FINAL REPORT ON HARDIMAN I PROTOTYPE FOR MACHINE AUGMENTATION OF HUMAN STRENGTH AND ENDURANCE

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Prepared By

Specialty Materials Handling Products Operation
General Electric Company
Schenectady, New York 12345

30 August 1971

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13. ABSTRACT

Summary of progress and achievements on the Hardiman I Prototype Project. This report covers the period from 1971 May through 1971 August in detail and refers to previous reports for overall program information.

In the performance of this contract, the state-of-the-art in bilateral manipulator type man-augmentation systems was dramatically advanced. At the inception of this program, such systems typically handled a maximum of approximately 100 lbs., were large and heavy in relation to their payloads and were generally suited only for remote operation. By contrast, the Hardiman I prototype, consisting of thirty powered joints, can lift itself plus loads equal to its own weight of 1500 lbs. It is packaged to be worn by a man and mimic his motions, maintaining the man's dexterity and "feel" of the task being performed. In addition to the obvious mechanical design constraints of packaging such a system, it was necessary to achieve substantial technical breakthroughs in the design and analysis of high-load bilateral servo systems. The control technology advances achieved on this program have been instrumental in the development of new concepts in handling ordnance and general cargo for military applications.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Hardiman Exoskeleton Manipulator Bilateral Servos Joints-in-series Man-augmentation Systems Human Factors						

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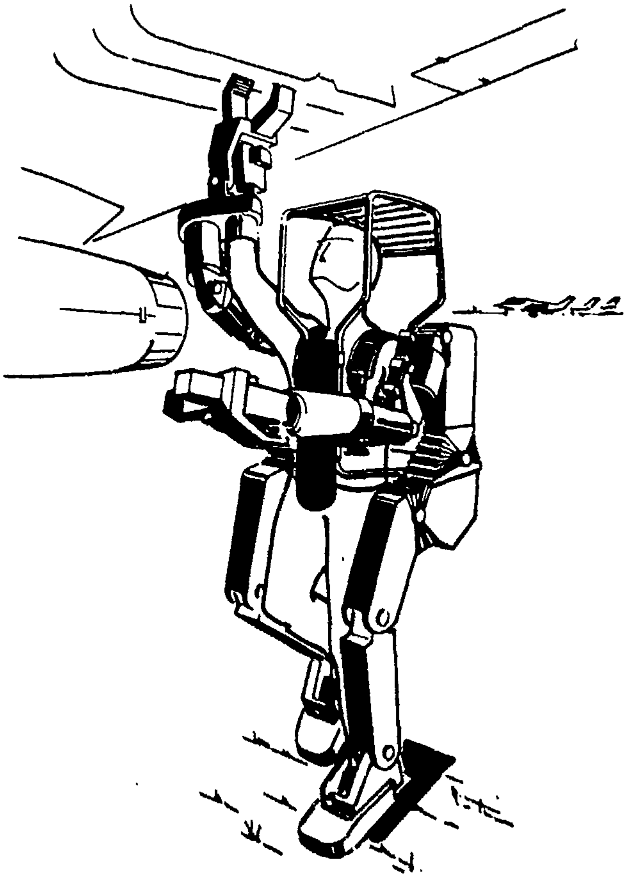

THE POWERED EXOSKELETON PROJECT

The Powered Exoskeleton concept is that of a material handling machine under intimate control of the operator.

"Worn as an outer mechanical garment, the exoskeletal structure will be powered to dramatically amplify the wearer's strength and endurance by a factor of approximately 25 to one, i. e., when the exoskeleton wearer lifts 25 pounds, he will 'feel' as if he is lifting only one pound. The device will provide him with a set of 'mechanical muscles' that enables him to lift and handle loads in excess of 1000 pounds. The human operator will 'feel' the objects and forces he is working with almost as if he were in direct body and muscle contact. This feature, called force feedback, will provide the operator with sensitive control of the structure and will act as a safeguard against the application of excessive force.

"The exoskeleton, called 'Hardiman,' mimics the movements of its wearer, presenting a literal union of man and machine. Thus, the human's flexibility, intellect, and versatility are combined with the machine's strength and endurance."*

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* Naval Research Reviews, July 1967

TABLE OF CONTENTS

FOREWORD

All work on the Hardiman I Program was completed as of 31 August 1971, the expiration date of Contract N00014-66-C0051.

Fabrication and assembly of the Hardiman I Research and Development Prototyp unit was completed as planned.

In checkout and evaluation of the major sub-systems, the arm system, as represented by the first completed arm assembly, met all design requirements.

Operation of the leg system was less extensive and only limited performance was attained within the funding and time authorized.

We believe that this has been a very successful Research and Development Program in terms of technical achievements in the many technologies related to man-augmentation systems.

During the performance of this contract, the state-of-the-art in man-augment systems was dramatically advanced.

