DESIGN OF A VERSATILE, TELEOPERABLE, TOWABLE LIFTING MACHINE WITH ROBOTIC CAPABILITIES FOR USE IN NASA'S LUNAR BASE OPERATIONS

Submitted to:

Mr. James A. Aliberti

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Advanced Projects, Technology, and Commercialization Office

Prepared by:

Elizabeth Harris
James Ogle, Team Leader
Dean Schoppe

Mechanical Engineering Department
THE UNIVERSITY OF TEXAS AT AUSTIN
Austin, Texas
Fall 1989

(NASA-CR-186688) DESIGN OF A VERSATILE, TELEOPERABLE, TOWABLE LIFTING MACHINE WITH ROBOTIC CAPABILITIES FOR USE IN NASA'S LUNAR BASE OPERATIONS (Texas Univ.) 108 p
CSCL 13I G3/37
N90-25345
Unclas
0289170

MECHANICAL ENGINEERING DESIGN PROJECTS PROGRAM
THE UNIVERSITY OF TEXAS AT AUSTIN

ETC 4.102 • Austin, Texas 78712-1063 • (512) 471-3900

November 15, 1989

James A. Aliberti, Manager of Research Programs
Mail Stop PT-PMO
Kennedy Space Center, Fl 32899

Dear Mr. Aliberti:

Attached please find our final report entitled "Design of a Versatile, Teleoperable, Towable Lifting Machine with Robotic Capabilities for use in NASA'S Lunar Base Operations". The report contains a discussion of alternate designs developed by the design team, the final design solution, and our conclusions and recommendations. The final design solution is a variable angle crane with a telescoping boom, a cable and hook for heavy lifts, and a robot arm with a three jaw gripper for light, dextrous lifts.

The design team appreciated the opportunity to work on this project and looks forward to seeing you at our design presentation. The presentation will take place on Tuesday, December 5, 1989, at 11:00am in the Engineering Teaching Center II, ETC 4.110, on the campus of The University of Texas at Austin. A catered luncheon will follow the presentation.

Thank you for your support.

Sincerely,

Elizabeth Harris
Elizabeth Harris

Dean Schoppe
Dean Schoppe

James Ogle
James Ogle, Team Leader

ACKNOWLEDGEMENTS

The design team would like to thank the Universities Space Research Administration and Mr. James A. Aliberti from the Advanced Projects, Technology, and Commercialization Office of the National Aeronautics and Space Administration for sponsoring this project.

Special thanks goes to Dr. Robert Freeman from the Mechanical Engineering Department at The University of Texas at Austin for serving as faculty advisor to the design team and providing guidance.

Thanks also goes to Dr. Wallace Fowler, Mr. George Davis, and Ms. Barbara Kozel from the Aerospace Department at The University of Texas at Austin for providing much needed information and advice throughout the project.

We would also like to thank Mr. Wendell Dean at The University of Texas at Austin for his lectures and graphics help.

We thank Mr. Bert Herigstad at The University of Texas at Austin for his suggestions, clerical help, and assistance with preparing the written report.

Thanks also go to Mr. Rick Connell, our teaching assistant at The University of Texas at Austin, for all of the help, suggestions, and inspiration in planning and preparing the report.

And finally, special thanks also go to Dr. Stephen P. Nichols, Professor of Mechanical Engineering at The University of Texas at Austin, for overseeing the Senior Design Projects Program and for his lectures throughout the semester.

ABSTRACT

DESIGN OF A VERSATILE, TELEOPERABLE, TOWABLE LIFTING MACHINE WITH ROBOTIC CAPABILITIES FOR USE IN NASA'S LUNAR BASE OPERATIONS

The Universities Space Research Association (USRA) in conjunction with NASA has requested the design team to design a versatile lifting machine for lunar base surface operations. The lifting machine will assist in lifting cargo off of landers sent to the moon and in the construction of a lunar base.

The design team considered three possible designs for the overall configuration of the lifting machine: the variable angle crane, the tower crane, and the gantry crane. The design team also developed alternate designs for the major components of the lifting machine.

The design team chose a teleoperable, variable angle crane as its final design. The design consists of a telescoping boom mounted to a chassis that is supported by two conical wheels for towing and four outriggers for stability. Attached to the end of the boom is a seven degree of freedom robot arm for light, dexterous, lifting operations. A cable and hook suspends from the end of the boom for heavy, gross, lifting operations.

The design team determined approximate structural sizes for the lifter and its components. However, further analysis is needed to determine the optimum design dimensions.

Lastly, the design team constructed a model of the design which demonstrates its features and operating principals. This model is capable of integration with the models built by the other NASA teams in The University of Texas at Austin Mechanical Engineering Design Projects Program.

KEY WORDS: CRANE, LIFTER, ROBOTIC, LUNAR, TELEOPERATED

Elizabeth Harris
Elizabeth Harris

James Ogle
James Ogle, Team Leader

Dean Schoppe
Dean Schoppe

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

TABLE OF CONTENTS (cont.)

APPENDICES

LIST OF FIGURES

LIST OF FIGURES (cont.)

INTRODUCTION

The sponsors for this design project are the Universities Space Research Association (USRA) and the United States National Aeronautics and Space Administration (NASA). USRA is a private, non-profit corporation organized in 1969 by the National Academy of Sciences. Its membership includes 58 universities across the United States. USRA assists universities and other research institutions in developing space science and technology. Presently, USRA directs several programs and institutes for NASA. In one of the programs, called the Advanced Design Program, USRA provides money to universities allowing senior engineering design classes to work on design projects related to space engineering. Through this program, The University of Texas at Austin Mechanical Engineering Design Projects Program will design a versatile lifting machine for lunar base operations.

This report contains the development of a versatile, teleoperable, towable lifting machine with robotic capabilities for use in NASA'S lunar base operations. The first chapter of this report describes the alternate designs for the overall configuration of the lunar lifter and its components. The next chapter describes the final design chosen by the design team. The remaining chapters are the conclusions and recommendations of the design team and the appendices.

1.1 BACKGROUND

NASA studied the feasibility of a manned lunar base through the early 1970's, but the study was curtailed in the mid-1970's. Currently, NASA is conducting a study of a manned lunar base to determine what equipment must be developed prior to the landing of the first mission. In the present scenario, missions will occur every six months and will alternate between cargo and manned missions. The first cargo lander will be sent to the moon by the year 2001 and the first manned mission will be sent approximately six months afterward.

The primary commercial benefit for establishing a lunar base is the extraction of oxygen from the lunar soil. The feasibility of future space exploration is enhanced by the availability of lunar oxygen (LUNOX) to provide life support and to oxidize the fuel needed for propulsion. LUNOX can be put into low lunar orbit (LLO) with less energy than oxygen obtained on Earth thus reducing costs of future missions. One goal of the lunar base is that the moon can serve as an oxygen supply station.

The establishment of a lunar base will require the development of specialized equipment. There is a need for a versatile lifting machine capable of performing a variety of lifting and robotic operations. This lunar lifter design project was submitted with the following requirements and criteria.

1.2 PROJECT REQUIREMENTS

The design team has been asked to perform the tasks listed below:

1. Design a versatile lifting machine for lunar base surface operations.
2. Construct a model which demonstrates features and operating principles.

1.3 DESIGN CRITERIA

The criteria for the lifting machine are as follows:

1. Capable of heavy and light, dextrous lift operations.
2. Configured for towing on the lunar surface.
3. Capable of being operated by teleoperations (remote control) from within a pressurized vehicle or by a person in an extravehicular activity (EVA) suit.
4. Powered by a separate energy source.
5. Capable of employing energy storage devices to minimize power consumption.
6. Be lightweight to minimize the cost of transporting to the moon.
7. Be of compact design to consume minimal cargo space.
8. Operated with minimal manpower.
9. Designed for operation in the lunar environment.

1.4 DESIGN METHODOLOGY

The design team conducted a survey of literature to locate work already done on lunar lifting machines or similar devices on the Earth or moon. The characteristics of the lunar environment were determined to identify factors that influenced the design of the lifting machine (see Appendix A). Throughout the design process, the team consulted with the three other teams from The University of Texas Mechanical Engineering Design Projects Program working on NASA projects, engineering professors, their faculty advisor, Dr. Robert Freeman, and others.

Due to the complex nature of the lunar lifter design, the design team identified the major components required for the lunar lifter. The design team generated and evaluated several alternate designs for the overall configuration of the lunar lifting device as well as for its individual components.

Using a decision matrix, the design team chose the best design for the overall configuration of the lunar lifting device and for its components. The final overall configuration for the lunar lifter was developed by optimizing the individual components of the overall design.

Computer Aided Design (CAD) was used to create drawings of the chosen design as well as the alternates. Finally, the team constructed a model that demonstrates the operations and features of the chosen lifter design solution. The model is capable of integration with the other NASA models built by the above mentioned Mechanical Engineering teams to form a composite demonstration model.

ALTERNATE DESIGNS OF THE LUNAR LIFTER AND ITS COMPONENTS

The brainstorming sessions conducted by the design team resulted in three alternate designs for the overall configuration of the lunar lifter. A description of each design along with the advantages and disadvantages of each is given in this section. These designs are as follows:

1. Variable angle crane,
2. Tower crane, and
3. Gantry lifter.

Due to the complex nature of the possible lunar lifter designs, the design team identified the major components required for each lifter design. The components of the lunar lifter designs were considered individually in order to simplify the design process. A description of each component along with its alternate designs are presented later in this section. The components involved in the design of the previously mentioned alternates are as follows:

1. Boom,
2. Lifting Mechanism,
3. Stabilizers,
4. Transport media, and
5. Energy conversion and storage mechanism.

The team also considered possible materials for the structural components of the lifter. As stated in the project criteria, the materials used in the lifter design must be lightweight, strong, and compatible with the lunar environment. These materials must resist or be protected from the damaging effects of ultraviolet radiation and thermal expansion due to extreme temperature variations (-175 to 150 degrees Celsius). The three materials for further consideration are as follows:

1. Kevlar and/or graphite epoxy or resin composite structures,
2. Aluminum alloys, and
3. Magnesium alloys.

2.1 OVERALL CONFIGURATIONS FOR THE LUNAR LIFTER

This section considers designs for the overall configuration of the lunar lifter. The design team generated three alternate designs based on the design criteria for the project. The three alternate designs are the variable angle crane, the tower crane, and the gantry lifter.

2.1.1 Variable Angle Crane

The first idea considered for the overall design of the lunar lifter is the variable angle crane (see Figure 2.1). This design

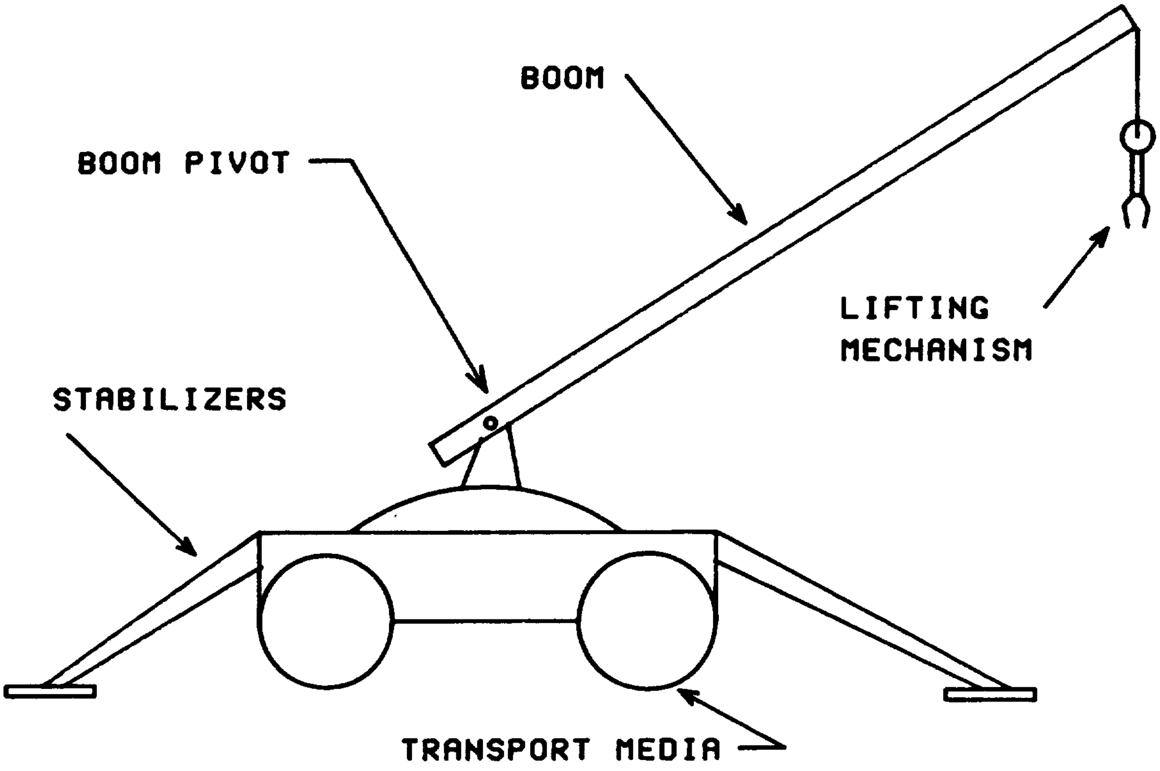


Figure 2.1: VARIABLE ANGLE CRANE

consists of a boom attached to a chassis. The boom is capable of varying its angle horizontally as well as vertically. A robot manipulator is attached to the end of the boom for dextrous operations and possibly heavy vertical lifting. This design will require a mechanism to insure stability.

The advantages of the variable angle crane are as follows:

1. Versatile design; boom angle may vary in pitch and yaw.
2. Has a low boom pivot point which allows the robot arm to perform ground level operations.

