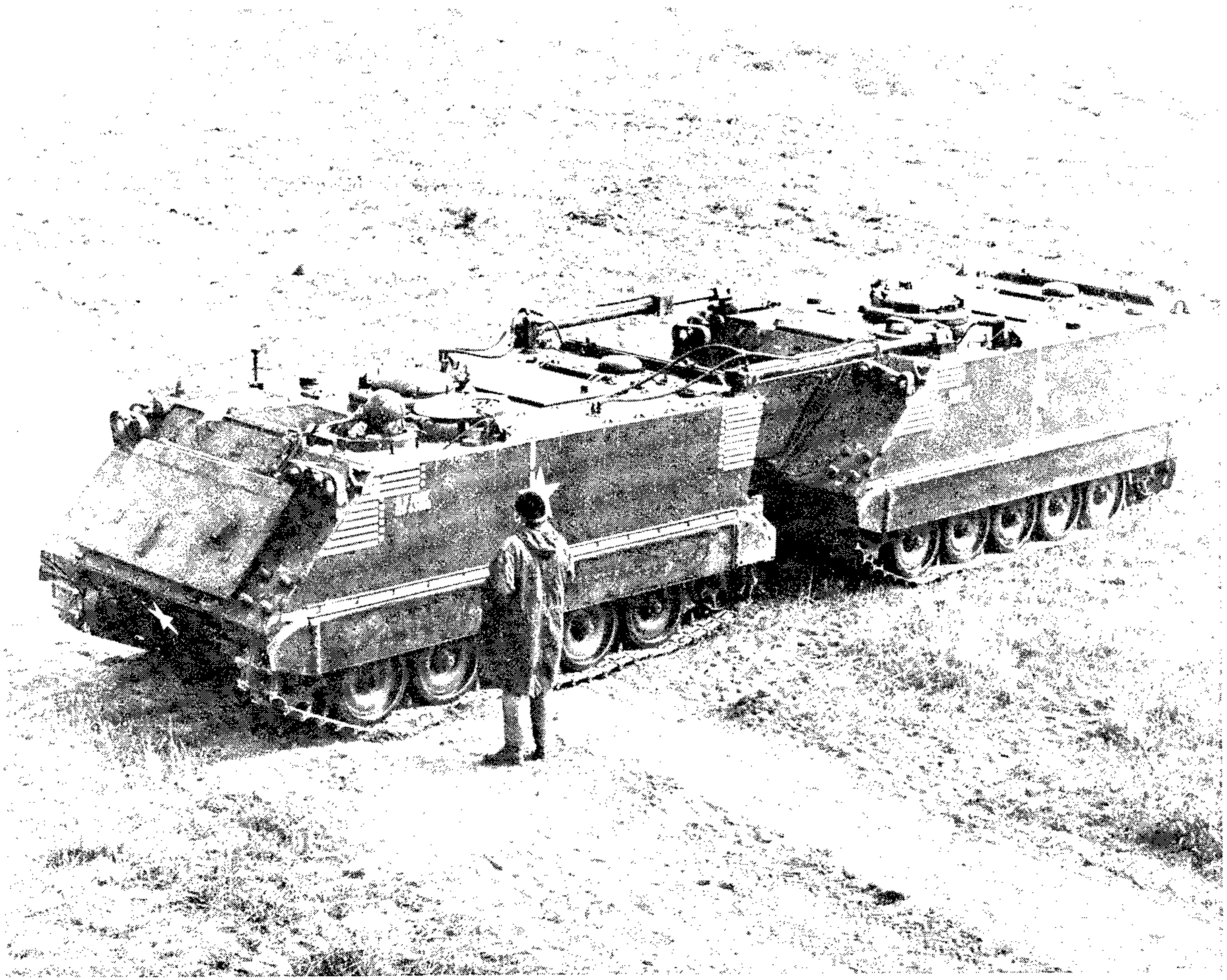


Figure 1: Cybernetically Coupled M113 APC's

5. To provide a means of verifying the theoretical analysis and mathematical models of cybernetically controlled articulated vehicle systems.

6. To apply the theory established to the design of future vehicle systems employing articulation with or without cybernetic feedback.

## III. SYSTEM DESCRIPTION

The cybernetically controlled articulation joint coupling the two vehicles features positive pitch and yaw control with roll freedom. Force feedback is provided for the pitch motion only. The system is controlled by a single "joy-stick" lever located in the driver's compartment. Both the engine and transmission controls of each unit are sychronized so that the vehicles can be driven as one unit from either cockpit. The individual vehicle integrity is not disturbed so each vehicle can operate independently when uncoupled.

The articulation motion is controlled by an electro-hydraulic servo system, the engine and transmission controls by an electro-mechanical servo system. All the components are standard off-the-shelf commercial items with the exception of the drawbar and the cylinder mounts.

The inter-vehicle connection basically consists of a spherical ball joint and two hydraulic cylinders. The ball joint socket is mounted in the apex of an A-frame which is rigidly attached to the base of the rear vehicle. The connection to the forward vehicle extends from this ball joint which is the geometric center of rotation between the two vehicles and provides the necessary freedom in roll, pitch and yaw (Figure 2). The two hydraulic cylinders mounted on the adjoining top corners of the vehicles provide the forces and moments necessary for both pitch and yaw control. Thus, the design may be called a "three-point coupling". The basic layout of this coupling system is shown in Figure 3.