The progress in technology from the remote handling manipulators of the earl '60's (used in nuclear work) to the completion of the Hardiman I prototype was marked by a series of breakthroughs in control system design, analytical techniq and man-machine interface methods.

The resulting prototype unit is a unique embodiment of the high load capaci co-axial man-augmentation system first envisioned by the authors of the Hardiman program.

With technical feasibility proven, and basic capability demonstrated by sub-system tests, the frontier of a new era in machine augmentation of human strengt and endurance has been reached. The opportunity now exists to advance beyond th frontier to the eventual deployment of operational hardware tailored to the needs of specific military applications.

FOREWORD

(Continued)

This can be achieved through further experimentation and refinement of the Hardiman system as a basic vehicle for the continuing development and evaluation of the man-machine interface and by applying the knowledge gained to the solution of specific operational problems in man-machine systems.

Immediate goals in this respect would be the upgrading of the observed limited performance characteristics in the leg system and the achievement of full walking capability at full load. Detailed performance testing, incorporation of refinements and the documentation of their effects on system performance could then follow.

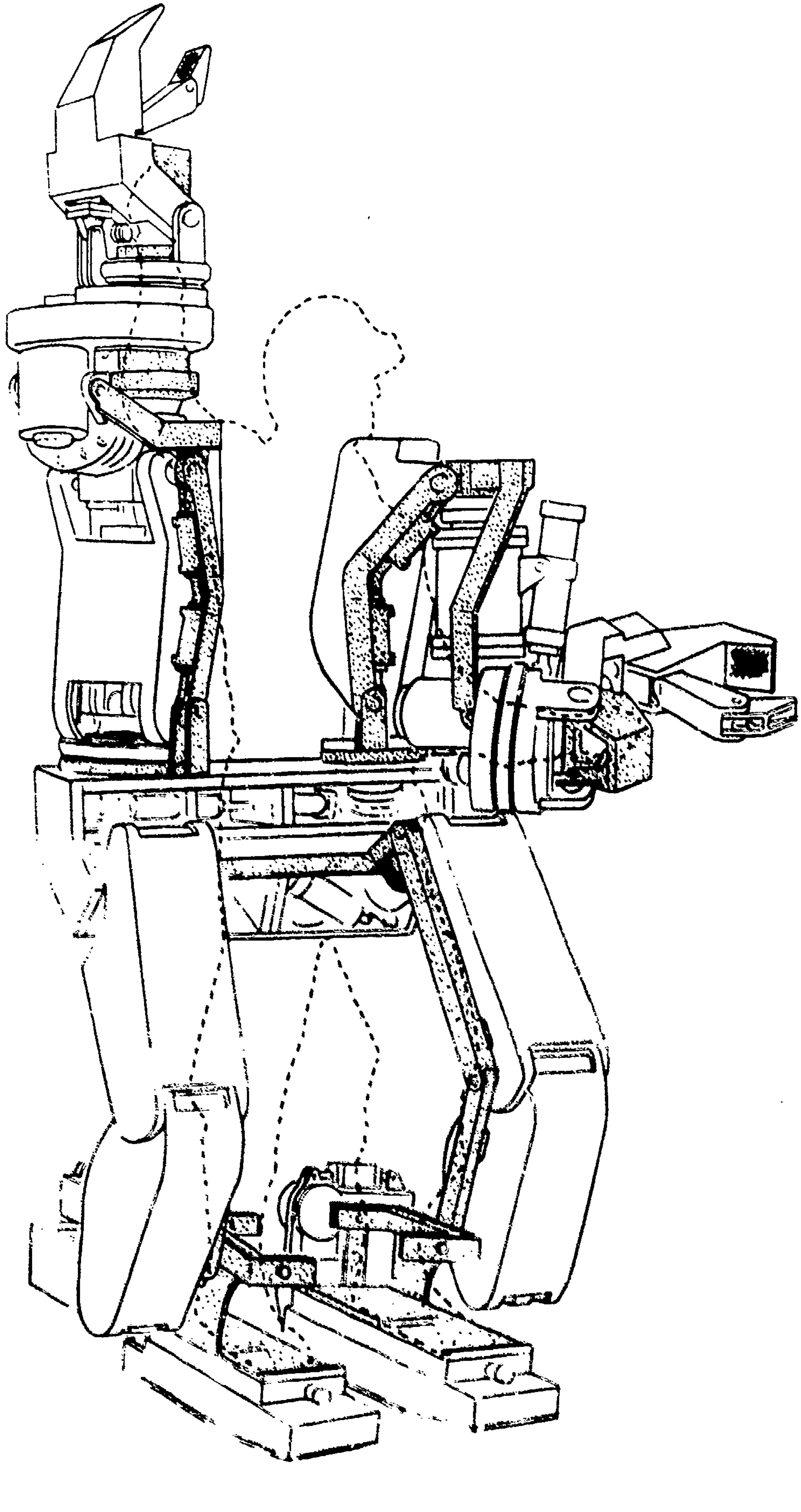


Figure 1. Hardiman I

Section 1

INTRODUCTION

The research contract for the development of Hardiman I was initiated as a joint Army-Navy program in November 1965.