The disadvantages of the variable angle crane are as follows:

1. Requires a stabilizing mechanism.
2. Relatively complex design.

2.1.2 Tower Crane

The second idea considered for the overall design of the lunar lifter is the tower crane (see Figure 2.2). This design consists of a boom attached to a vertical column which is connected to a chassis. Attached to one end of the boom is a robot manipulator for lifting operations. The opposite end supports a positionable counter ballast weight for stability. The boom is capable of angular movement in

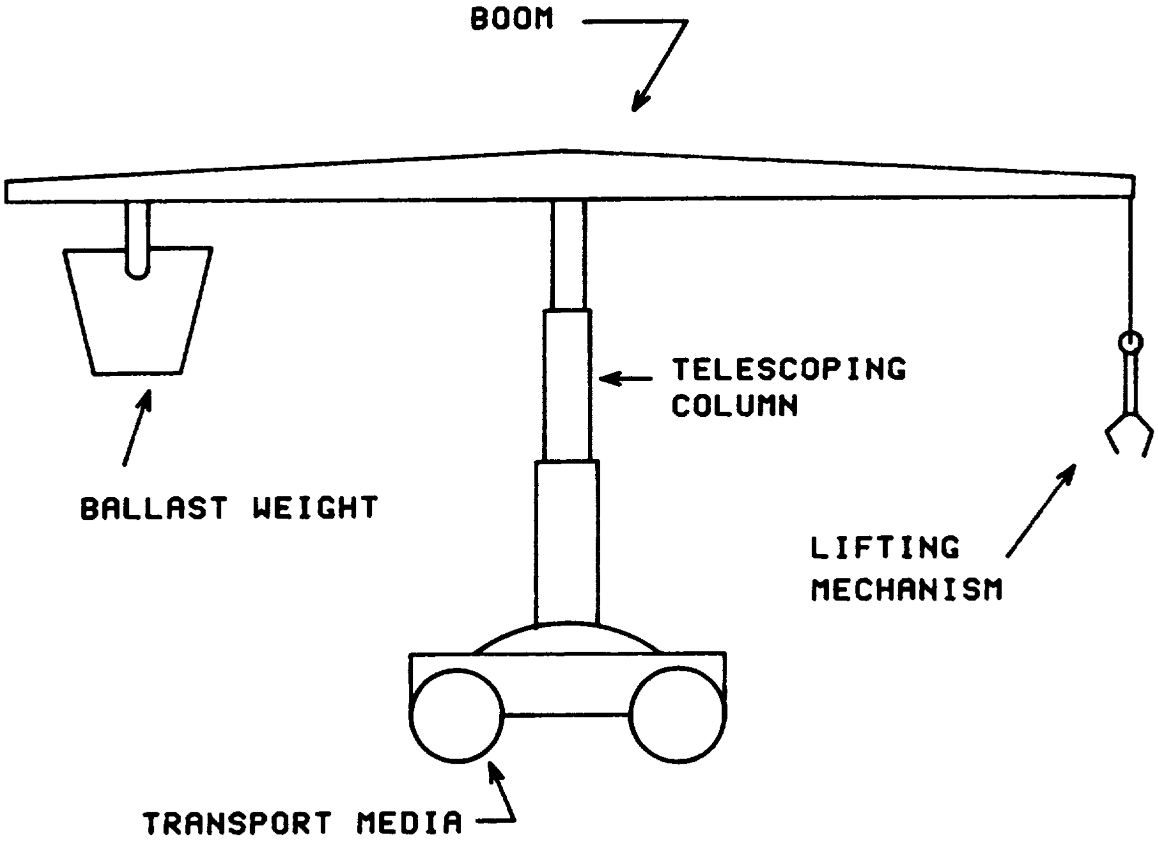


Figure 2.2: TOWER CRANE

the horizontal plane only. Gross vertical positioning is provided by extension or contraction of the vertical column.

The advantages of the tower crane are as follows:

1. Relatively simple design.
2. Counter ballast mechanism reduces moment loading on chassis.

The disadvantages of the tower crane are as follows:

1. Limited to flat surfaces or inclined surfaces of small angles.
2. May require knowledge of weight to be lifted in order to position the counter ballast weight.

2.1.3 Gantry Lifter

The third idea considered for the overall design of the lunar lifter is the gantry lifter (see Figure 2.3). The gantry lifter has a robot manipulator that suspends vertically in a rectangular truss structure. The truss structure is supported by four legs. The position of the manipulator within the rectangular truss is controlled by movable support beams that cross to form right angles. Wheels or other transport mechanisms allow gross movement of the lifted cargo.

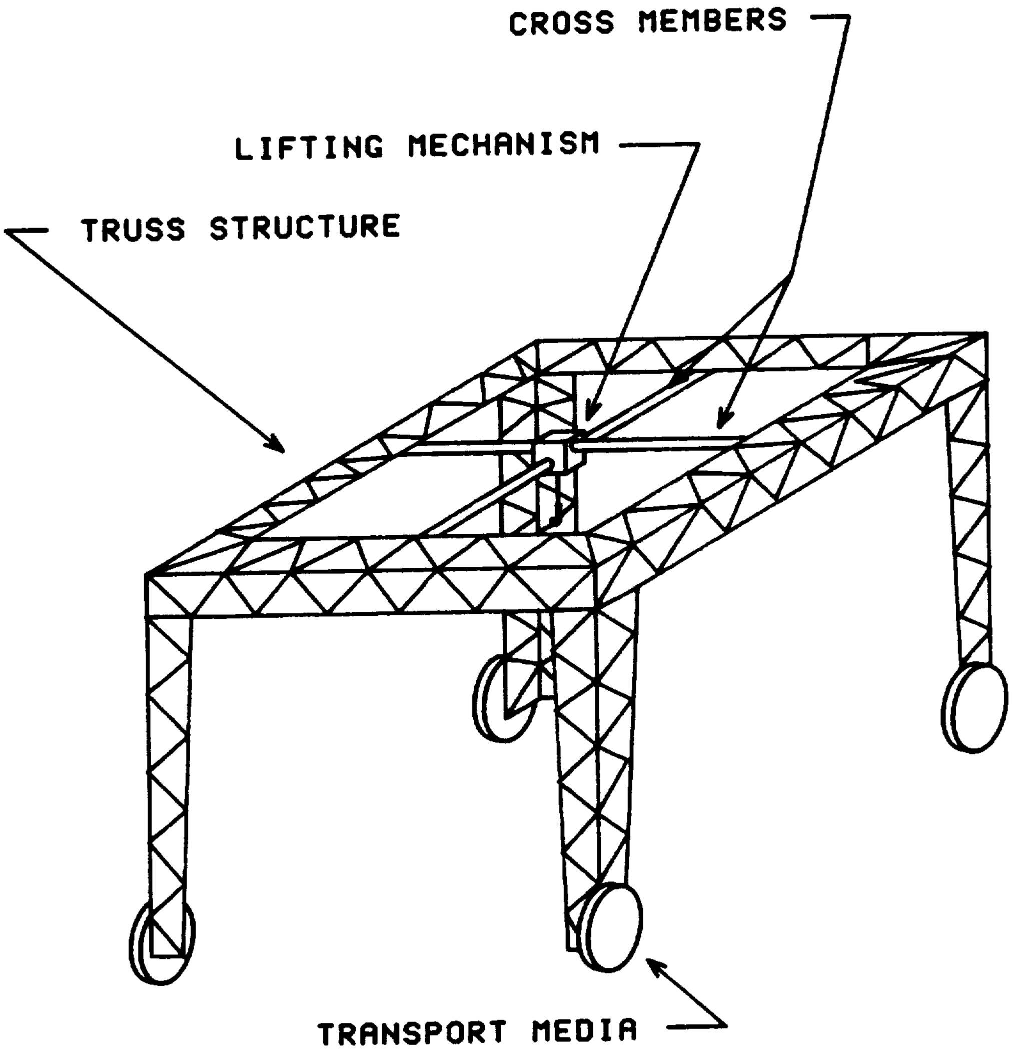


Figure 2.3: GANTRY LIFTER

The advantages of the gantry lifter are as follows:

1. Simple design.
2. Few moving parts.
3. Self stabilizing; does not require ballast weights.

The disadvantages of the gantry lifter are as follows:

1. Lack of versatility; the lifter must be positioned over the object. This may not always be possible.
2. Not a compact design; bulky for towing or transport to the moon.

2.2 COMPONENTS OF THE LUNAR LIFTER DESIGN

This section describes the individual components required for the design of the lunar lifter. These components are as follows: boom, lifting mechanism, stabilizers, transport media, and energy conversion and storage mechanism. The alternate designs of the components are described in this section along with the advantages and disadvantages of each.

The boom component is not utilized in the gantry lifter design. Also, the fixed angle crane and the gantry crane are inherently self stabilizing, therefore the stabilizers are designed for the variable angle crane only.

2.2.1 Boom Component

One of the components of the lunar lifter design is the boom. The boom enables the varying and fixed angle designs to extend a lifting mechanism over the object to be lifted. The boom and lifting mechanism can then provide a lifting force to elevate the cargo. Several ideas were generated for the boom design and from these, four alternate designs were considered. These designs are as follows:

1. Plain truss boom,
2. Folding boom,
3. Telescoping boom, and
4. Tong boom.

2.2.1.1 Plain Truss Boom. The plain truss boom consists of many rigidly attached links that are assembled into a truss structure (see Figure 2.4). The boom has a shape similar to a tall, slender pyramid.

The advantages of the plain truss boom are as follows:

1. Simple, proven technology.
2. Requires no additional energy for extension or retraction of the boom.
3. Easy to maintain.

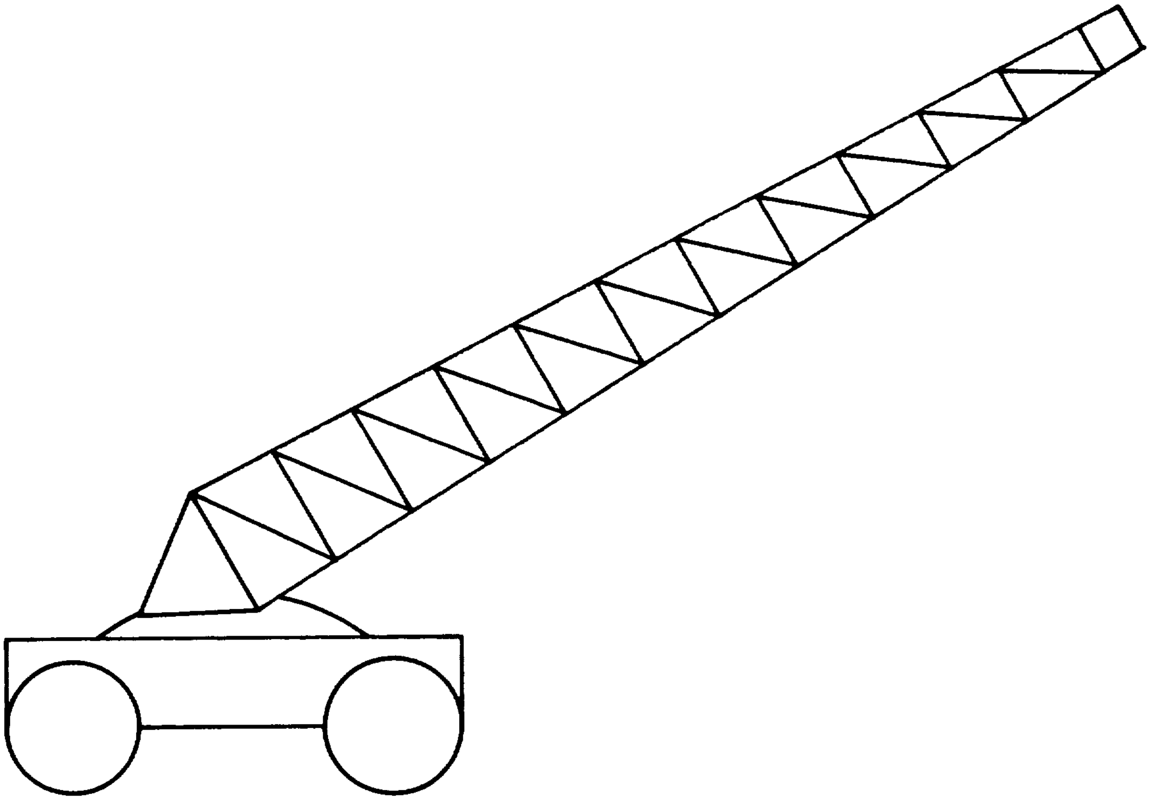


Figure 2.4: PLAIN TRUSS BOOM

The disadvantages of the plain truss boom are as follows:

1. Not versatile; unable to extend or retract.
2. Bulky; would take up a lot of cargo space.
3. Unstable during towing over rough terrain due to the bouncing of the extended boom.

2.2.1.2 Folding Boom. The folding boom consists of several hinged sections that enable the boom to fold to a compact form or be extended to various lengths (see Figure 2.5). The variability in length makes the folding boom useful for various lifting and robotic operations. The hinges could be arranged so that the boom could unfold vertically or horizontally.

The advantages of the folding boom are as follows:

1. Relatively simple design.
2. Capable of becoming compact for transport to the moon and for stability during towing on the lunar surface.
3. Easy to maintain and repair because all parts are external and accessible.
4. Versatile because of adjustability of length.

The disadvantages of the folding boom are as follows:

1. Not able to extend or contract continuously.
2. Requires energy to fold and unfold.

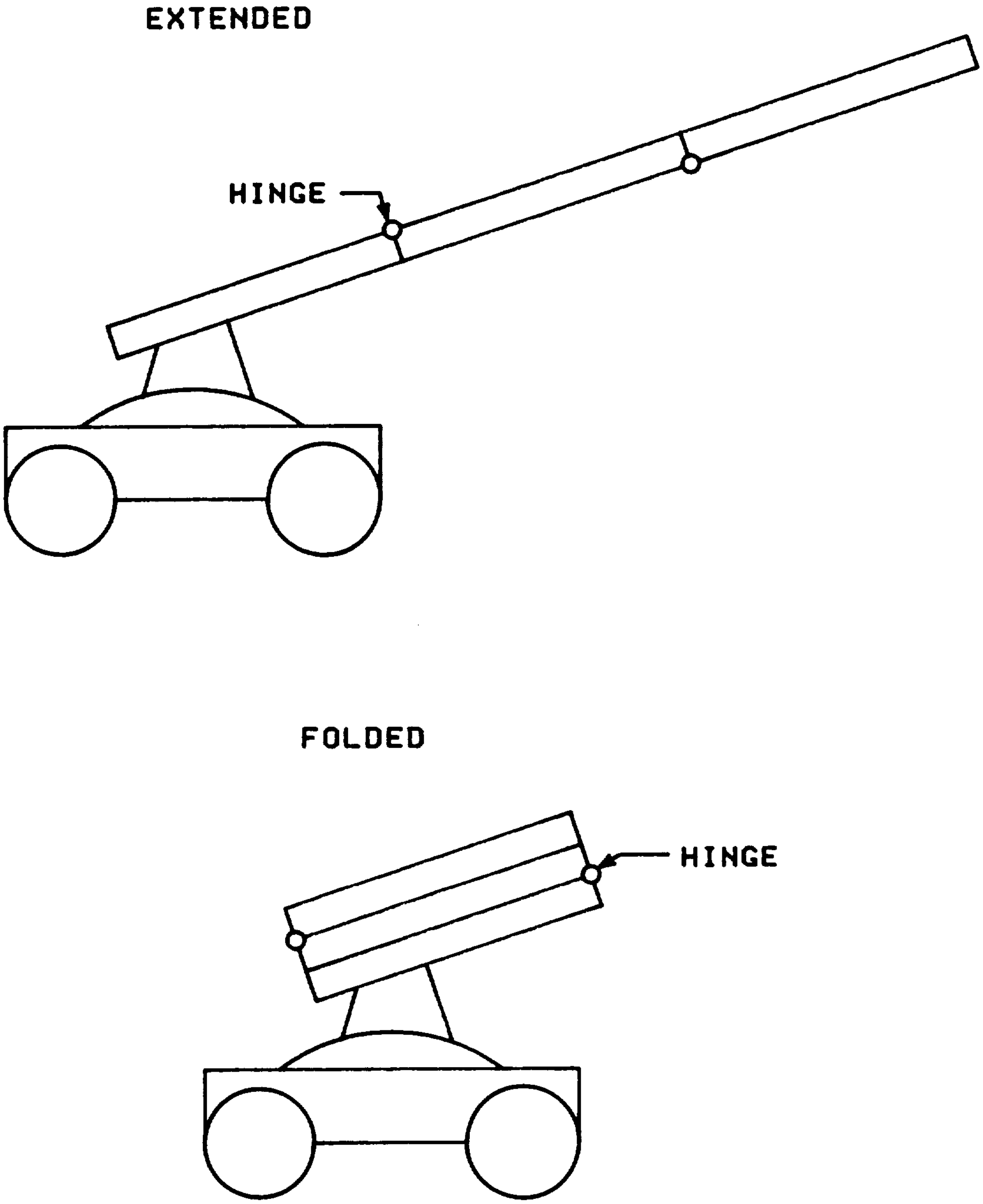


Figure 2.5: FOLDING BOOM

3. Requires development of a system to operate and lock the hinged sections.

2.2.1.3 Telescoping Boom. The telescoping boom would extend similar to the way a radio antenna extends (see Figure 2.6). Some possible cross-sectional shapes are cylindrical and rectangular.