In order to counteract the nose-heaviness of the M113, the ball joint was located as close as possible toward the forward vehicle. This increases the moment

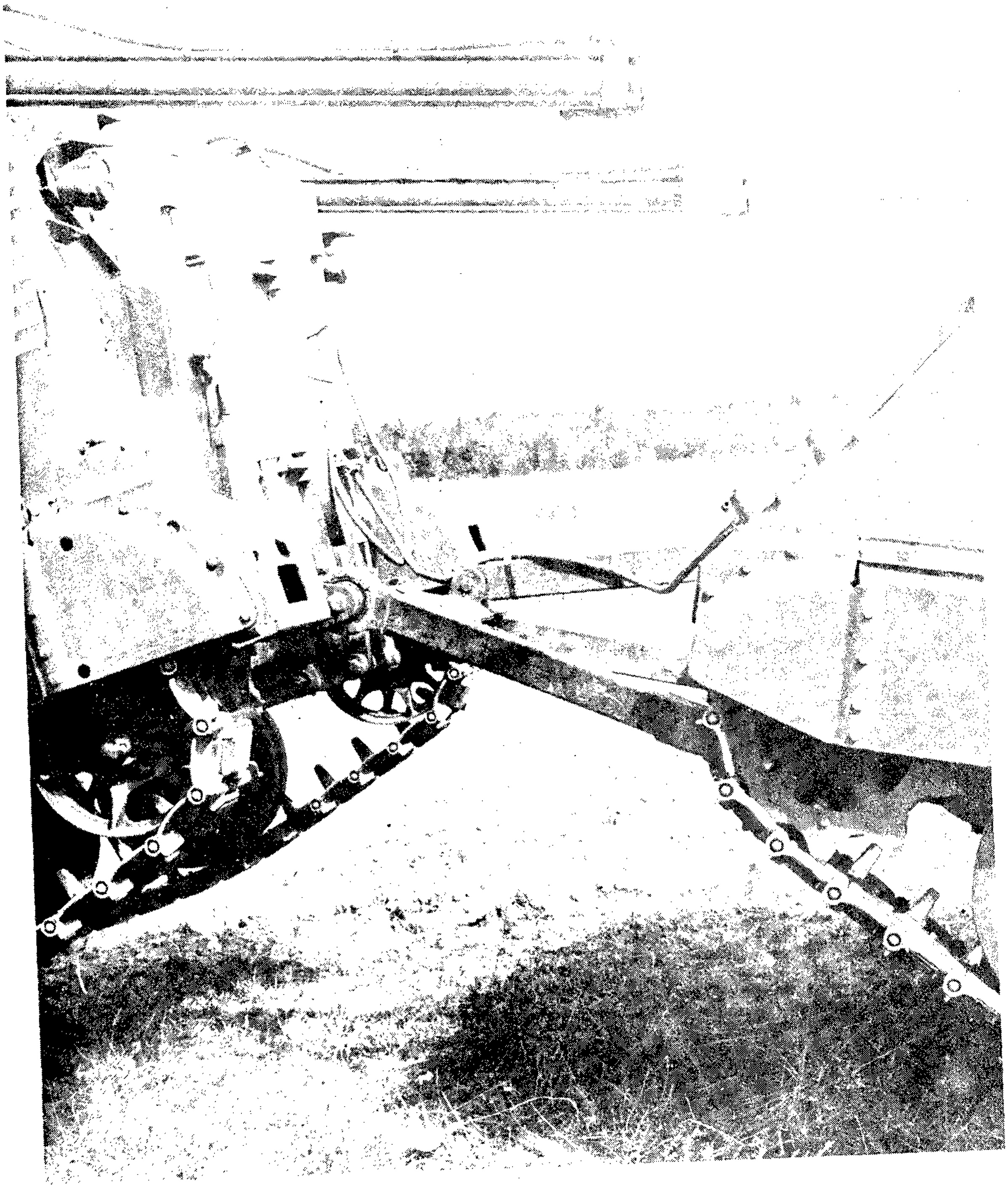


Figure 2: Inter-Vehicle Joint, Free to Pitch, Yaw and Roll

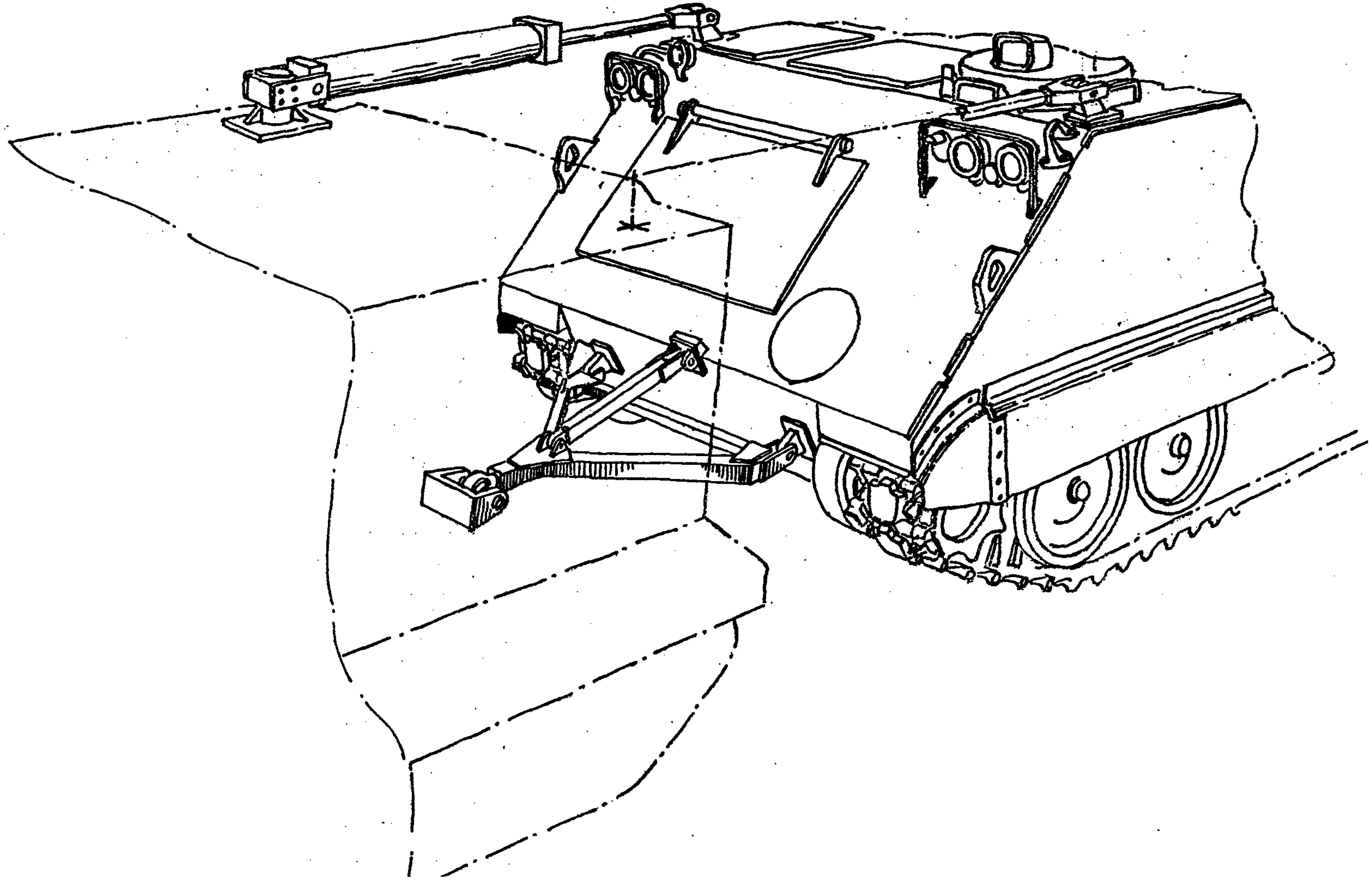


Figure 3: Basic Layout of Coupling System

arm between the pitch pivot point and the center of gravity of the rear vehicle, thereby increasing the pitch angle of the forward vehicle during pitch articulation. The two hydraulic cylinders generate pitch motion by simultaneous contraction or extension (Figures 4 and 5). Yaw motion is generated by simultaneously contracting one cylinder and extending the other (Figure 6). Roll motion is not controlled but the vehicles are allowed to conform to the terrain. The available pitch motion is 25 degrees up and 28 degrees down, mechanical restrictions make greater angles impractical. Yaw motion is 31 degrees in both directions.

All of the hydraulic components and their controls are located in the forward vehicle. Each hydraulic cylinder (actuator) is powered by its own 45 gpm, variable delivery, in-line piston pump. The rate of actuator travel is a function of both pump speed and pump stroke. Both pumps are driven by a common shaft connected by a coupling to the transfercase power take-off, thus pump speed is directly proportional to engine speed. The amount of pump stroke, and therefore the flow direction and delivery of each pump is controlled by an electronic servo control system. Flow in one direction will cause the cylinder to contract; flow in the other, to extend. The times to reach maximum pitch from a level attitude are 2 and 4 seconds respectively for full up and down. Maximum yaw takes 5 seconds to either side from straight ahead.

The electronic servo system which controls the pump stroke responds to a command voltage proportional to control stick position. In order to be able to control pitch and/or yaw attitude between the two vehicles (actuator displacement as distinguished from actuator velocity), a position feedback potentiometer was attached to the rod end of each actuator. With this added feature, percent pump stroke is therefore a function of the difference between the control stick position and actuator displacement. Because the position feedback potentiometer on the actuator piston nulls the command signal from the control signal when the appropriate actuator displacement is achieved, the pumps automatically return to neutral stroke (zero flow) and the desired vehicle attitude is maintained. Without this position feedback potentiometer a distinct actuator displacement could not be maintained since a conventional hydraulic servo system is inherently a velocity (flow) control system.