The goal of this program was to develop and demonstrate the potential of a powered exoskeleton. This is a powered, jointed, load-bearing structure designed to be worn by man and augment his strength and endurance. Typical applications for the Hardiman I will include loading and unloading cargo from vehicle to ground and vice versa, stacking and moving cargo from place to place, and similar associated tasks. The Hardiman I will be designed so that the wearer can walk, bend, turn, etc., with minimum restraint.

The exoskeleton design concept is shown pictorially in Figure 1.

The exoskeleton system is a master-slave device. That is, there are two complete "skeletons"--the exoskeleton proper or slave, which carries the working load, and a master skeleton which is attached to the operator. The master skeleton is the shaded portion in Figure 1. Each joint of the exoskeleton has a duplicate on the master. The master and slave are geometrically superposed so that corresponding joint axes are approximately collinear.

The operator is attached to the master skeleton at appropriate places, and can cause the slave to assume desired postures and hand positions by moving the master. The bilateral servos reflect the working forces of the slave to the operator, reduced by a factor of 25, so that he can sense the operation of the machine as it works.

The operator stands inside this structure, to a large extent surrounded and protected by it. Just below the elbow, the operator's arm, the master, and the slave become concentric. There are several advantages to this: the controls are simplified, human factor correspondence is improved by having the slave hand in axial line with the operator's hand, and the operator's hand is protected by being inside the slave housing.

In the first laboratory prototype, electric and hydraulic power will be suppl through an umbilical connection. Future versions may incorporate a self-contained power supply.

Since the man and machine must be so intimately associated in this device, the human factors related to the man-machine interface and control system play a crucial role in its design. Early in the program, it was found that much of the human factors data that might have been applied were not available in forms readil applicable to this concept. The required information was developed from existing sources and augmented by laboratory studies using mockups simulating possible configurations of joint designs. It is apparent that the operation and test of the Hardiman I prototype will in itself generate and greatly clarify human factors data in the area of walking anthropomorphic machines and other man-augmentation devices. The Hardiman I prototype as it now exists is shown in Figures 2 and 3.

A detailed account of the technical activities from the initiation of the program through 1 May 1971 is contained in the earlier program reports which are listed below.

HARDIMAN I REPORTS

Final Report on Phase I	S-67-1011	28 Oct. 1966
Appendix to Final Report on Phase I	S-67-1016	28 Oct. 1966
Appendix X to Final Report on Phase I	S-67-1098	16 June 1967
Special Status Report	S-67-1151	30 Sept. 1967
Special Interim Study	S-68-1060	19 April 1968
Special Technical Report on Joints in Series	S-68-1081	10 June 1968
Machine Augmentation of Human Strength & Endurance	S-69-1116	1 July 1969
Hardiman I Arm Test	S-70-1019	31 Dec. 1969
Research & Development Prototype for Machine Augmentation of Human Strength and Endurance	S-71-1056	1 May 1971