The advantages of the telescoping boom are as follows:

1. Capable of becoming compact for transport to the moon and for stability during towing on the lunar surface.
2. Versatile; able to extend or contract.

The disadvantages of the telescoping boom are as follows:

1. Relatively complex design.
2. Difficult to repair and replace internal parts.
3. Requires energy to extend or retract.
4. Requires additional controls to operate the extension and retraction of the boom.
5. Tolerance problems exist due to the large thermal expansion effects on the moon.

2.2.1.4 Tong Boom. The tong boom has characteristics similar to a pair of fireplace tongs (see Figure 2.7). The boom assembly consists of two tongs that are parallel to each other and connected

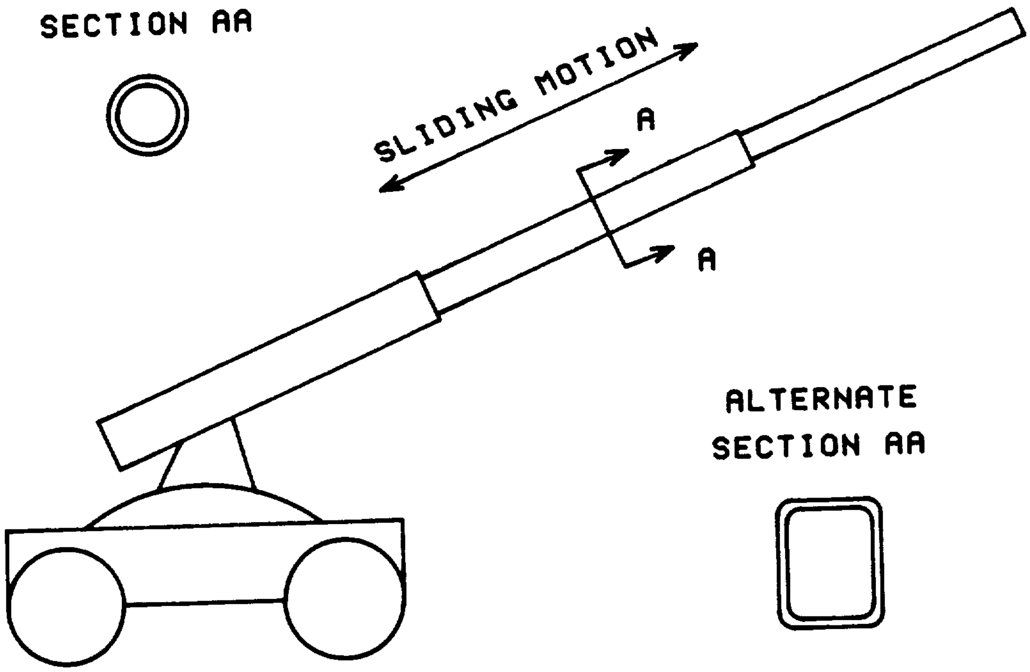


Figure 2.6: TELESCOPING BOOM

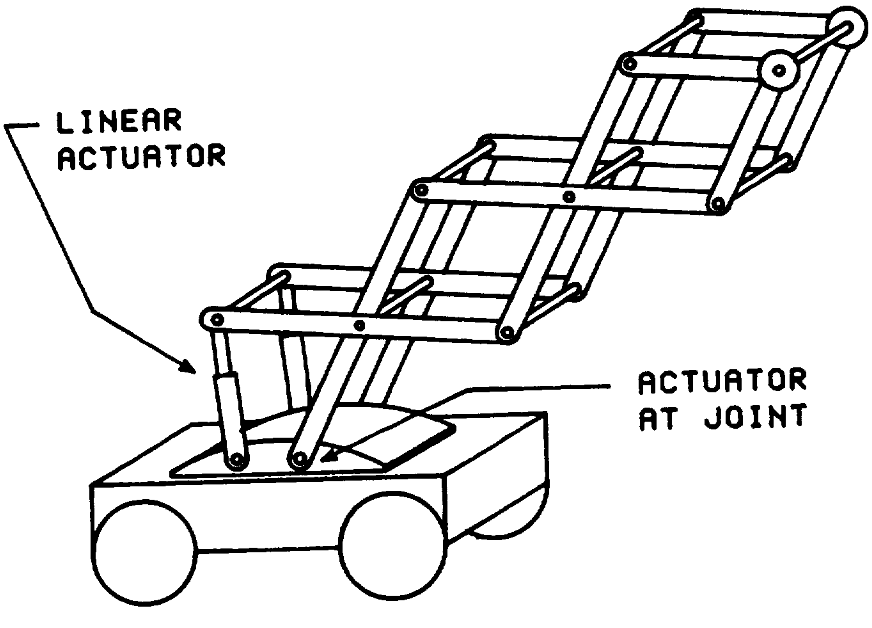


Figure 2.7: TONG BOOM

by links at each identical joint. The boom would operate in a relatively simple manner. As the linear actuator retracts, the boom extends and as the linear actuator extends, the boom retracts. Vertical positioning of the end of the boom is accomplished by using both the joint actuator and the linear actuator.

The advantages of the tong boom are as follows:

1. Capable of becoming compact for transport to the moon and for stability during towing on the lunar surface.
2. Versatile; able to extend or contract.
3. Relatively simple design.
4. Easy to maintain and operate because all parts are external and accessible.

The disadvantages of the tong boom are as follows:

1. Requires energy for extension and contraction.
2. Requires movement of several parts when in operation.
3. High loads in joints may exist.

2.2.2 Lifting Mechanism Component

The second component of the lunar lifter design considered is the lifting mechanism component. The lifting mechanism connects the cross member box of the gantry lifter or the boom of the other designs to the object being lifted. The lifting mechanism is located at the end of the variable and fixed angle crane booms and at the cross member box. The payload will be secured to the lifting mechanism by a combination of an end effector and either a robot arm or cable powered by a winch.

One possible lifting configuration is to use the cable and robot arm in conjunction with each other. In this configuration the cable would be used for heavy lift operations. For cable use a method for stabilizing the payload during lifting would have to be developed. The robot arm would be used for light dexterous lifting and as an aid for the placement of the cable's end effector. Another possible lifting configuration is to use the robot arm exclusively for heavy and light lift operations.

2.2.2.1 Robot Arm End Effectors. The end effector on the robot arm is used for light dextrous lifting and possibly as an aid for positioning the cable end effector and the cargo tag lines. Several ideas were generated for the end effector for the robot arm and from these, three alternate designs were generated. These designs are as follows:

1. Parallel gripper,
2. Three jaw gripper, and
3. Bayonet mount.

2.2.2.1.1 Parallel Gripper. The parallel gripper operates by grasping an object between two parallel plates (see Figure 2.8). The parallel gripper would be connected to a robot arm that would be attached to the boom.

The advantages of the parallel gripper are as follows:

1. Multifunctional; can grasp various shaped objects.
2. Simple design.

The disadvantages of the parallel gripper are as follows:

1. Objects slip out of grasp easily.
2. Cannot handle heavy loads.

2.2.2.1.2 Three Jaw Gripper. The three jaw gripper has three individually rotatable jaws that would be inserted into or around a receptacle on the object to be lifted (see Figure 2.9). The jaws would then expand or contract into the slots on the receptacle to make a secure connection. The jaws would also be capable of grasping other objects without receptacles such as tubular shapes or objects with a protrusion. The three jaw gripper would be connected to a robot arm that would be attached to the boom.

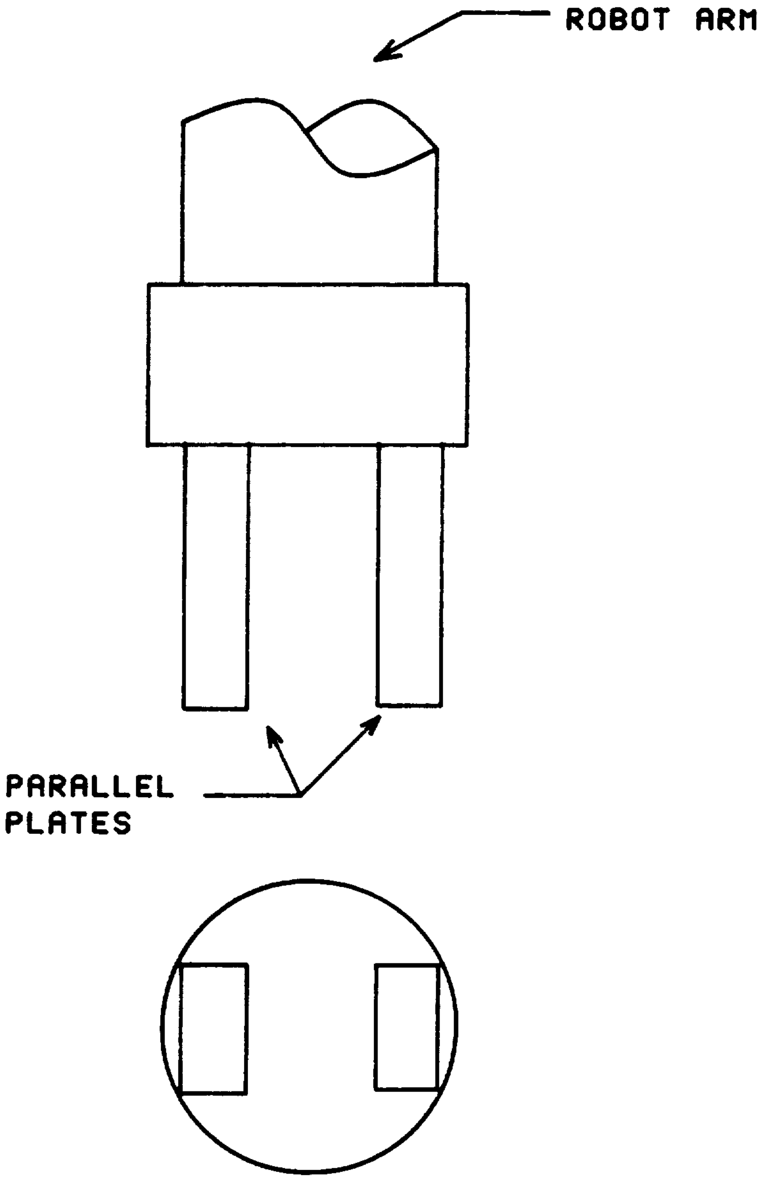


Figure 2.8: PARALLEL GRIPPER

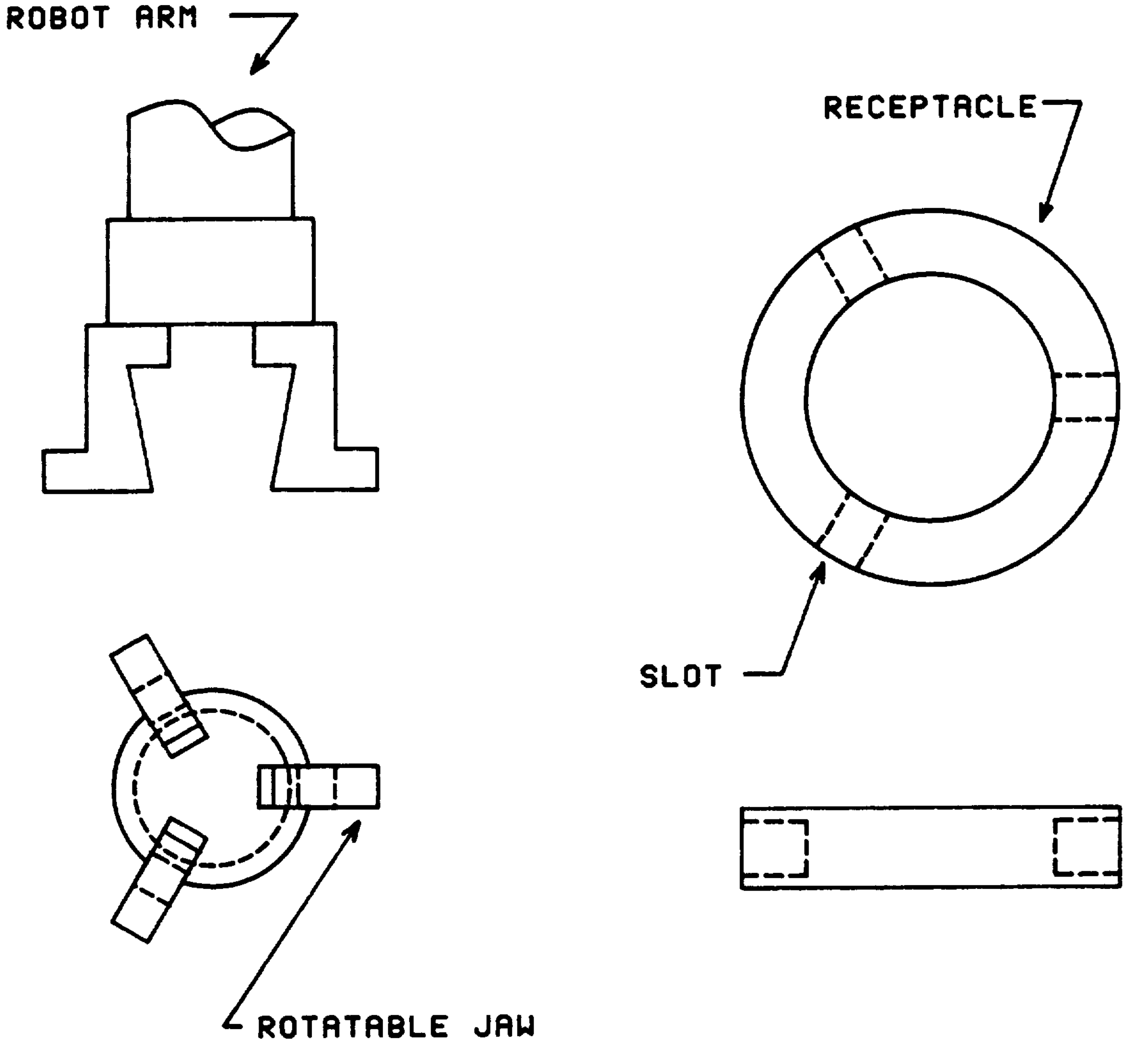


Figure 2.9: 3 JAW GRIPPER AND RECEPTACLE

The advantages of the the three jaw gripper are as follows:

1. Provides a secure connection with no slipping, turning, or pivoting.
2. Capable of grasping various shaped lightweight objects without a receptacle.
3. Capable of heavy vertical lifting operations.
4. Capable of lifting and positioning lighter objects in any orientation (objects that have a mating receptacle).