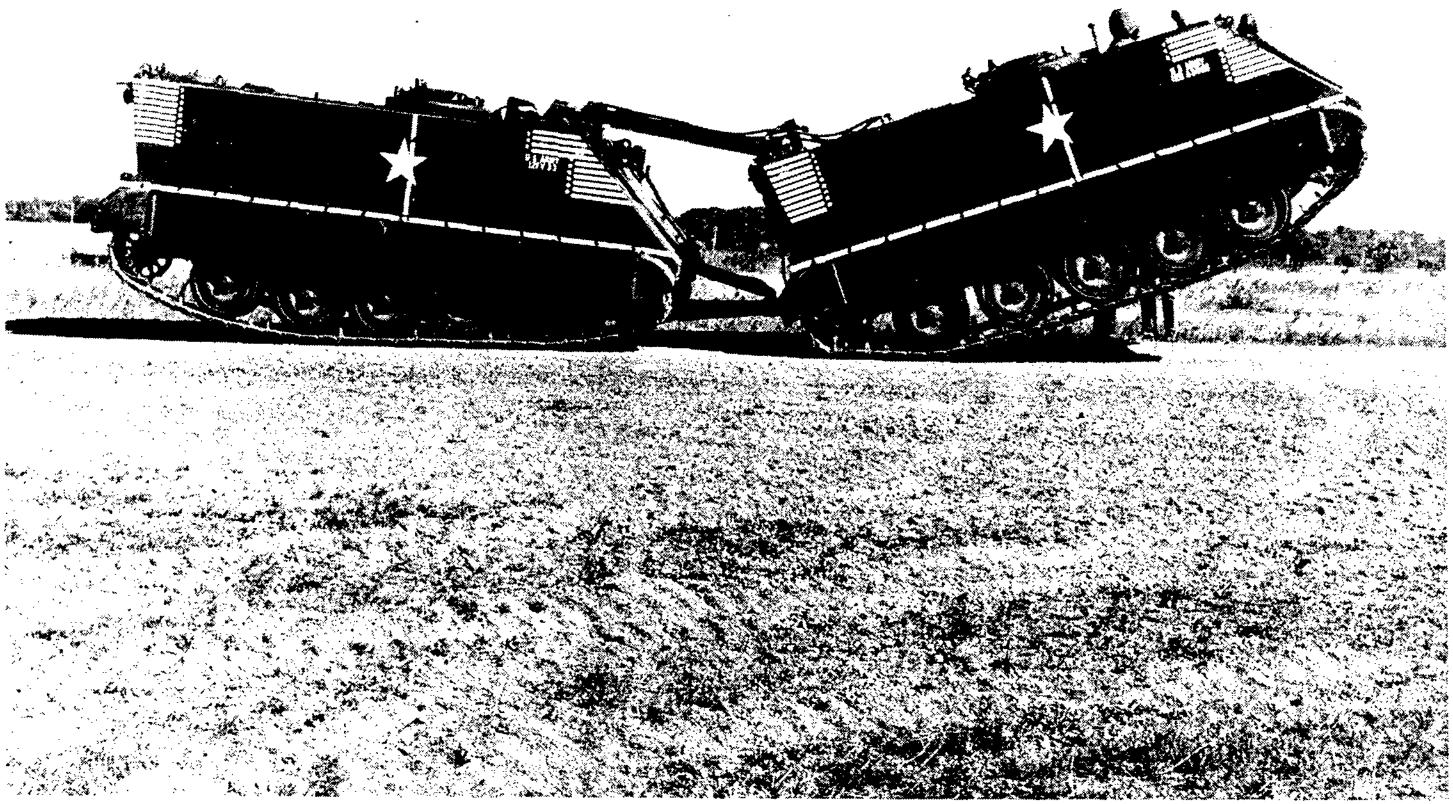


Figure 4:  Coupled Vehicles Pitching Up

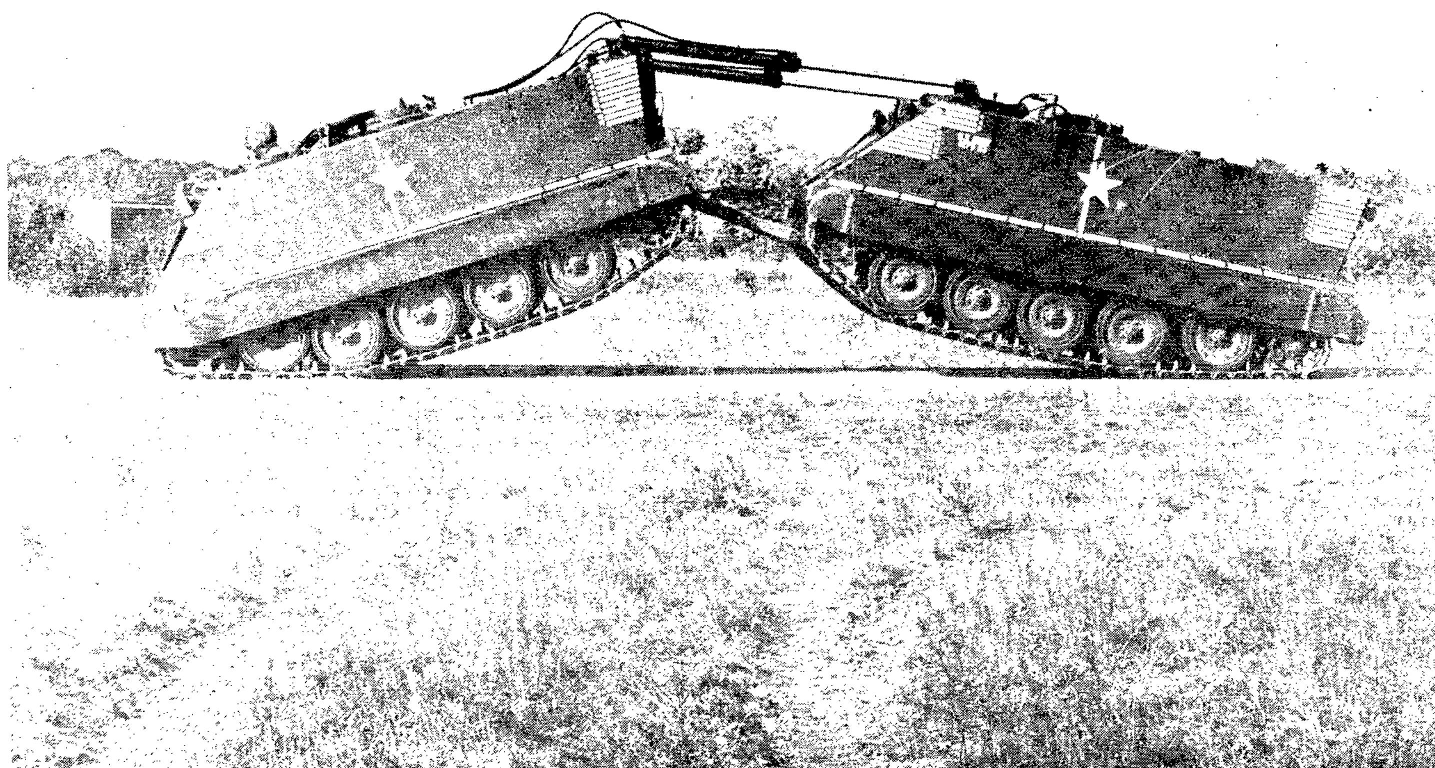


Figure 5: Coupled Vehicles Pitching Down

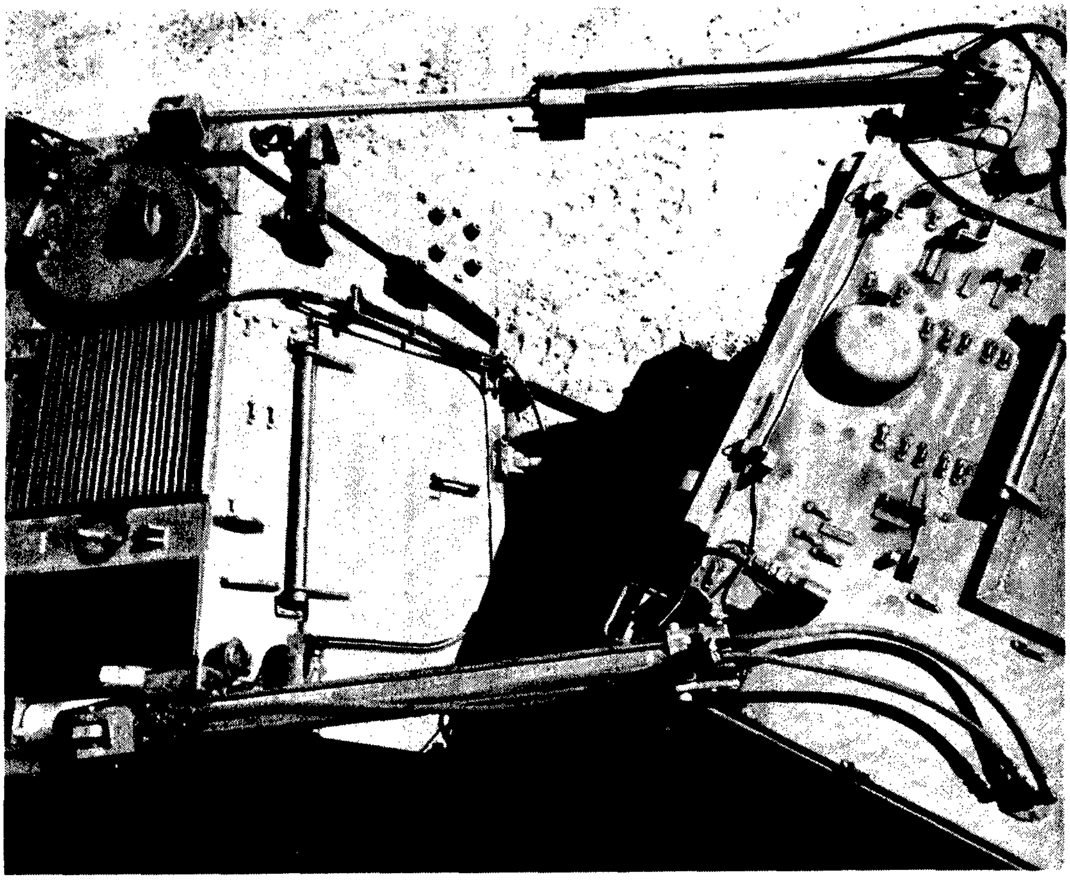


Figure 6: Coupled Vehicles in Yaw

Thus, the hydraulic control system is now a positional control system that responds to the difference between the control stick and the feedback potentiometer signals. Rearward motion of the control stick causes both pumps to simultaneously displace fluid into the rod end of the actuators, thus producing a pitch up motion. Actuator displacement (pitch motion) stops when the feedback voltage equals the command stick voltage. Forward motion of the control stick produces a pitch down attitude. Sideward motion of the control stick causes the two pumps to pump in opposite directions, contracting one actuator while extending the other thus producing yaw motion between the two vehicles. The control stick can also be moved in any oblique direction in order to obtain simultaneous yaw and pitch motion and is self-centering so that both the control and the vehicle will return to zero pitch and yaw when released.

The system can be operated either with force feedback or without it. The control and operation of the articulation system is the same in either case. The only difference between the two cases is that with the force feedback active, the reaction forces in the control stick vary with inter-vehicle forces, thus providing a "sense of feel" as an additional driving cue.