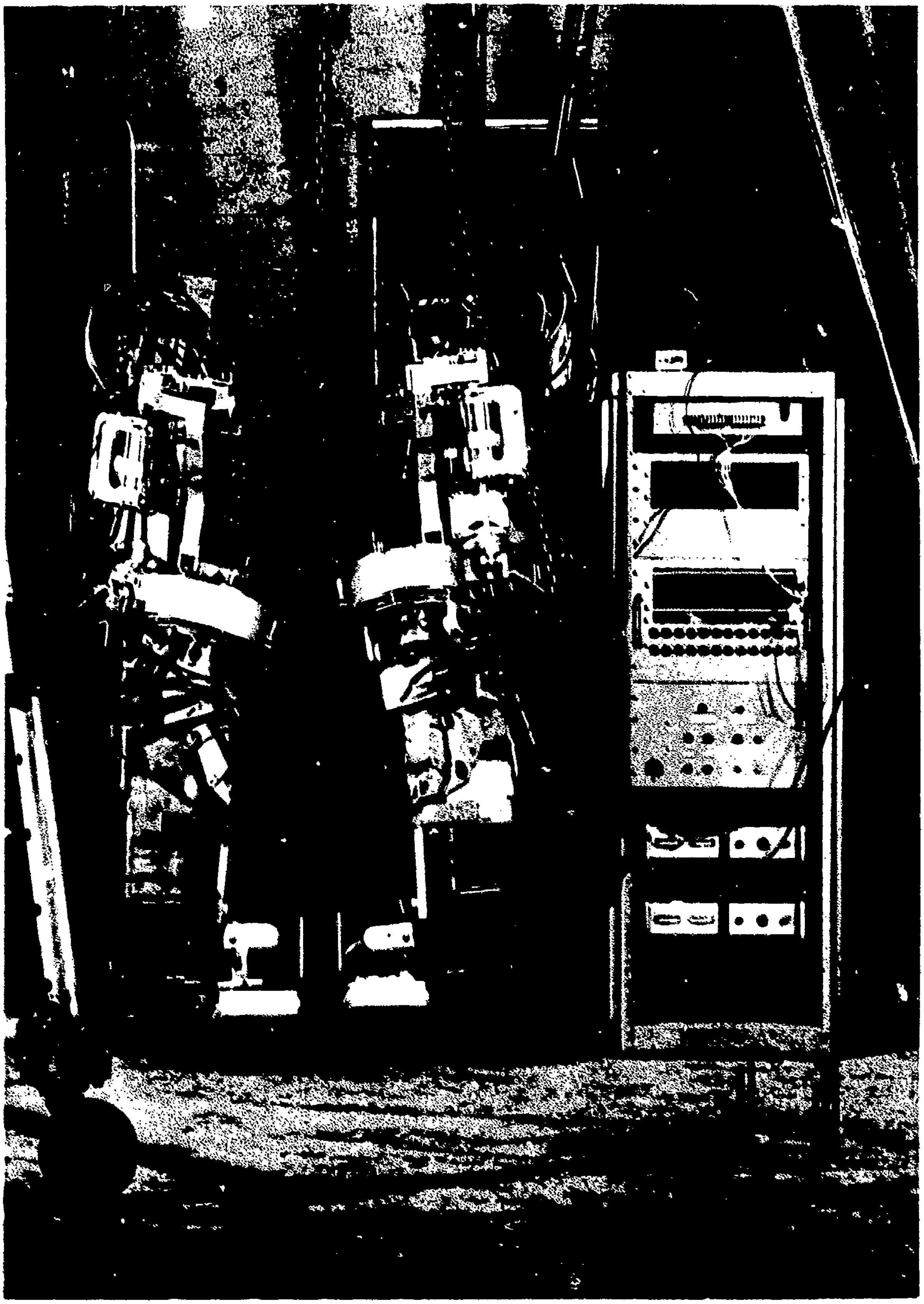


Figure 2. Hardiman I Prototype

Figure 3. Hardiman I and Operator

Section 2

PROGRAM SUMMARY

At the time the Hardiman I Program was initiated, there had been established a good technical basis upon which to build.

The General Electric Company had developed a hydromechanical bilateral servo system that was being incorporated into the first heavy duty industrial manipulators.

In pre-proposal work, the General Electric Company had made an investigation of the human factors and kinematics with a passive exoskeletal device that provided a means of measuring joint motions and determining the minimum number of joints required to give a man sufficient mobility. A small scale model had also been built and used to illustrate basic features of the proposed system.

The primary assumptions that were made, which went beyond the then existing state of the art were:

1. That bilateral servo technology could be advanced to meet the increased load requirement of the Hardiman system.
2. That the system could be physically packaged.
3. That the control of the biped walking system could be achieved.

Satisfying these assumptions meant doing things that had not been done before. It was felt that the risks were well balanced against the General Electric Company's past record of technical achievement - but it was recognized that substantial technical risk did exist.

The first phases of work under the contract consisted of in-depth studies of the man-machine interface. This led to the pinpointing of specific system and sub-system requirements.

As we began to get specific numbers on the forces, velocities and power for individual joints and as we addressed the problem of mechanically packaging the system, and as we looked in-depth at how to attach the man to the machine, and looked at the relative motions between master and slave, the system was growing in complexity and specific problems related to the system configuration and servos were being defined.

Then followed a problem solving phase in which were developed the new designs, techniques, and analytical tools that were required. This was a phase of laboratory experiments as well as paper studies.

With baseline solutions to the individual problems established, work proceeded to integrate these into the overall system, and proceed with building the major hardware.

To relate this to key events and chronology more specifically, we can look at a summary of program milestones.

The Program started in late 1965. The bulk of human factors and kinematic conc was done in 1966.

At this point, it had been concluded that a basic change had to be made in the original concept. We had envisioned a complete master skeleton and slave skeleton - connected only by the position sensing devices. Practical considerations related to the buildup and compliance of servo systems made it necessary to split the master and have separate masters for the arm and leg systems.

There were two basic methods of implementing the split master.

One we called the "operator walk" system - this was the original intent of the program wherein the operator would carry his weight on his feet.

In the second method, or "operator ride" configuration, the operator's weight would be carried on a seat and he would operate the foot pedals, somewhat in the manner of a bicycle - or like operating the Quadruped Transporter.

The control system for "operator ride" system would have been easier to impleme but the method of walking would not really be natural or manlike. It would be more like learning to ride a bicycle or drive a car than like the instinctive control characteristics of an ideal man-augmentation system.