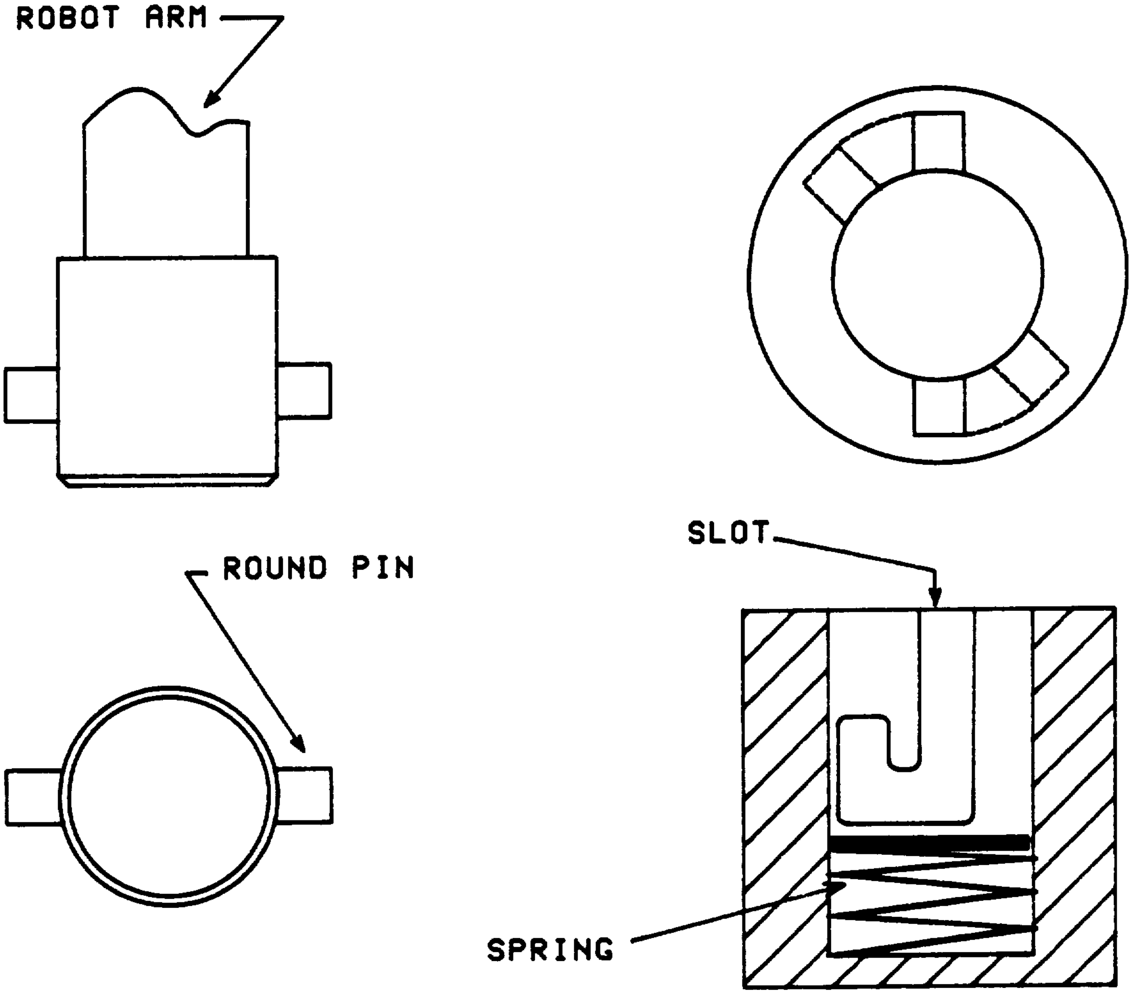
The disadvantages of the three jaw are as follows:

1. More complex design.
2. Requires special fittings for secure connections.
3. Tolerances difficult to maintain due to thermal expansion effects.

2.2.2.1.3 Bayonet mount. This gripper would connect to the payload similar to the way an automobile brake light is put into position (see Figure 2.10). The gripper would be inserted into a receptacle, pushed forward against a spring force, turned, and released so that it is locked into position. The Bayonet mount would be connected to a robot arm that would be attached to the boom.

The advantages of the bayonet mount are as follows:

1. Provides a solid connection with no slipping, turning, or pivoting.



MALE CONNECTOR

FEMALE RECEPTACLE

Figure 2.10: BAYONET CONNECTOR

2. Capable of vertical heavy lift operations.
3. Capable of lifting and positioning lighter objects in any orientation.
4. Simple design with no moving parts.

The disadvantages of the bayonet mount are as follows:

1. Not versatile; cannot lift objects without a mating receptacle.
2. Maintenance of tolerances could be a problem.

2.2.2.2 Cable End Effectors. The end effectors on the end of the cable are used for heavy vertical lifting. Several ideas were generated for the end effector for the cable and from these, three alternate designs were generated. These designs are as follows:

1. Hook,
2. Ball, and
3. Electromagnet.

2.2.2.2.1. Hook. A hook would be attached to the end of the cable and would fit into a receptacle attached to an object being lifted (see Figure 2.11).

The advantages of the hook are as follows:

1. Simple; proven technology.

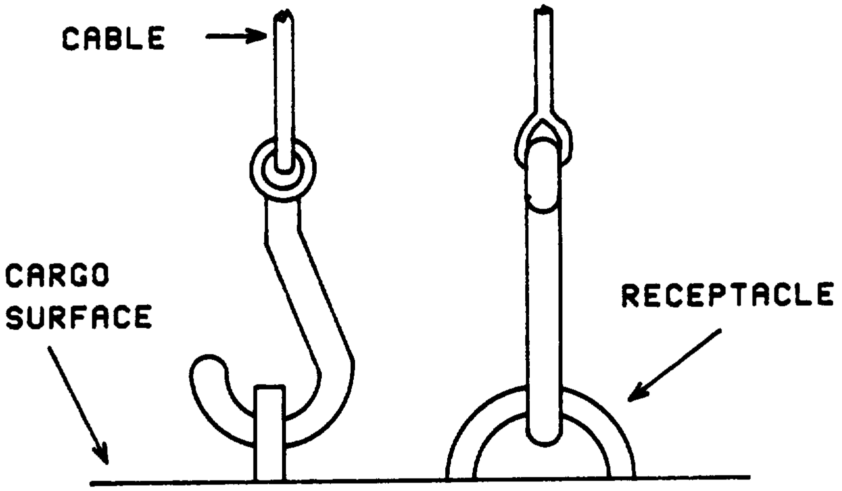


Figure 2.11: HOOK

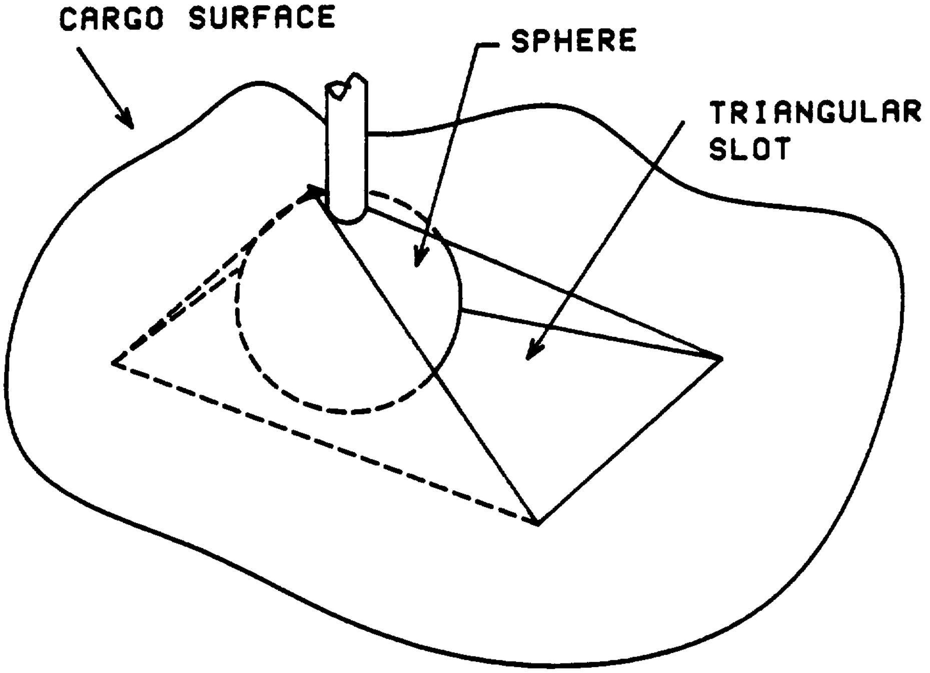


Figure 2.12: BALL

2. Reliable; no moving parts.

The disadvantages of the hook are as follows:

1. Difficult to connect to receptacle because it requires guidance to hook onto objects.
2. Only hooks into rings or loops.

2.2.2.2.2. Ball. A ball would be attached to the end of the cable and would fit into a triangular receptacle attached or built into an object being lifted (see Figure 2.12).

The advantages of the ball are as follows:

1. Simple; proven technology.
2. Reliable; no moving parts.
3. Easily connected to receptacle.

The disadvantages of the ball are as follows:

1. Possibility of ball getting lodged in receptacle.
2. Requires a complex receptacle.
3. Unreliable, ball could come out of socket if payload hangs up.

2.2.2.2.3 Electromagnet. An electromagnet would be attached to the cable and would electromagnetically connect to a smooth surface receptacle on the object being lifted.

The advantages of the electromagnet are as follows:

1. Easy to connect.
2. Utilizes an nonprotruding receptacle.
3. Simple design; no moving parts.

The disadvantages of the electromagnet are as follows:

1. Requires a large amount of energy to operate.
2. Must be made of a magnetic material (most are heavy).
3. Unsafe; loss of energy results in the payload being dropped.

2.2.3 Stabilizer Component

The third component of the lunar lifter design considered is the stabilizers. Stabilizers will keep the lifter from becoming unbalanced and tipping over when lifting a load. Several ideas were generated for the stabilizers and from these, five alternate designs were considered. These designs are as follows:

1. Counter balance boom,
2. Outriggers,
3. Anchors,
4. Hooking lifter to solid stationary structure, and
5. Trough of regolith.

2.2.3.1 Counter Balance Boom. An extra boom would operate as a mirror image to the lifting boom (see Figure 2.13). A load equal to the load being lifted would be attached to the extra boom.

The advantages of the counter balance boom are as follows:

1. Has dual functions; could also be used as an energy storage device (see section 2.2.5.3 Dual Boom).
2. Would counter balance the weight being lifted.
3. Reduce moment loading on the chassis.

The disadvantages of the counter balance boom are as follows:

1. Heavy, massive design.
2. Requires extra controls to mirror the operation of the lifting boom.
3. Requires a balanced weight equal to that of the payload.

2.2.3.2 Outriggers. Four outriggers would be attached at the chassis and would extend by teleoperation providing support for the lifter (see Figure 2.14). The outriggers would raise the lifter off of its wheels during heavy lift operations. The legs would be capable of folding for storage and towing.

The advantages of the outriggers are as follows:

1. The design uses proven technology.

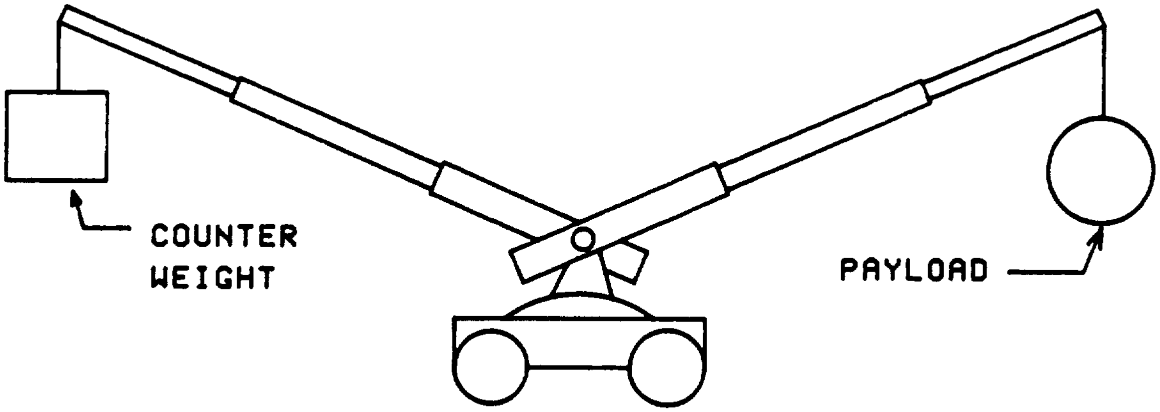


Figure 2.13: COUNTER BALANCE BOOM

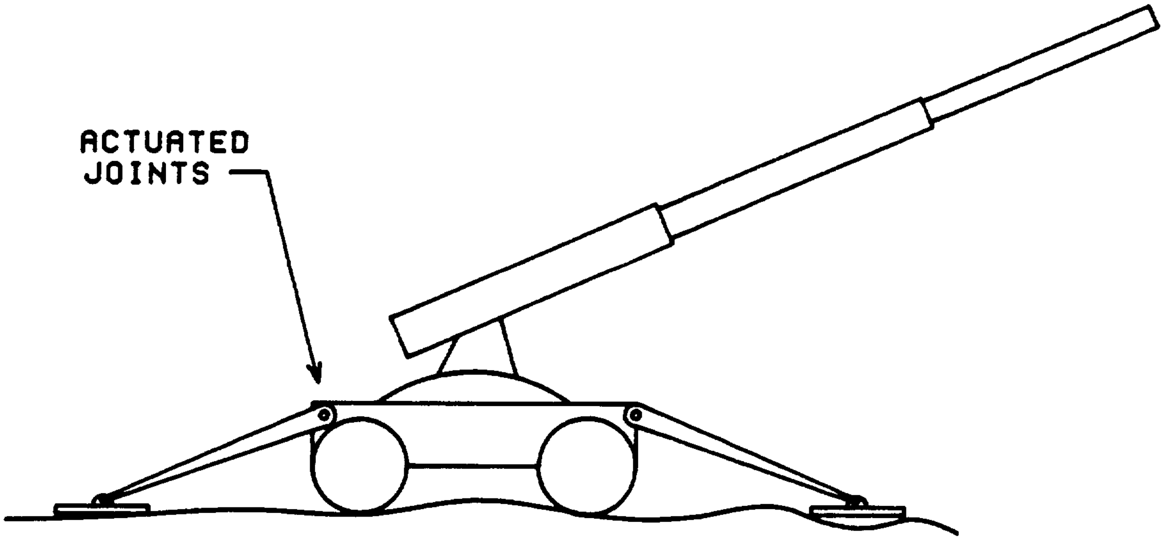


Figure 2.14: OUTRIGGERS

2. Versatile design; capable of being used on rough terrain.
3. Does not require a weight to balance load being lifted.
4. Wheels do not have to carry the load of the heavy lift operations.