The cybernetic force feedback control system applies a force to the control stick proportional to the forces generated by the actuators. The control signal for the force feedback control system is generated by four pressure transducers responding to the pressures developed by the hydraulic system. The electrical output signals of these sensors are proportional to the pressures generated and are paired such that their signals add when pitching up or down and cancel in yaw. This signal is amplified and transmitted to an electromechanical actuator which produces a forward or backward force on the control stick. Thus, the force feedback system applies a force to the control stick proportional only to those forces acting to pitch the vehicle.

Ignoring dynamical forces, inter-vehicle forces arise only from the interaction of track and ground. As designed, the force feedback mode will always seek to reduce the inter-vehicle pitch moments to zero. In this manner, the force exerted by the force feedback on the control stick can also perform a function similar to that of an auto-pilot. However, the operator can, and must at times in order to fully exploit the concept, provide manual control to supplement or override the force feedback. Because the force feedback servo responds only to pitch moments, it does not influence yaw behavior. The result is an automatically self-centering steering system.

## IV. RESULTS OF TESTS CONDUCTED TO DATE

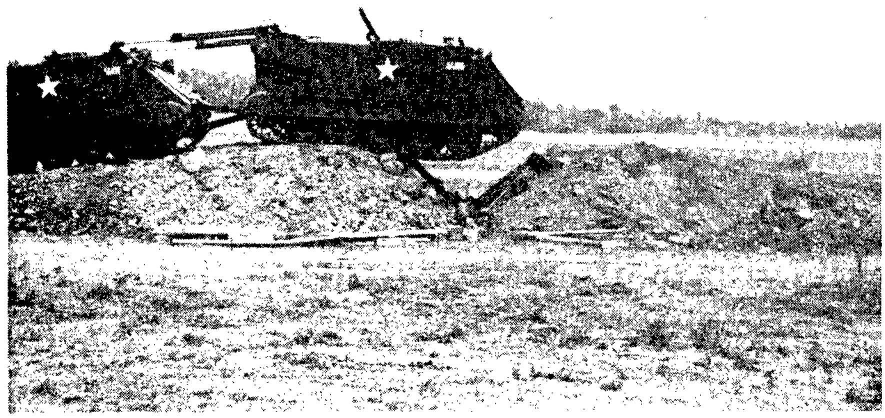
To date the coupled vehicle system has been tested with and without force feedback for proper functioning of all components and to establish its operational capabilities, especially in obstacle crossing.

The coupled vehicles have negotiated v-ditches of 6, 8 and 10 feet in width (Figure 7); open trenches of 5, 7, 9 and 11 feet in width (Figure 8); and rigid vertical obstacles of 2, 3, 4 and 4-1/2 feet in height (Figure 9). By comparison, the single vehicle is limited to an 8 foot v-ditch, a 7 foot open trench and a 2 foot vertical wall. Wider and higher obstacles are being constructed in order to ascertain the performance limits of the coupled vehicles.

The coupled units exhibit stable ride and steering characteristics while operating at all speeds cross-country. The operational performance of the coupled system is superior to the single vehicle in all respects with the exception of the turning radius. For the coupled system it is 40 feet; for the single unit it is 14 feet.

Drawbar pull tests have been conducted in both the coupled and single unit configurations. The tests reveal that both the maximum drawbar pull/weight ratio and the maximum tractive efficiency are about equal for both the single and coupled units. However, the coupled units maintain the maximum tractive efficiency over a significantly wider range of slip conditions; thus the coupled units display superior mobility in soft soils.