The "operator walk" system satisfied the requirements for instinctive control, but made it necessary to innovate new control techniques whose very newness increase the technical risk.

Because the aim of the program was to achieve the most natural man-augmentation system, ONR directed that the "operator walk" approach be pursued.

By the end of 1967, completed design layouts for the mechanical hardware had been completed. The Hardiman prototype as now built is substantially in accordance with these layouts as far as the slave or load bearing joints. Most of the subsequent changes we have made since then have had to do with the master and the details of the control system.

At this point, the main problems remaining were related to the servo system. We had not succeeded in developing a completely hydromechanical servo system to the point where it could handle the exoskeleton requirement.

On the Quadruped program, we had succeeded in developing hydromechanical compensation networks to stabilize the servos. However, these required unusual precision in manufacturing and could not be further improved to meet the Exoskeleton performance specifications.

Here a special study was initiated to determine whether solutions to the control problem could be achieved by any available means. The obvious alternate of course, would have been to drop the Program.

For the study we put together a team of the best servo experts within the General Electric Company. The effort was spearheaded by Dr. Chestnut and his Systems Engineerin Branch in R&DC. But we also drew from our Ordnance Department and Turbine Departments and made use of consultants outside of the Company. A contract report on the Special Interim Study was published in April of 1968.

The basic conclusion reached was that a solution was attainable by going to electrohydraulic servos. We had hoped to avoid the use of electronics but had reached the practical limits of manufacturing purely hydromechanical system.

Here too we dealt with a fundamental problem that is usually ignored in mult joint manipulator systems. That is the interaction of servo controlled joints in series. In lower powered units the individual joints could be overdesigned to pr overall operating margin without rigorous optimization of the system. In Hardima this luxury was not available because we were pressed by size and power limitatio Each servo required a high degree of optimization to achieve the performance and package density needed. This required an in-depth understanding of the effects o joints in series. In addition the use of the "tickler" method of position contro had never before been implemented in a manipulator system and its effects on join in series was unknown.

Again, with the help of Dr. Chestnut's group and an RPI graduate student who used the work for his doctoral thesis, we were able to construct a computer model the system and use it to arrive at a solution.

After the interim study we went into what could be called the problem solvin phase. We demonstrated the single joint unilateral and bilateral systems with re hardware. This was actually done as part of General Electric's Independent Resea and Development Program - but the actual parameters of the Exoskeleton servos wer used.

At this point, we could say for the first time that we had a control with th performance needed to meet the Hardiman requirements.

The next step was to verify the joints in series analysis - which we did wit the actual hardware for the ankle, knee, and hip joints of one leg.

From here on the main thrust of the program was to complete the hardware. Th was a major effort involving some 25,000 hours of shop time alone.

At this point, we were redirected by ONR to concentrate on a complete arm sy Before this, the plan had been to build the leg system first since the whole prog hinged on the ability to walk.

It was recognized that the arm system involved a lower risk and that the demonstrated success of a major sub-system was essential to continued support of the program.

The first arm was operated in the summer of 1969, and was highly successful in meeting the design goals.

The leg and girdle system was completed in late 1970 and initial tests were encouraging. However, debugging of the system in the foot grounded mode consumed far more time than had been expected.

As time and funding were running out, we concentrated on showing the best result we could with limited performance capability rather than a detailed investigation of the problem.

We achieved limited success in walking, that is, the machine responds to the man's motion, but we were not able to balance or walk without support. After documenting the walking experiments on film, we completed the assembly of Hardiman but have not run the completed system.

To achieve all of the original performance goals of the Hardiman Program, the first effort required will be to resolve the present control limitations which were observed in the operation of the leg system.

The greater complexity of this control problem stems from the fact that the leg system must operate in three different control modes and that all of the twelve joints comprising both legs interact during walking.

By contrast, the arms operate in only one mode and function as independent subsystems with nine joints in each.

The individual leg joints performed successfully, and when combined in the "foot floating" mode (which is similar to the operating mode of the arms) achieved the limited walking performance which has been demonstrated.

In the more complex operating modes, recent experience indicates that fundamental kinematic problems exist which are not represented in sufficient detail in the mathematical models which have been used for system analysis and design.

It is possible that an even greater depth of analytical study of the master-slave kinematics will disclose an overconstraint of the leg system in the "both feet grounded" mode. Once the problem has been more fully understood, a solution might be achieved by relatively simple expedients such as deactivating the control of certain joints and allowing them to comply to the control of the active joints. Subtle modifications of master and tickler kinematics are also envisioned.

Successful refinement and modification of the leg system control will make it possible to proceed with demonstration of the first walking biped, man-augmentation system.

PROGRAM ACHIEVEMENTS

The initial implementation of the Hardiman concept for evaluation of its feasibility has produced many significant advances in the technologies related man-augmentation systems.