The disadvantages of the outriggers are as follows:

1. Requires actuators for each foot thus increasing the weight of the design.
2. Requires energy to set up the outriggers.

2.2.3.3 Anchors. Four anchors would be inserted into the ground and attached to each side of the chassis by a cable (see Figure 2.15). The anchors would be in the shape of an arrow head spike. A procedure for inserting the anchors securely in the ground would have to be determined.

The advantages of the anchor are as follows:

1. Relatively simple design.
2. Requires minimal space and weight.
3. Good for a permanent lifting site.
4. Does not require a weight to balance the load being lifted.

The disadvantages of the anchor are as follows:

1. Requires energy to insert anchors into ground.
2. Unreliable; not sure if anchor will hold in the ground.

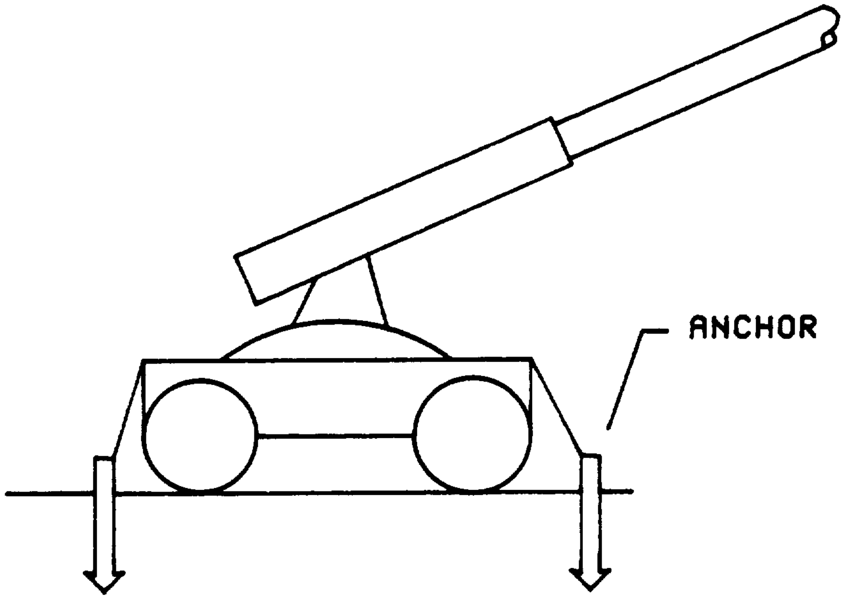


Figure 2.15: ANCHOR STABILIZER

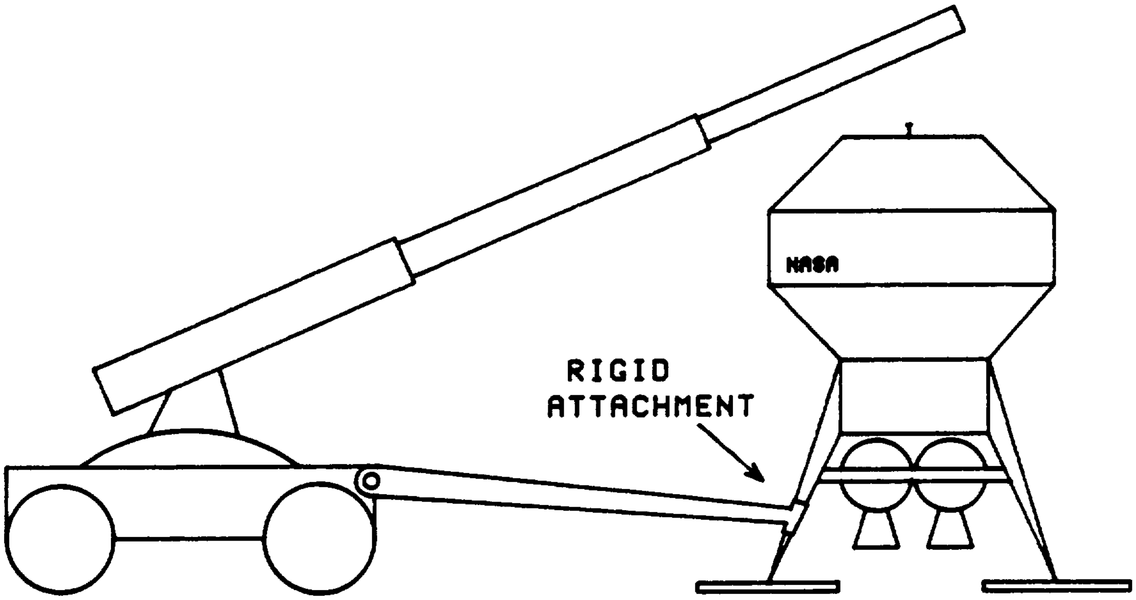


Figure 2.16: HOOK LIFTER TO OBJECT

3. Wasteful; the anchor could not be removed from the ground and reused.

2.2.3.4 Hook Lifter to Solid Stationary Structure. The design involves attaching the lifter's chassis to a solid stationary structure such as the lander (see Figure 2.16). The lifter would attach to the structure by a rigid attachment mechanism.

The advantages of hooking the lifter to a solid stationary structure are as follows:

1. Utilizes existing structures on the moon, such as the lander, therefore reducing the amount of extra equipment taken to the moon.
2. Does not require a weight to balance load being lifted.

The disadvantages of hooking the lifter to a solid stationary structure are as follows:

1. Not versatile; a solid stationary structure must be present to stabilize the lifter.
2. Requires energy to set up the connections between the lifter and the structure.

2.2.3.5 Trough of Regolith (Lunar Soil). A trough surrounds the chassis and is filled with regolith (see Figure 2.17). A procedure for filling and emptying the trough of regolith would be developed. Possible procedures might be a human in an EVA suit or a teleoperated shovel operation.

The advantages of the trough of regolith are as follows:

1. Relatively simple design.
2. Lightweight when empty.
3. Utilizes materials on the moon (regolith).

The disadvantages of the trough of regolith are as follows:

1. Requires knowledge of weight needed to balance the load being lifted.
2. Requires energy to insert the regolith.

2.2.4 Transport Media Component

The fourth component of the lunar lifter design considered is the transport media. The lifter will need a transport media to allow towing on the lunar surface. Several ideas were generated for the transport media and from these, five alternate designs were considered. These designs are as follows:

1. Conventional wheels,
2. Conical wheels,

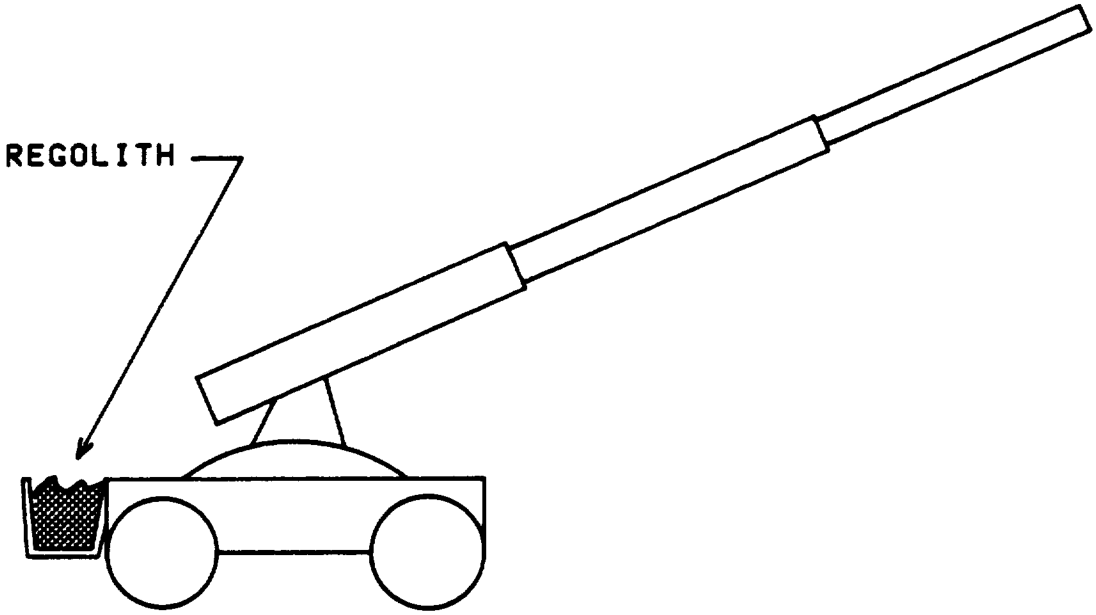


Figure 2.17: TROUGH OF REGOLITH

3. Track,
4. Walking/trailer combination, and
5. Tri-star assembly.

2.2.4.1 Conventional Wheels. Four wheels, similar in design to automobile wheels on Earth, would be attached to the chassis for towing behind a separate vehicle (see Figure 2.18). The wheels could be inflatable or made from wire mesh. On the Apollo mission, the wheels of the lunar rover were made of wire mesh.

The advantages of the conventional wheels are as follows:

1. Simple design; uses proven technology on Earth.
2. Suitable for use on the lunar surface.

The disadvantages of the conventional wheels are as follows:

1. The inflatable wheels are subject to punctures and adverse effects of thermal expansion.
2. Difficult to repair.

2.2.4.2 Conical Wheels. The conical wheels have a gradual tapering towards the axle (see Figure 2.19). The wheels could be inflatable or made of wire mesh.

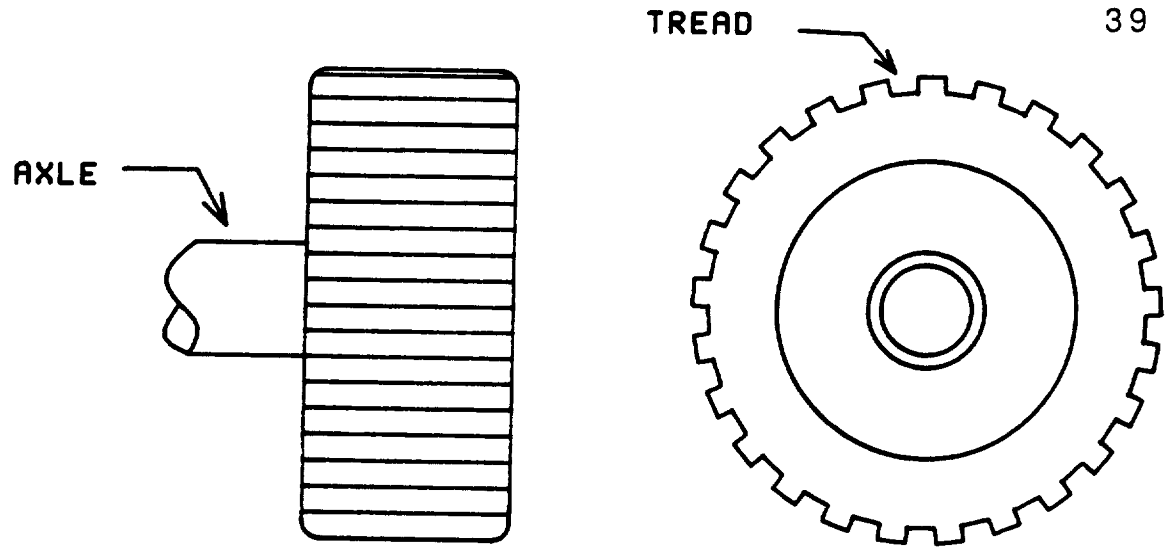


Figure 2.18: CONVENTIONAL WHEELS

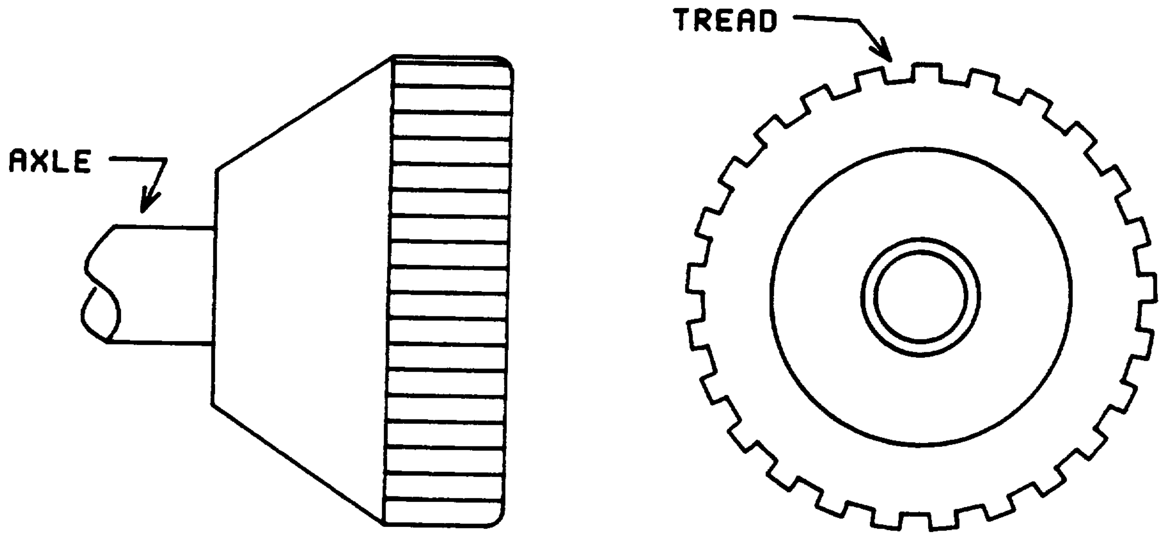


Figure 2.19: CONICAL WHEELS

The advantages of conical wheels are as follows:

1. Provides a wider wheel base for the same length axle.
2. Wheels can be nested together for shipping and storage.

The disadvantages of conical wheels are as follows:

1. Not as structurally sound as conventional wheels which have one more side wall.
2. More complex to design than conventional wheels.