The slope climbing ability of the coupled units is superior to that of the single unit. On short slopes the unit on the level assists the one climbing; on long, steep slopes the rear unit has a higher maximum traction than the single unit because of weight transfer.



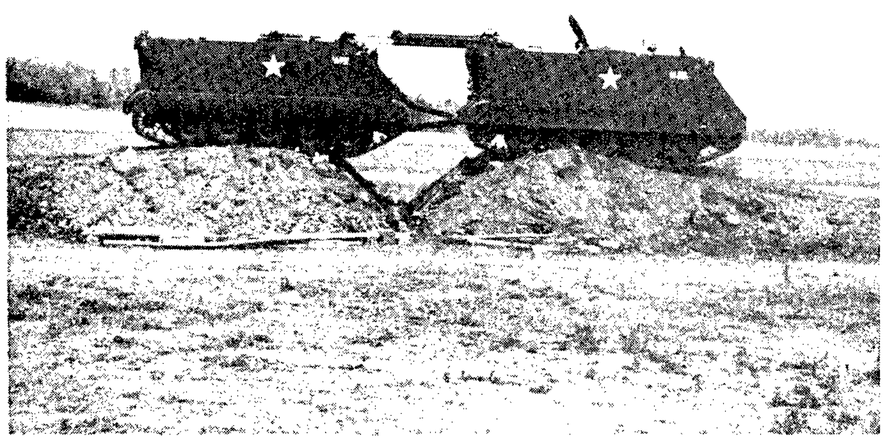


Figure 7:  Negotiation of the 10' V-Ditch

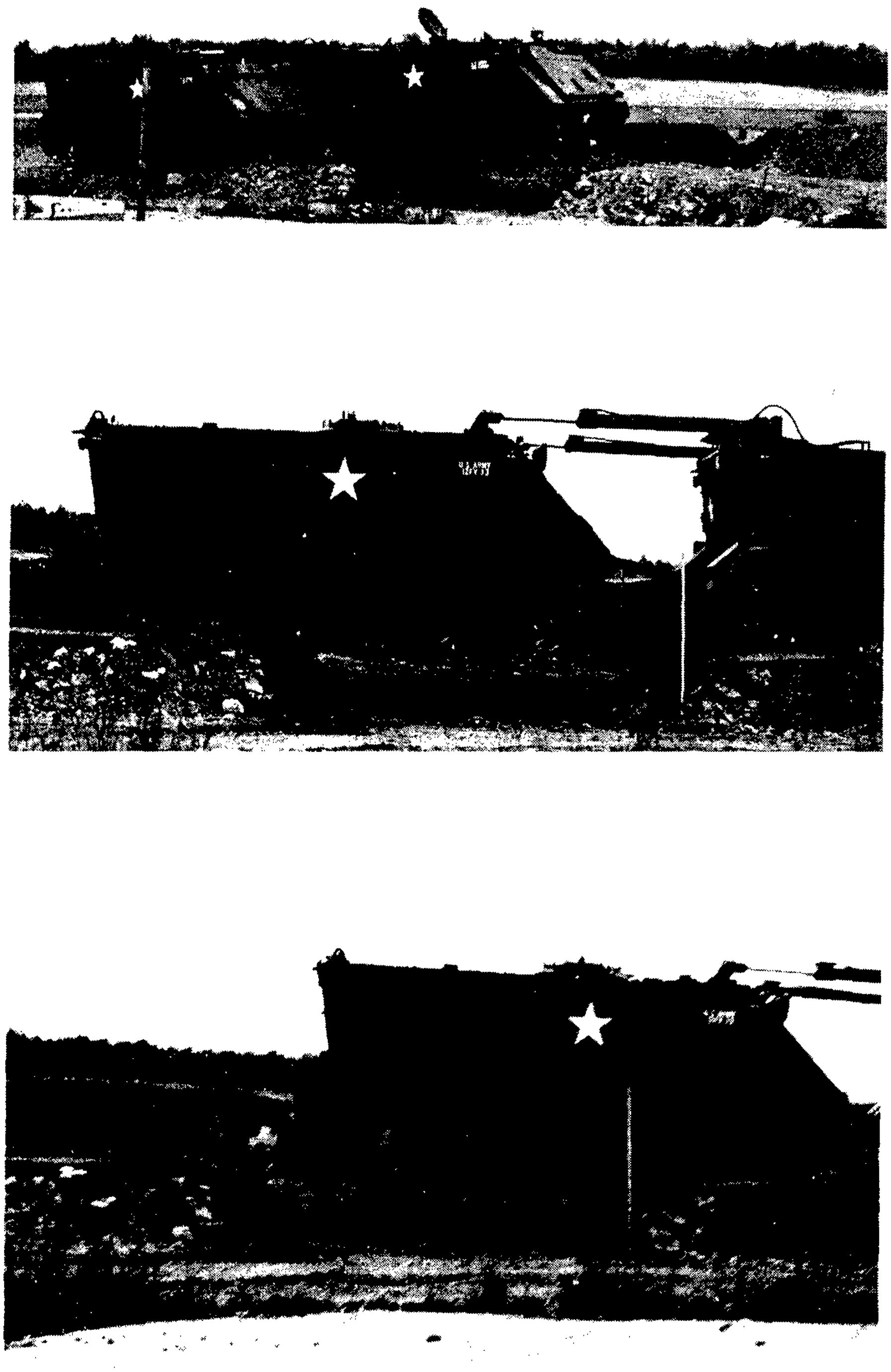


Figure 8: Negotiation of the 11' Trench

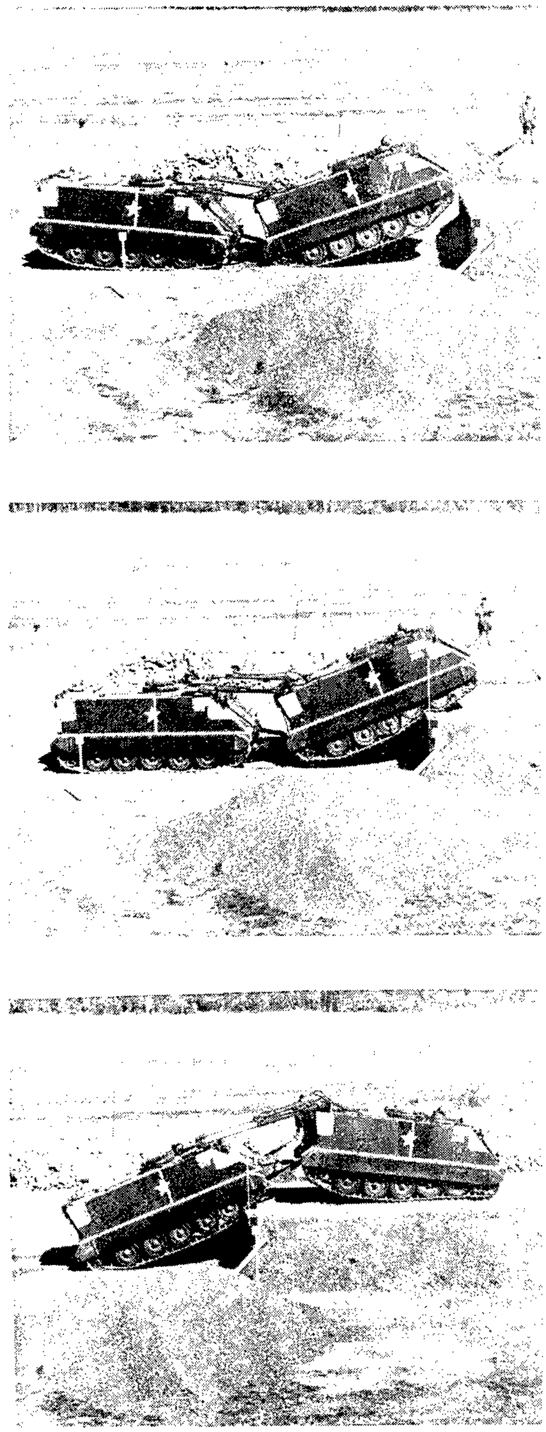


Figure 9: Negotiation of the 4-1/2' Step Obstacle

Most of the testing to date has been performed without cybernetic force feedback, however, those tests performed with the cybernetic system have indicated that the feedback system is an asset in vertical obstacle climbing. During the climb the system seeks to maintain zero pitch moment between the two vehicles, thus making a smoother ascent. Initially, the driver must "lift" the front vehicle onto the obstacle; after that he often need not supply further control. However, when crossing the wide trenches (those beyond a single vehicle's capability), it is necessary to override the force feedback, otherwise the unsupported portion of the vehicle will tend to drop into the ditch.

The response rate of the force feedback servo system is sufficient for the speeds required for obstacle crossing, but lacks sufficient response at cross-country speeds in excess of about 15 mph. No problems are encountered above this speed, however. The system just acts as if there were no force feedback to the control stick, and the operator is still capable of performing all necessary control functions.

## V. THE FUTURE

Present plans call for winter tests to evaluate performance of the coupled system over snow and ice and spring tests to evaluate performance afloat and while exiting from water, and against larger obstacles.

If funding permits, additional instrumentation will be installed and the vehicle will be used as a research tool to validate theoretical analyses and to investigate the man-machine relationship. Verified analysis and design procedures can then be used, together with the widely variable characteristics of this research vehicle, to check out future designs of vehicles employing controlled articulation.

The success of the program to date indicates that this system has many potential applications in military hardware.

1. A kit could be developed to provide increased mobility to selected vehicles of a unit.

2. Commercial vehicles of limited mobility could be employed in the coupled configuration to meet military requirements.

3. Amphibious vehicles could be coupled to reduce hydrodynamic resistance and to aid in negotiating the berms and escarpments found on beaches.

4. Vehicles with superior mobility may be coupled to less mobile vehicles for special purpose applications.

5. Tank-infantry teams can operate more closely, utilizing the armor protection of the tank partially to shield the thinner skinned vehicle, and at the same time, to improve mobility.

## VI. ACKNOWLEDGMENTS

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