This program has not only dealt with the theory of the man-machine interface, but has attacked in-depth the practical hardware problems requiring realistic solutions.

The most important technical advances made on this program are those related to the development of a control system which would form a suitable communication link between the man and this complex, powerful machine.

The man-machine interface problem in the Hardiman I prototype has been a severe one. The high power gain, the complexity of the multi-jointed system and the intimate coupling of the man and machine imposed many design constraints and made heavy demands on existing technology.

Initial attempts to utilize existing control methods fell short of the performance required for such an ambitious goal as the realization of a complete exoskeletal man-augmentation device.

The solution to the control problem required the utilization of advanced analytical technologies, computer simulation and laboratory testing before success was achieved.

The key accomplishments on this program can be summarized as follows:

1. Successful matching of machine kinematics and force levels to man's motion and power capability and an understanding of the human factor considerations encompassed in a machine of this type.
2. Mechanical packaging of thirty powered joints into a practical co-axial exoskeleton configuration.
3. Design and development of advanced, high performance electrohydraulic servos with sensitive force feedback.

Section 3 (Continued)

4. Solution of the complex dynamic problems related the interactions between high gain servo joints operated in series or cascade, and the development of computer programs and analytical techniques required to analyze future problems of this type.
5. Advancement of control technology with resulting spin-off potential in the areas of material handling; ordnance loading; and underwater and space manipulators.
6. Completion of the first prototype of a complete co-axial, exoskeletal man-augmentation system.

Section 4

LEG SYSTEM OPERATION

Summary

During the period March 31, 1971 to August 31, 1971, the fabrication and assembly of the Hardiman prototype was completed and a detailed checkout program of the Hardiman leg system implemented.

All fabrication, assembly, wiring and plumbing were completed. Modifications to the leg system for operator safety including mechanical stops and shields were installed and test fixtures and support equipment required for testing were prepared.

Testing of the leg system was then initiated and satisfactory operation of each leg joint operating independently was attained. Serial operation of multiple leg joints was then attempted with the operator remote from the machine using extension handles from the master control. During these tests a number of kinematic and control complications were exposed that could not be readily corrected. In order to demonstrate at least a limited level of performance with an operator in the machine, a simple but basic change was made in the relationship between operator, master, and slave that circumvented some of the technical problems uncovered.

The approach taken was to fasten the master leg system to the slave at the girdle and support the operator by a seat attached to the slave. This enables an operator to control the leg system in the "operator ride" mode, a manner similar to operating the pedals of a bicycle. This is in contrast to the intended mode of operation wherein the operator stands and balances himself and the machine on his own feet making use of the sensory forces on the bottom of his feet to aid in balancing.

Because the Hardiman prototype was not designed to operate in the "operator ride" mode, the servo control circuit would have to be modified to permit control operation at gains sufficient to permit the machine to carry its full weight. In addition, it is felt that due to the absence of force cues to the operator's feet in the ride mode of operation, it would be necessary to install force feedback in the leg system to enable an operator to walk unassisted.

Section 4

(Continued)

Within these constraints and with the assistance of a supporting tether it was possible to demonstrate a limited ambulatory capability with the leg system of the Hardiman prototype. A movie documenting these tests sequences was made for future reference and will be made available on request.

After undergoing limited testing the Hardiman leg system was joined to its arms to complete the assembly of the Hardiman.

A test program conducted with the left arm had previously demonstrated the functional capability of the arm's design and is documented in a Report issued December 31, 1969, titled "Hardiman I Arm Tests".

Further improvement in the performance of the Hardiman prototype will require a return to the original "operator walk" concept of operation and the resolution of the technical difficulties uncovered during the test and evaluation of the legs.

Technical Discussion

A chronology of the test and evaluation program and the manifestation of technical problems follows.

During the evaluation of the leg system numerous combinations of leg motion, postures, and loading were evaluated. Initially each servo motion was operated independently with satisfactory results. Then the right slave leg was clamped to t floor and one joint at a time was activated. During this procedure the left leg was hydraulically locked in a folded position and the girdle and legs semi-supporte by a safety tether. The complete right leg was then operated supporting the weight of the girdle and left leg. While the performance of the right leg in this mode was inhibited by intermittent instabilities it is believed that operation in this mode can be made fully satisfactory with further optimization of the servo compensation networks. During this phase of testing an unexpected loss of control occurred when the leg was at full extension (knee and hip joint against their stop) and the operator attempted to further extend the leg. In attempting to extend the leg furt the operator would inadvertently ground the master to the slave, and rotate the master about the point of contact. The resulting rotation of the master about this interference point would introduce a control signal that would cause the knee joint to fold up and pull the master and operator down with it. The instinctive reaction of the operator was to lift the master girdle and fight the slave thereby introducing an even greater down signal. Only by making a conscious effort to lower and counter-rotate the master, faster than the slave, could the operator avoid this run-away condition. By installing mechanical stops on the master to limit its range of motion to less than that of the slave this condition can be eliminated.