2.2.4.3 Track. The lifter could be rolled on tracks (treads) similar to those used on tractors and tanks (see Figure 2.20). The track is a continuous belt type structure that rotates around rollers that are attached to the lifter.

The advantages of the track are as follows:

1. Capable of covering rough terrain.
2. Utilizes current technology on Earth.

The disadvantages of the track are as follows:

1. Complex design.
2. Many moving parts to protect from lunar dust.
3. Unreliable due to the many moving parts.
4. Difficult to tow due to the friction and inertia of the many moving parts.
5. Treads would "plow" into the lunar surface.

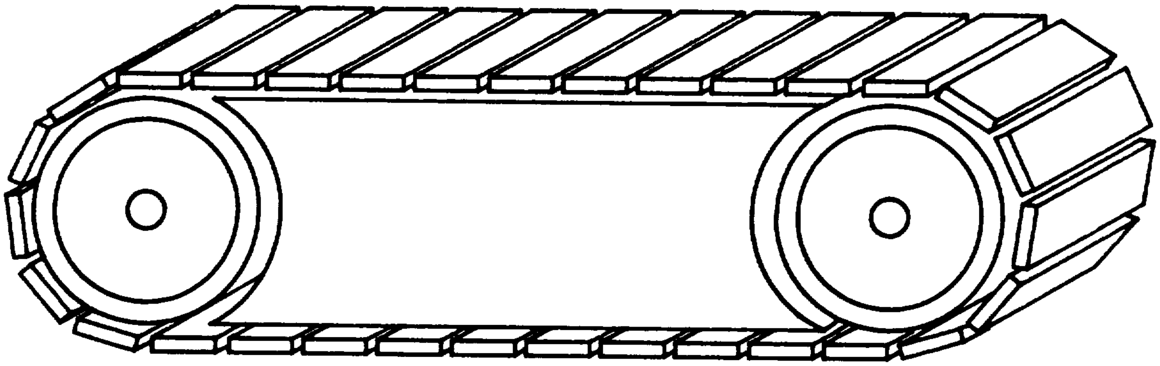


Figure 2.20: TRACK

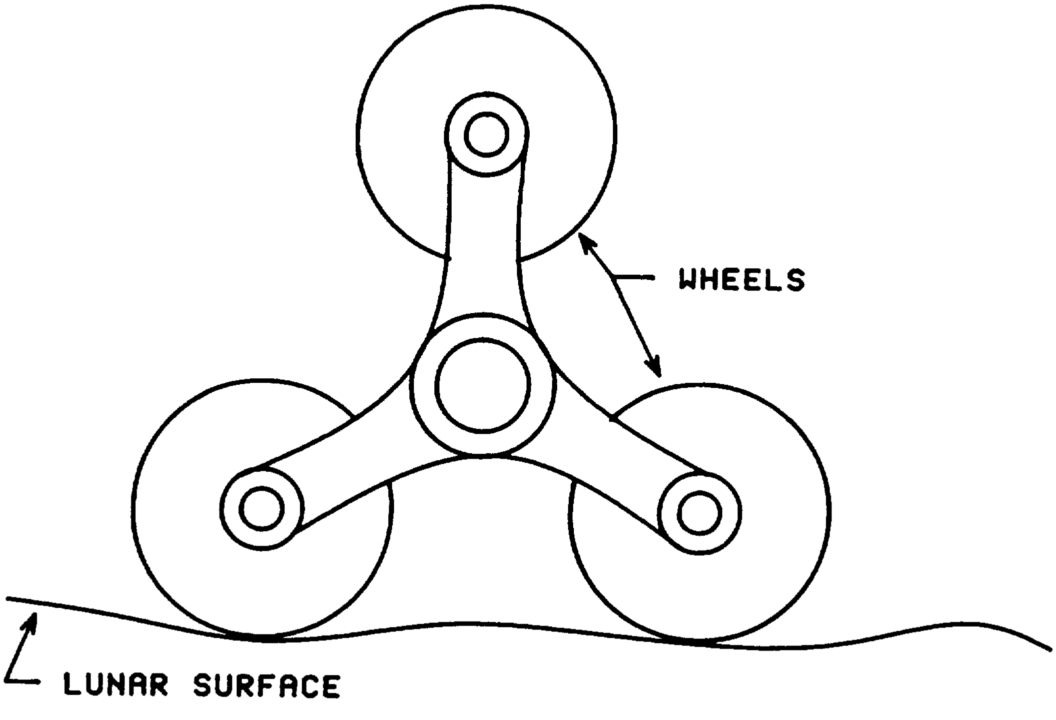


Figure 2.21: TRI-STAR WHEELS

2.2.4.4 Tri-star Assembly. A Tri-star assembly is composed of three wheels (see Figure 2.21) Two wheels are always in contact with the ground and the third wheel is idle. If one of the wheels hits an obstruction the assembly rotates over the obstruction. The idle wheel comes in contact with the ground and the back wheel rotates out of contact with the ground and becomes the idle wheel.

The advantages of a tri-star assembly are as follows:

1. Capable of covering rough terrain.
2. Lifter is still towable if one of the three tires on each assembly fails since only two tires are needed.

The disadvantages of a tri-star assembly are as follows:

1. Complex design.
2. Assembly becomes large as wheel diameter increases.
3. Rotation of assembly upon hitting an obstruction could cause lifter and/or payload damage due to shock loading.

2.2.4.5 Walking/Trailer Combination. The lifter is supported by teleoperable support legs extending from each corner of the chassis (see Figure 2.22). This gives the lifter the ability to make minor position adjustments by walking on the legs. Long distance transportation would be provided by a separate trailer.

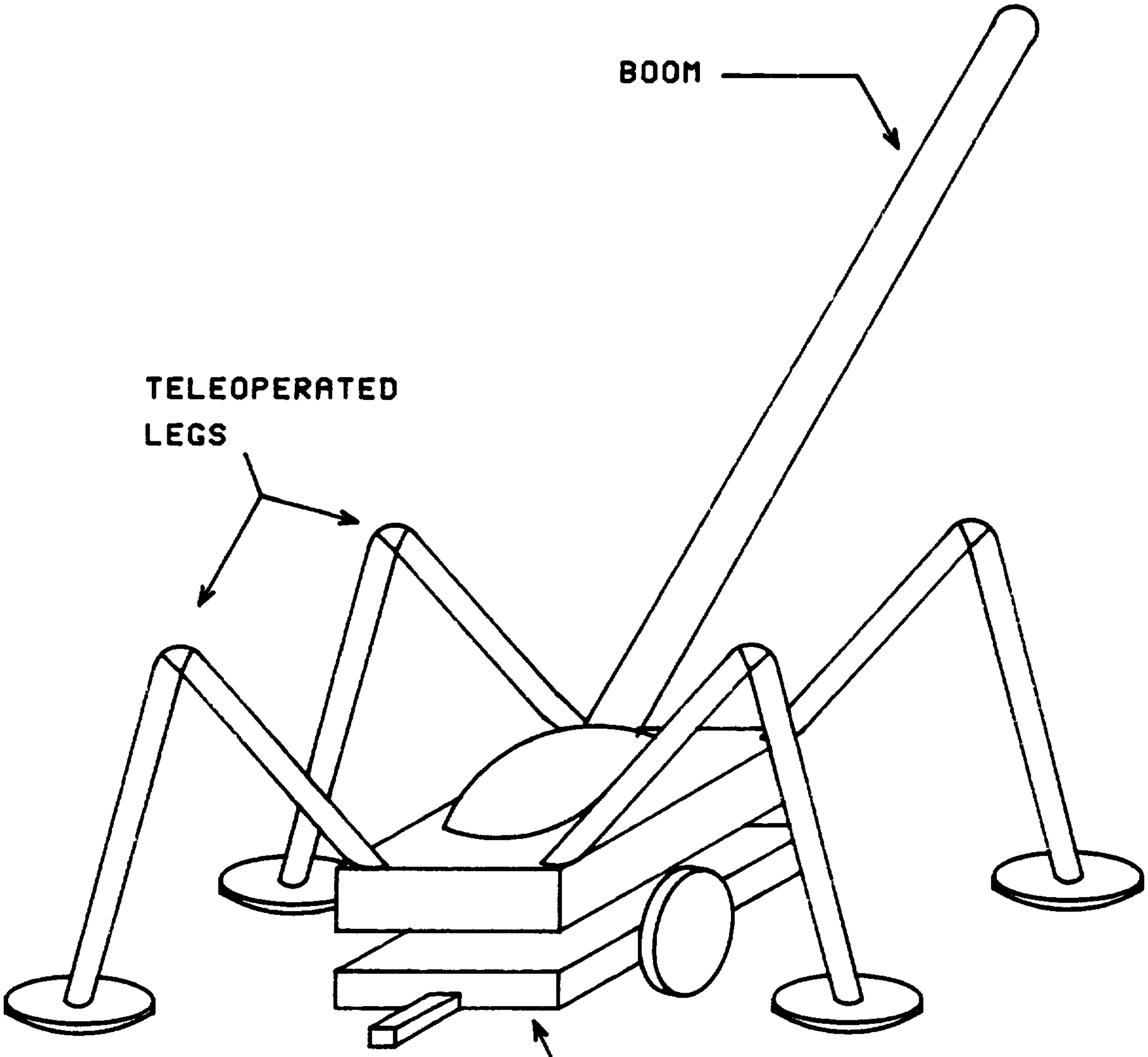


Figure 2.22: WALKING/TRAILER

The advantages of the walking/trailer combination are as follows:

1. Capable of operating on rough terrain.
2. Can adjust its position easily.
3. Could be self stabilizing if leg span is wide enough.
4. Trailer could be designed and utilized for various uses at the lunar base.

The disadvantages of the walking/trailer combination are as follows:

1. Complex design; requires a separate system to control movement of support legs.
2. More material since trailer is not an integral part of lifter.
3. Higher energy consumption than static designs due to the movement of the support legs.

2.2.5 Energy Conversion and Storage Mechanism Component

The last component of the lifter considered was the energy conversion and storage mechanism. An energy conversion and storage mechanism would enable the lifter to utilize the potential energy of the elevated cargo upon lowering it from the lander. Several ideas were generated for the energy conversion and storage mechanism and from these, four alternate designs were considered.

These designs are as follows:

1. Motor/generator,
2. Flywheel,
3. Dual boom, and
4. Spring.

2.2.5.1 Motor/generator. The motor/generator is a single device that has two separate functions. The motor is used for lifting operations and the generator is used for conversion of the potential energy to electrical energy.

The advantages of the motor/generator are as follows:

1. Dual purpose device.
2. Readily available.
3. Reduces lifter weight due to the integration of two functions if a motor is to be used as the driving mechanism.

The disadvantages of the motor/generator are as follows:

1. A motor/generator cannot be used if a motor is not being used as the driving mechanism.
2. Efficiency may be low for short, infrequent lifts.

2.2.5.2 Flywheel. A flywheel is a large disk that stores the potential energy of the raised cargo. The potential energy of the cargo is stored as rotational kinetic energy in the flywheel. The energy can be transferred to and from the flywheel via a clutch mechanism.

The advantages of the flywheel are as follows:

1. Common; readily available.
2. Simple; standard technology.

The disadvantages of the flywheel are as follows:

1. Must have large mass to store significant amounts of energy if low angular velocities are desired.
2. Dangerous if a lightweight high angular velocity flywheel is used.
3. Takes up large volume of space.

2.2.5.3 Dual Boom. The resulting energy gained from lowering the cargo off of the lander could be stored as potential energy in the dual boom's box of regolith (see Figure 2.13). As the cargo is lowered, the box of regolith is lifted and as the cargo is lifted, the box of regolith is lowered The cargo is attached to the box of regolith via a cable network.

The advantages of the dual boom are as follows:

1. Utilizes existing moon resources (regolith).
2. Has dual functions; also used as stabilizer (see 2.2.3.1 Counter Balance Boom).

The disadvantages of the dual boom are as follows:

1. Requires energy to fill the box with regolith.
2. Requires additional control procedures to coordinate the motion of the two booms and the box of regolith.

2.2.5.4 Spring. Springs would be attached at several locations on the lifter. The springs store the cargo's potential energy when the cargo is being lowered. This energy, stored in a compressional, pneumatic, or torsional spring, may be used to aid the lifting of the cargo.

The advantages of the spring are as follows:

1. Simple; standard technology.
2. Readily available.

The disadvantages of the spring are as follows:

1. Requires additional space to implement spring into design.

2. Design may require several different spring sizes and shapes.
3. Dangerous; failure could be harmful and catastrophic.

2.3 SUMMARY OF ALTERNATE DESIGNS

In summary, the design team's brainstorming sessions resulted in three alternate designs of the lunar lifter. These designs are the variable angle boom, the fixed angle boom, and the gantry lifter. Upon further consideration, the team decided to examine the individual components of the lifter separately. These components are the boom, lifting mechanism, stabilizers, transport media, and the energy conversion and storage mechanism. Several alternate designs for each component were generated and evaluated. Moreover, the team considered possible materials for the construction of the lifter.

For the next step in the design process, the team utilized decision matrix techniques to select the most desirable alternate from the lifter design and each of the component designs. The team then integrated these components into the chosen lifter design.

SUMMARY PAGE

ALTERNATE DESIGNS OF THE LUNAR LIFTER AND ITS COMPONENTS

2.1 OVERALL CONFIGURATIONS FOR THE LUNAR LIFTER

- **2.1.1 Variable Angle Crane**
- **2.1.2 Tower Crane**
- **2.1.3 Gantry Lifter**

2.2 COMPONENTS OF THE LUNAR LIFTER DESIGNS

- **2.2.1 Boom Component**
  - 2.2.1.1 Plain Truss Boom
  - 2.2.1.2 Folding Boom
  - 2.2.1.3 Telescoping Boom
  - 2.2.1.4 Tong Boom

- **2.2.2 Lifting Mechanism Component**
  - 2.2.2.1 Robot Arm End Effector
    - 2.2.2.1.1 Parallel Gripper
    - 2.2.2.1.2 Three Jaw Gripper
    - 2.2.2.1.3 Bayonet Mount
  - 2.2.2.2 Cable End Effector
    - 2.2.2.2.1 Hook
    - 2.2.2.2.2 Ball
    - 2.2.2.2.3 Electromagnet

- **2.2.3 Stabilizer Component**
  - 2.2.3.1 Counter Balance Boom
  - 2.2.3.2 Outriggers
  - 2.2.3.3 Anchors
  - 2.2.3.4 Hooking Lifter to Solid Stationary Structure
  - 2.2.3.5 Trough of Regolith (Lunar Soil)

- **2.2.4 Transport Media Component**
  - 2.2.4.1 Conventional Wheels
  - 2.2.4.2 Coned Shaped Wheels
  - 2.2.4.3 Track
  - 2.2.4.4 Walking/Trailer Combination
  - 2.2.4.5 Tri-star Assembly

- **2.2.5 Energy Conversion and Storage Mechanism Component**
  - 2.2.5.1 Motor/generator
  - 2.2.5.2 Flywheel
  - 2.2.5.3 Dual Boom
  - 2.2.5.4 Spring

DESIGN SOLUTION

This section presents the selection and design of the lunar lifter and its components. The best designs were selected from the alternate designs using a decision matrix process (see Appendix B). The criteria for the decision matrix include the following factors: safety, reliability, versatility, weight, energy usage, simplicity of operation, compactibility, simplicity of design, and durability. The following description of the final design is the result of two months of research and design.