The next phase of testing involved the operation of the left leg in the air (floating) while the right foot was clamped to the floor (grounded) and all servos in the right leg hydraulically locked. Joint motions were activated in a serial manner beginning with the foot rotate. Satisfactory operation of the three foot motions (ankle flex, foot rotate and ankle inversion) were attained. Activation of the knee and hip servos exposed similar problems to those encountered in the right leg. When the operator drove the ankle flex motion into its stop and attempted to further rotate the slave foot, the master foot would contact the slave and rotate about the point of contact. This rotation introduced a signal to the knee flex servo causing it to fold up. Again, the operator's instinctive reaction would act to aggravate the situation. This condition was greatly reduced by installing mechanical stops on the ankle flex and knee flex motions.

The foot centering mechanism and ankle inversion tickler mechanism were also removed to increase the relative motion possible between master and slave. It was observed that they did not permit sufficient lateral displacement between the master and slave foot to allow the generation of sufficiently large error signals to operate the knee and hip motions.

With the aforementioned modifications it was then possible to simultaneously operate the left leg ankle, knee, hip and hip ab-ad motions in the floating mode. Simultaneous operation with the ankle inversion and foot rotate motions will require modification to their corresponding position transducer input mechanisms (ticklers) and modification to the foot centering mechanism.

Simultaneous operation of both right and left legs was then attempted. This was an extension of the proceeding test and was performed with the right leg grounde and left leg floating. Activation of both legs simultaneously resulted in violent and uncontrollable motion by the machine. At this writing, the exact cause of this behavior has not been verified, however, possible intermittent instability in the hi ab-ad motion or jamming of a tickler position input mechanism (tickler) are suspect. The problem source must be identified and resolved before the machine can be walked in the intended mode of operation.

The final test mode evaluated was the mode in which both slave and master feet are clamped together to simulate the condition of the operator having both feet on the ground. During this mode of operation it was observed that the slave would not seek a posture of stable equilibrium. A perturbation to the master after the master and slave feet had been joined together resulted in a change in posture o the legs over which there was no direct control and resulted in the saturation of on or more joints.

After a preliminary analysis of this problem it appears that the basic cause of the behavior was the result of the added constraint of having the master and slave grounded together at both ends of the kinematic chain, i.e., both feet, as opposed to being grounded together at one end. This property is unique to the Hardiman leg system. It has the result of reducing the number of independently controllable motions of the leg system to a point where only a few of the joints can be actively controlled in this mode.

The behavior observed was the result of a condition of over control, where too many joints in the leg system were being actively controlled and began to fight each other. Consequently, the leg system could not find a posture that would simultaneously satisfy the servo equilibrium requirements of all the joints being actively controlled, once the master and slave feet were joined together.