3.1 OVERALL CONFIGURATION OF THE LIFTER

The design team chose the variable angle crane as the final design solution for the overall configuration (see Figure 3.1). A primary factor influencing the selection of the variable angle crane was its versatility. The boom of the variable angle crane has adjustable yaw (horizontal) and pitch (vertical); thus it has a large work space.

For heavy lifting, a cable and winch system is used. The winch, located on the chassis, controls a cable that extends through the center of the boom out through the end where it hangs freely. At the end of the cable is a hook that will be attached to the cargo to be lifted. To prevent the lifted cargo from becoming unstable (e.g.

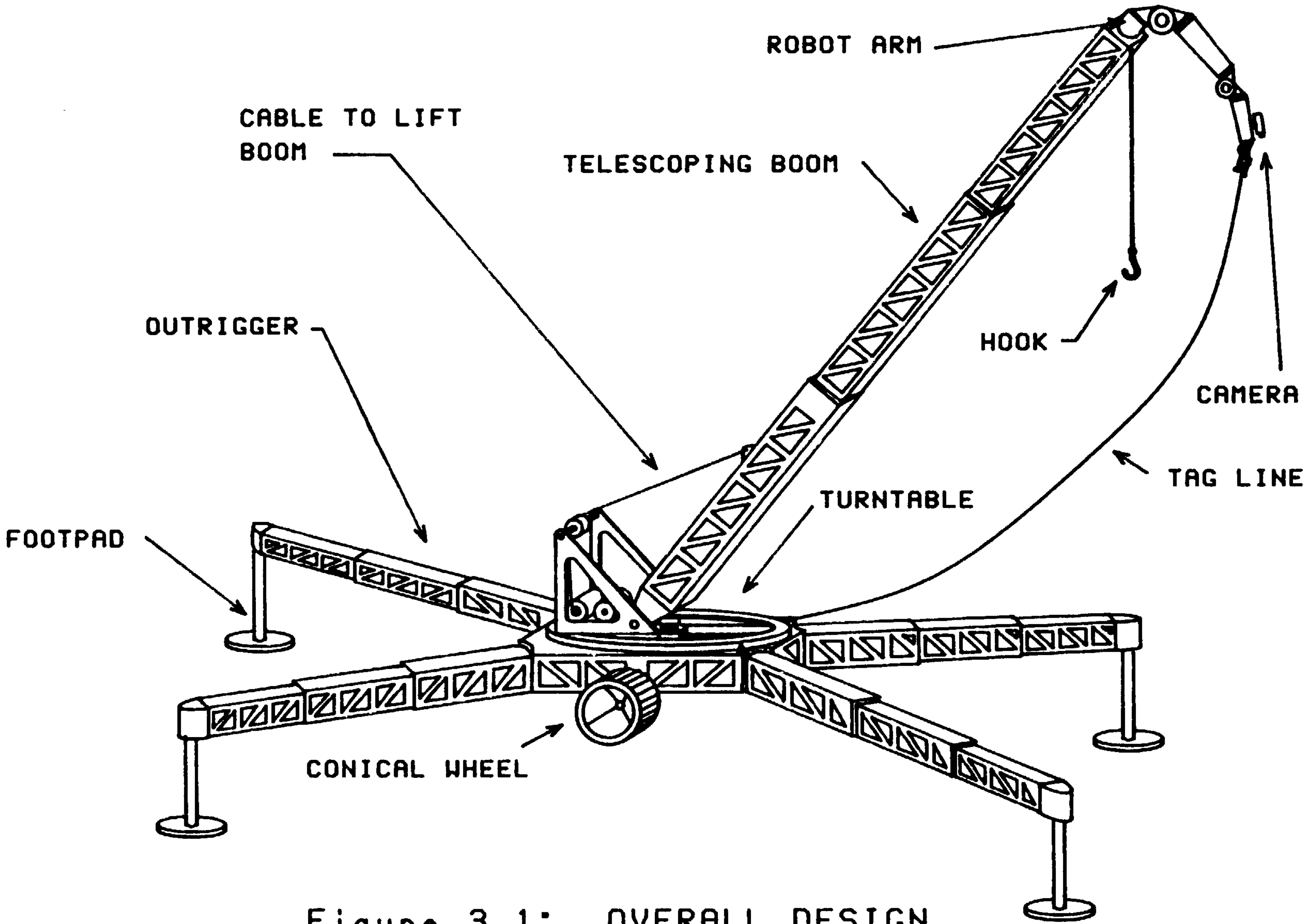


Figure 3.1: OVERALL DESIGN

turning or swaying), tag lines extending from the chassis will be connected to the cargo prior to lifting.

For light lift operations that require dexterity, a seven degree of freedom robot arm is used (see Figure 3.2). The seven degree of freedom robot arm was chosen for two reasons. The first reason is due to its increased dexterity and ability to maneuver around obstacles. The second reason is that in the event of a joint failure, the robot arm would still have six degrees of freedom which are the minimal requirements for positioning an object in any orientation. The robot arm is connected to the end of the boom. One function of the robot arm is to assist in the placement of the hook and tag lines. A camera is located on the robot arm to give the operator a close view of the operation being performed.

The boom is connected to a turntable on the chassis (see Figure 3.3). The turntable is a circular wheel pinned to the chassis with rollers along the circumference that allow smooth rotation for yaw control of the boom. The turntable is driven by a gear and motor located under the turntable. Pitch control of the boom is provided by a cable and winch. The cable is connected to the first section of the telescoping boom. To keep the center of gravity low, the winch is located on the turntable.

The chassis is a rectangular truss structure that connects all of the components into a single system. Within the chassis is a system that extends and retracts the outriggers. A connection

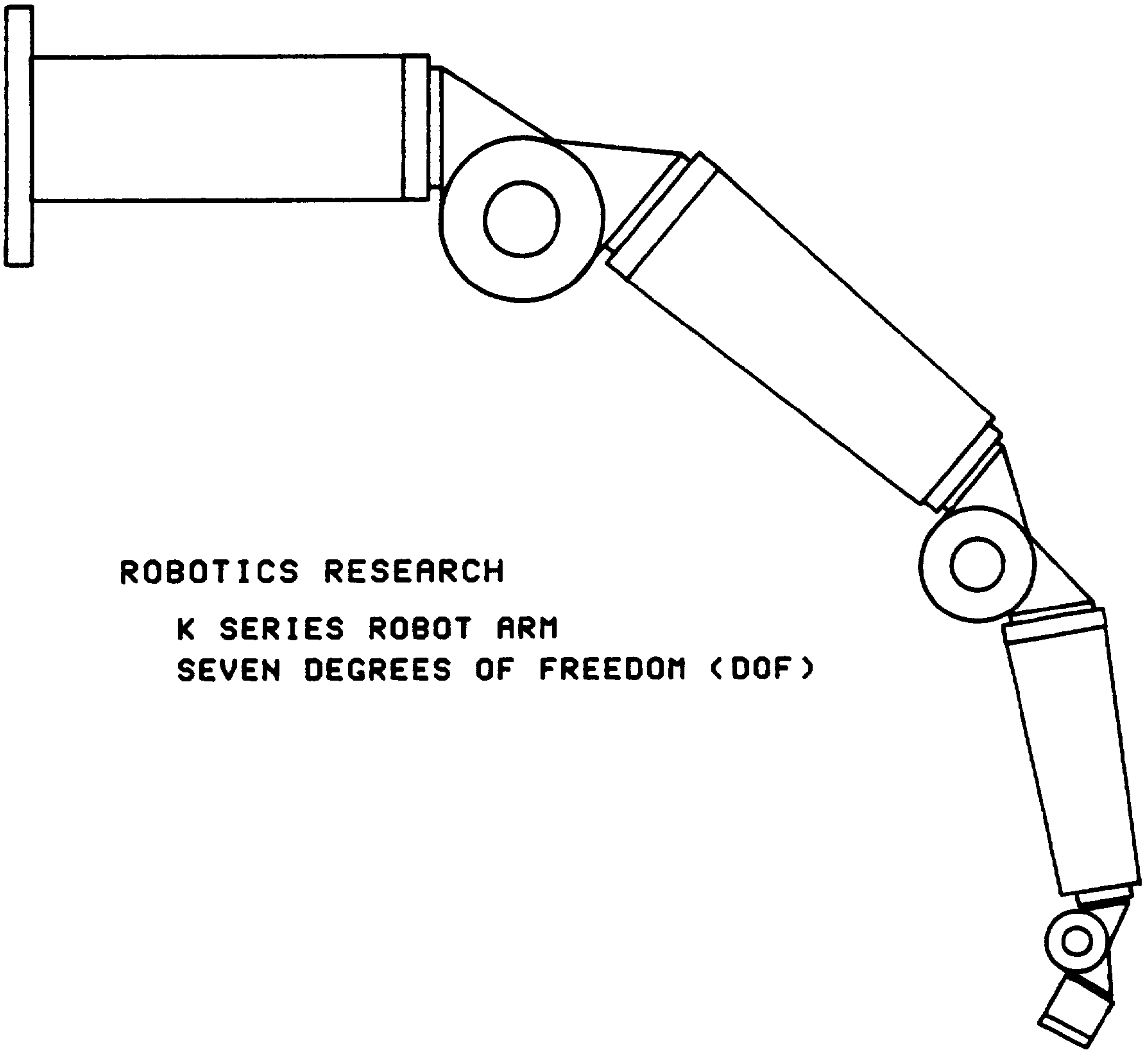
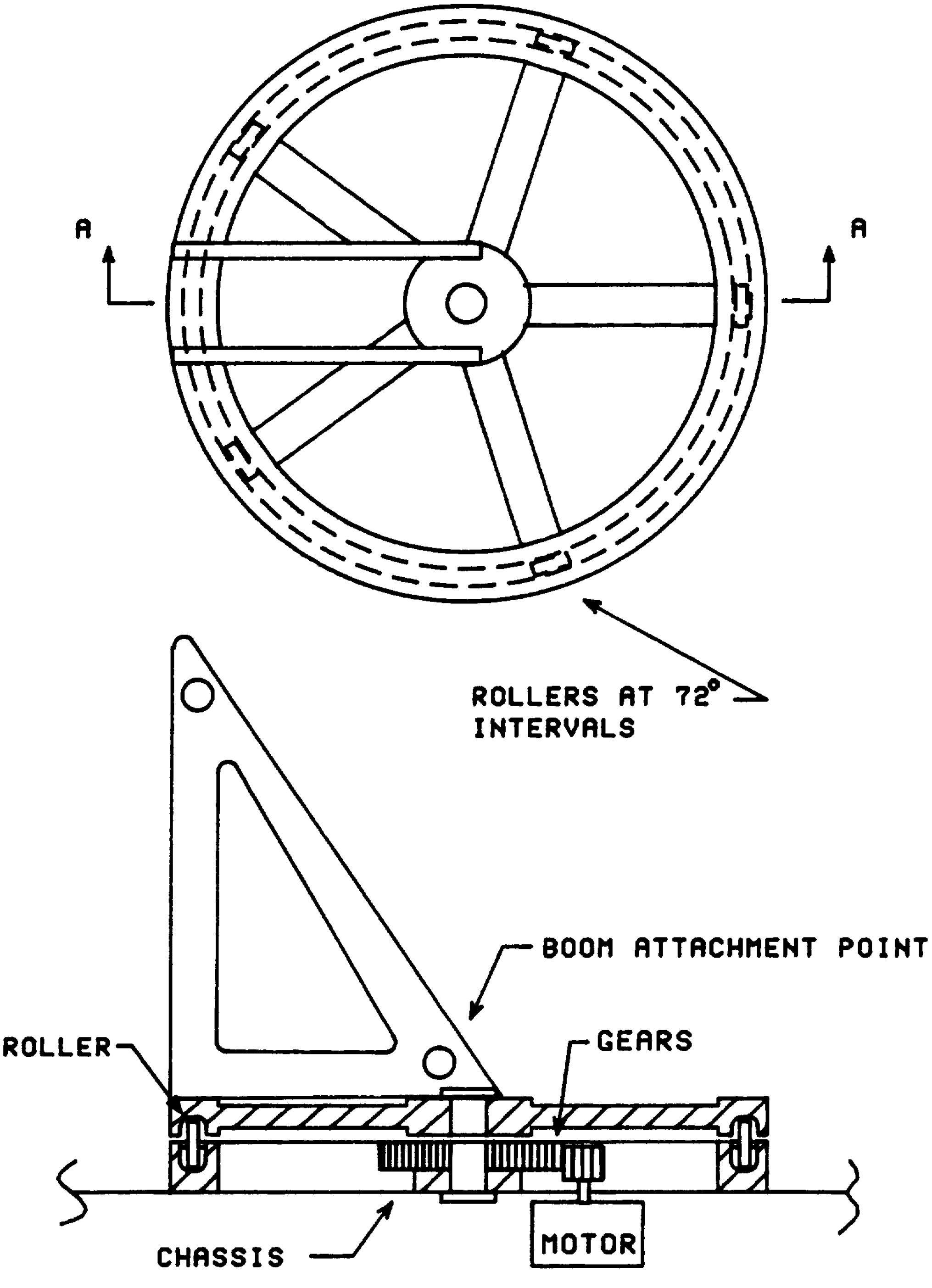


Figure 3.2: SEVEN DOF ROBOT ARM



SECTION AA

Figure 3.3: TURNTABLE

mechanism is included on the chassis for towing. Also located on the chassis are two small motors that control retraction of the tag lines.