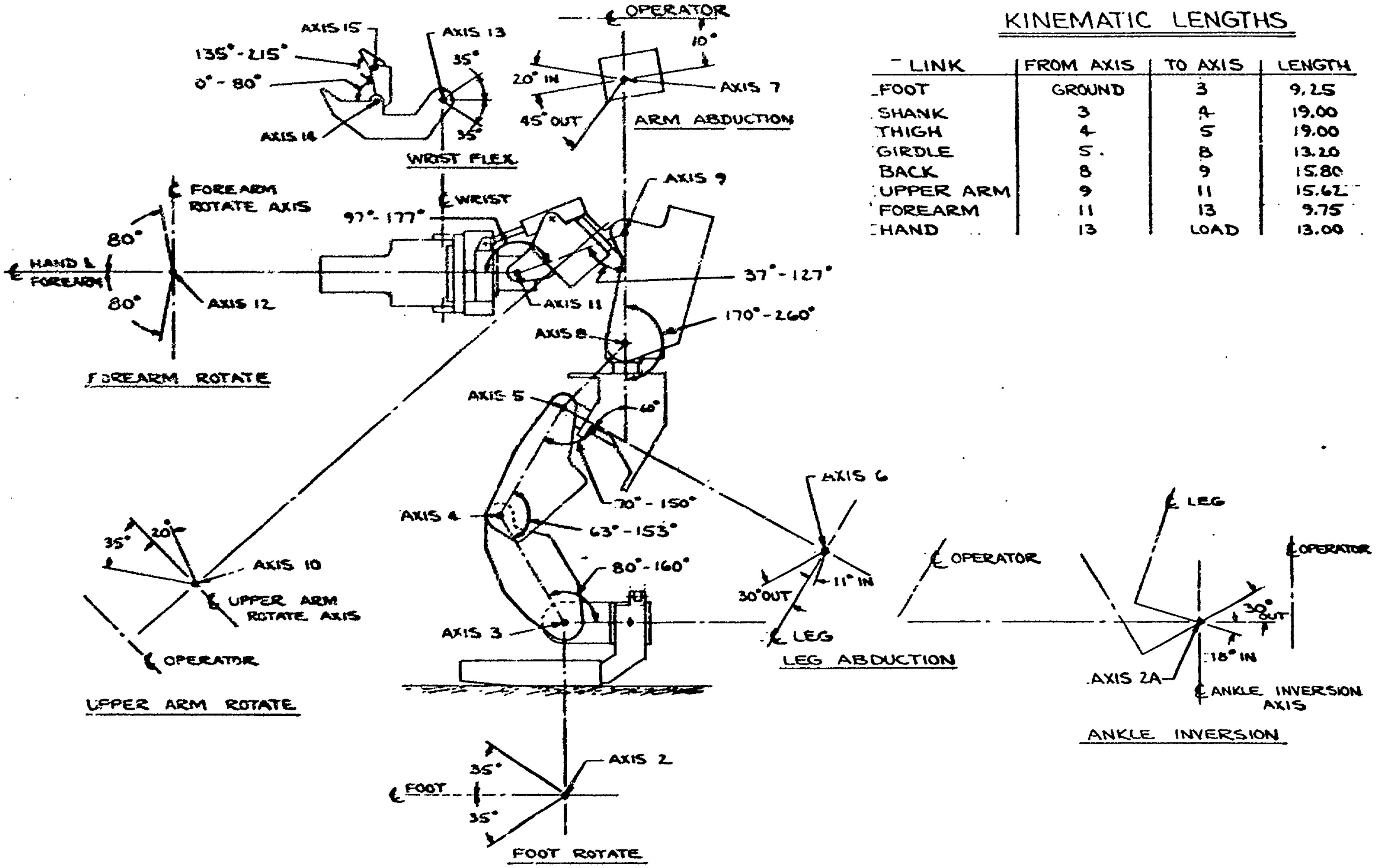
It is believed that this condition can be effectively eliminated by changing the control logic of the leg joints in the both feet grounded posture. This would entail the deactivation of certain joint servos in the leg system to allow them to comply under the control of the active servo joints.

Because the modifications required to correct these deficiencies were not feasible within available funding an attempt was made to demonstrate a limited ambulatory capability. Based on the success achieved in operating the legs in the foot floating posture the decision was made to perform a minor modification to the leg system to permit operation of the leg system in the "operator ride" mode. This mode of operation uses the same ticklers and control circuits as used in the "foot floating" posture which was successfully operated during earlier testing. In addition it eliminates the fundamental constraint of having the master feet grounded to the slave feet, (i.e. both ends of the master/slave kinematic chains tied together) by grounding the master to the slave at the girdle (center of master/slave kinematic chains tied together) thereby eliminating the condition of over control.

As a result of these minor modifications, it was possible to simultaneously operate both left and right legs (using the ankle, knee and hip motions) in an ambulatory manner. These tests were conducted with a safety tether which supported a majority of the machine's weight and an assistant using a fulcrum to provide rotational stability while walking.

APPENDIX A

(HARDIMAN I DESCRIPTION)



KINEMATIC LENGTHS

LINK	FROM AXIS	TO AXIS	LENGTH
FOOT	GROUND	3	9.25
SHANK	3	4	19.00
THIGH	4	5	19.00
GIRDLE	5	8	13.20
BACK	8	9	15.80
UPPER ARM	9	11	15.62
FOREARM	11	13	9.75
HAND	13	LOAD	13.00

Angular Excursions of Joints

SYSTEM SPECIFICATION

• **Size**	
Height	72"
Width (at hips)	39"
Fore & Aft	29"
• **Weight**	1500 lbs.
• **Lift Capability**	1500 lbs.
• **Power Requirements**	
Hydraulic	25 HP @ 3000 psi
Electric	± 15 V D.C. - 3 amps
• **Walking Speed**	2.5 ft./sec.
• **Reach**	
Vertical	72"
Horizontal	36"
• **Number of Joints**	
Hand (2 Joints)	Thumb Tip Flex Thumb Flex
Arm (7 Joints)	Wrist Flex Forearm Rotate Elbow Flex Upper Arm Rotate Shoulder Flex Back Flex Arm Abduction - Arm Adduction
Leg (4 Joints)	Hip Abduction - Arm Adduction Hip Flex Knee Flex Ankle Flex
Foot (2 Joints)	Ankle Inversion Foot Rotate
Total - 15 per side x 2 = 30 Joints	
• **Type of Controls**	
Hand	Hydromechanical Rate Control with Force Feedback.
Arm	Electrohydraulic Bilateral Servo Control. Force Feedback Ratio 25:1.
Leg and Foot	Electrohydraulic Unilateral Servo. Indirect Force Feedback.

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