3.2 COMPONENTS OF THE LIFTER

As a result of the decision matrices performed, the following components have been selected to be incorporated into the final design:

Table 1. Final Chosen Components

COMPONENTS	CHOSEN DESIGNS
Boom	Telescoping
Robot Lifting Mechanism	Three Jaw Gripper
Cable Lifting Mechanism	Hook
Stabilizers	Outriggers
Transport Media	Conical Shaped Wheels
Energy Conversion Mechanism	Motor/Generator

3.2.1 Telescoping Boom

The telescoping boom consists of three rectangular truss sections nested within each other (see Figure 3.4). Telescoping between the sections is provided by rollers that are located along

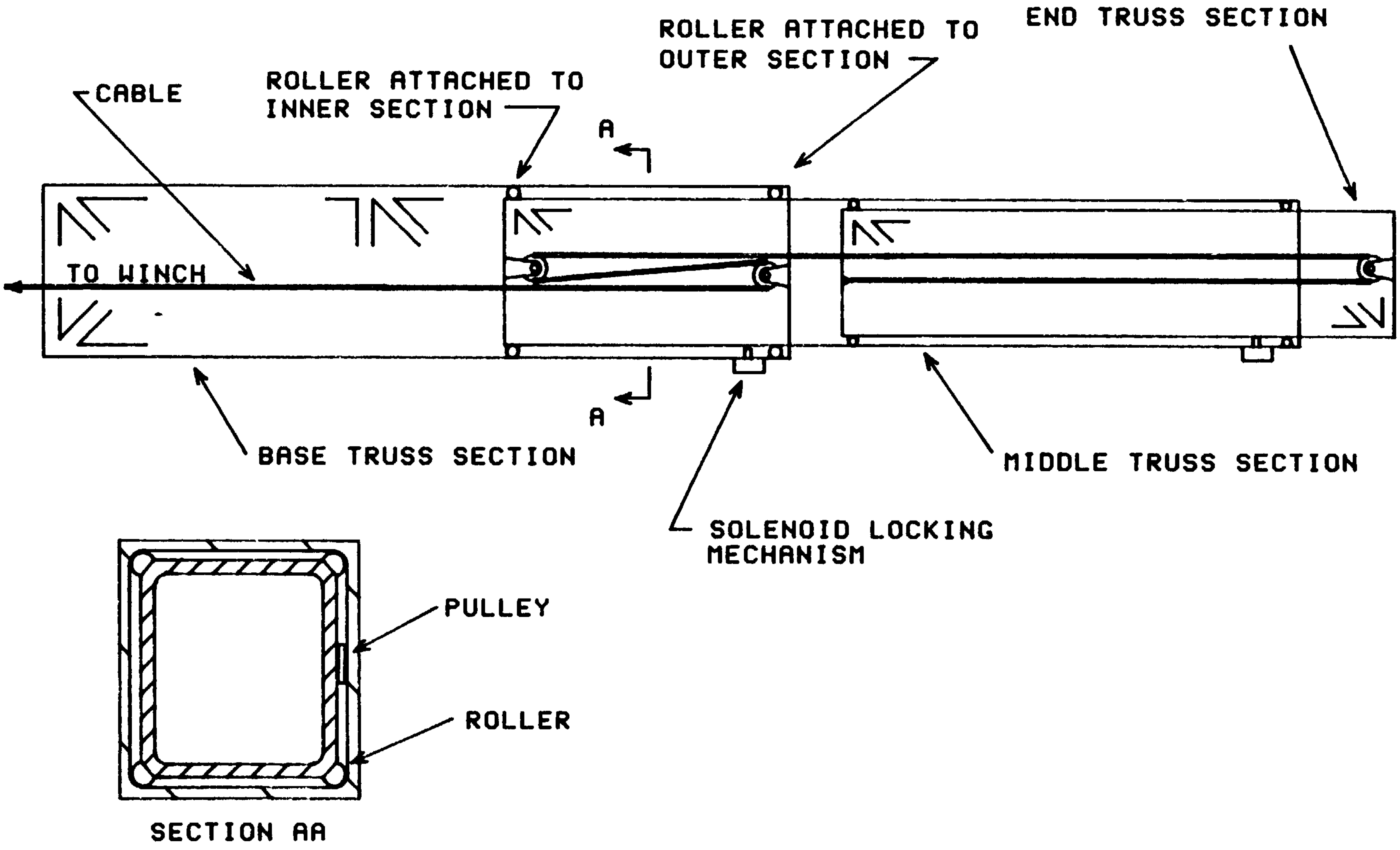


Figure 3.4: BOOM AND OUTRIGGER TELESCOPING SECTIONS

the corner members. Extension of the sections is provided by a cable and pulley system driven by a winch located within the chassis. A locking mechanism is located on each section so that the extension of each section can be controlled and the sections will be held securely during lifting operations. Retraction of the boom will be accomplished by the retrieval of the main lifting cable. When the hook is drawn to the end of the boom, it will hit a stop and cause the sections to be pulled into the retracted position. Design and analysis of the boom is found in Appendix C.

3.2.2 Three Jaw Gripper

A simplified three jaw gripper was chosen as the end effector for the robot arm for light dextrous lifting (see Figure 3.5). Contrary to the gripper proposed in Section 2.2.2.1.2, the jaws are not individually rotatable. The jaws are inserted into a receptacle and expand radially outward into slots in the receptacle wall providing a secure connection. The jaw positions are controlled by a motor and threaded disk system similar to a lathe chuck. The jaws are also capable of grasping other objects without receptacles such as tubular shapes or objects with a protrusion.

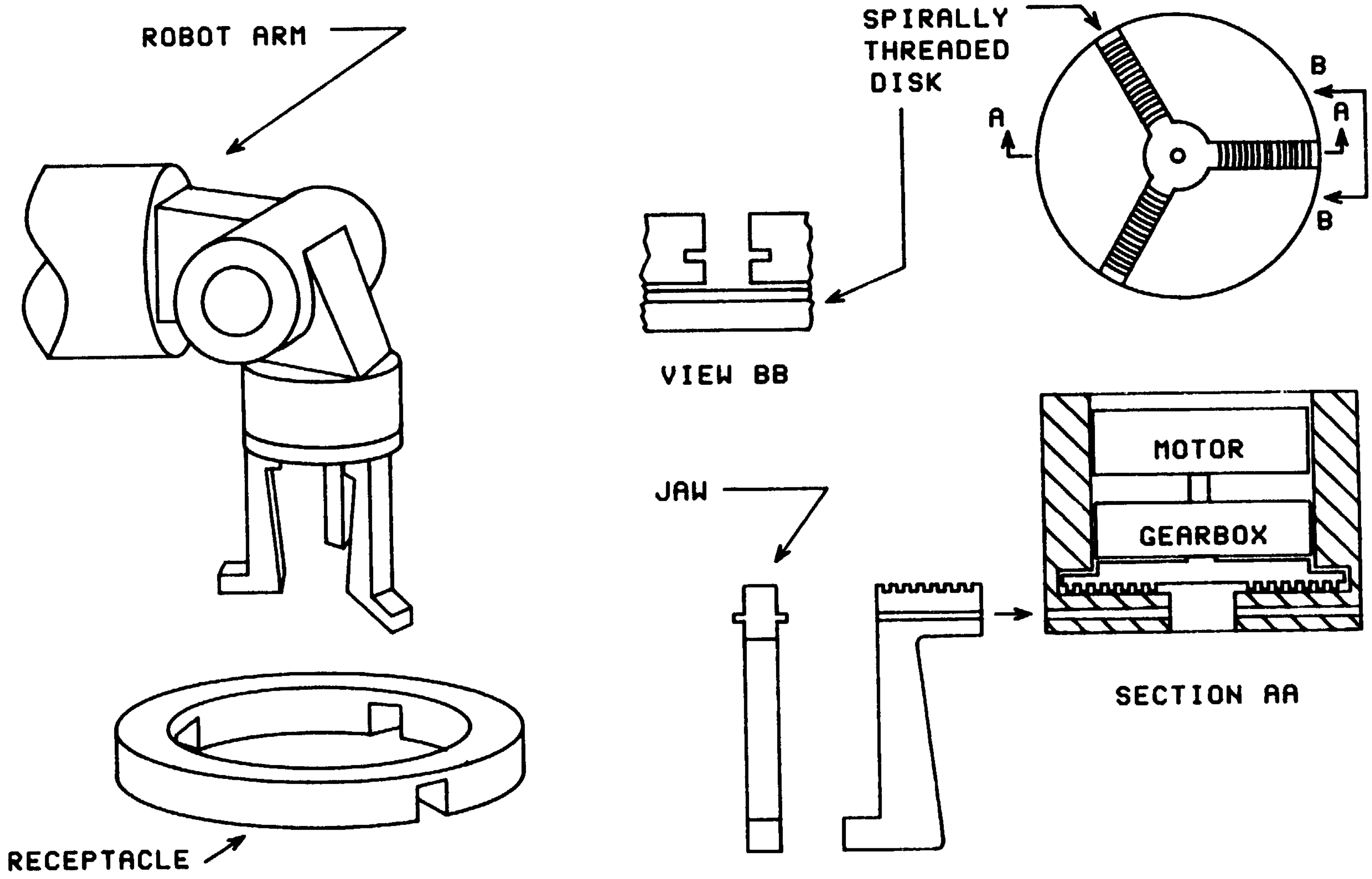


Figure 3.5: THREE JAW GRIPPER

3.2.3 Hook

A hook was chosen as the end effector for the cable for heavy lift operations (see Figure 3.6). The hook consists of a laminated plate construction. This construction increases the reliability of the hook because a crack in one plate will not propagate through to the next plate. The hook requires a receptacle on the object to be lifted.

3.2.4 Outriggers

Four telescoping outriggers are used as the stabilizing mechanism for the lunar lifter. The lifter is stabilized by extending the outriggers and foot pads causing the chassis to lift off of the lunar surface.

Each outrigger consists of three rectangular truss sections nested within each other located at each corner of the chassis. The outriggers extend at 135 degree angles from the chassis walls. Extension and retraction of the outriggers is provided by a pulley and cable system that operates in the same way as the boom's (see Figure 3.4). This pulley and cable system is located within the chassis. A separate motor for each outrigger will power the pulley and cable system. In case of motor failure, the outriggers may be operated manually by a hand crank.

Telescoping between the chassis and outriggers is provided by rollers that are located on guides within the chassis. Solenoid

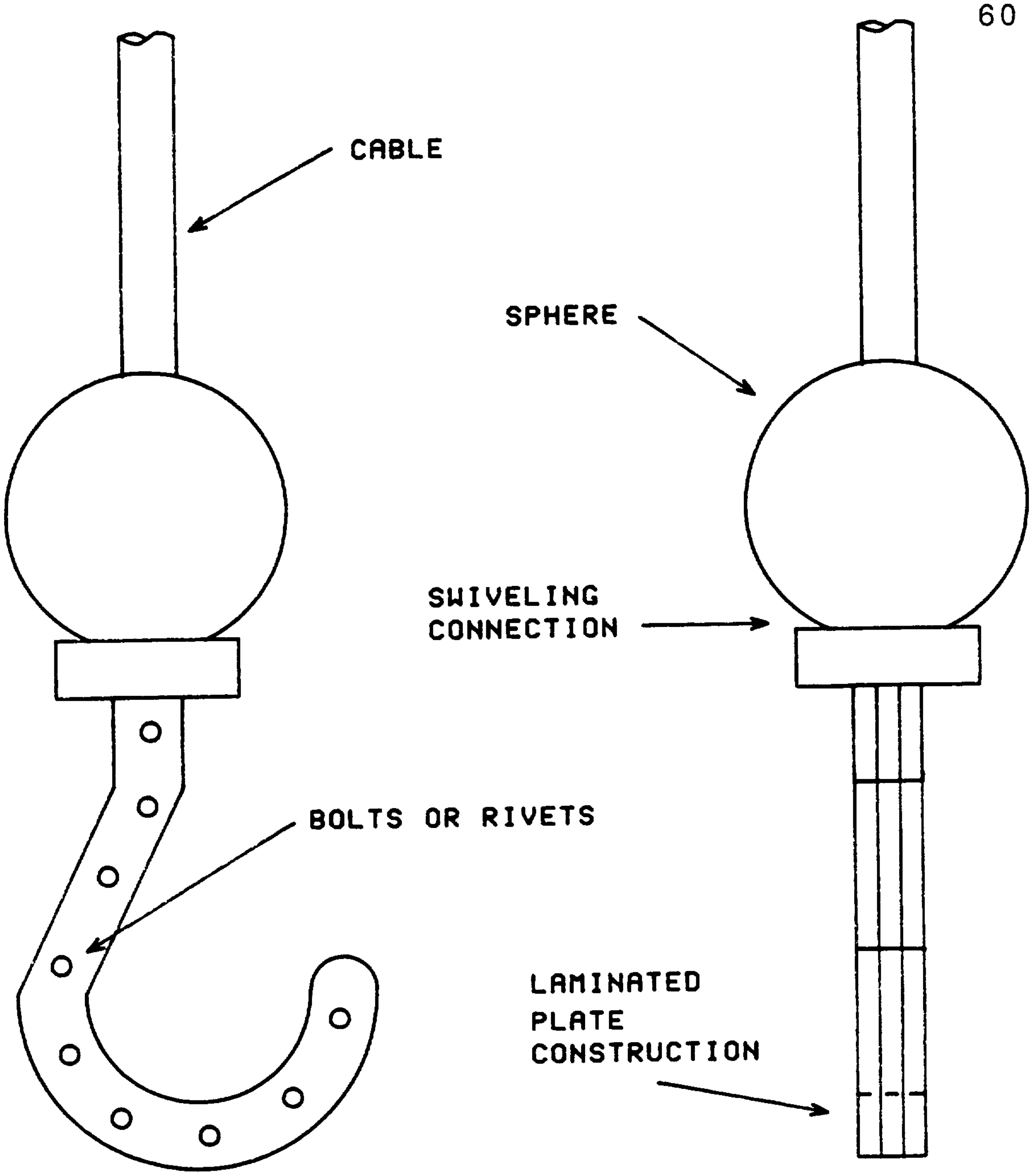


Figure 3.6: HOOK DETAIL

operated locking mechanisms are located on the guides and are used to lock the outriggers at desired locations.

Attached to the ends of the outriggers are foot pads (see Figure 3.7). The foot pads extend and retract vertically via a motor and worm gear system. An sensor will provide feedback to the operator to check that the chassis is level before the lifting operation begins. Analysis of the outriggers is found in Appendix D.

3.2.5 Conical Wheels

Conical shaped wheels were selected to permit the lifter to be towed on the lunar surface (see Figure 3.8). The wheels are a non-inflatable design with hollow rims and have a suitable tread covering the surfaces that will contact the ground. Two wheels are connected to the chassis via an axle and spring damper suspension system. The wheels are covered by fenders attached to the chassis to protect the lifter from regolith.

3.2.6 Motor/Generator

The motors described in this section will also act as generators to convert the potential energy of the raised payload to electrical energy that can be stored in the energy supply vehicle. Two motor/generators are connected to the chassis next to the base of the boom. One of these motors powers the cable and hook system that lifts the cargo. This motor/generator has an output of six

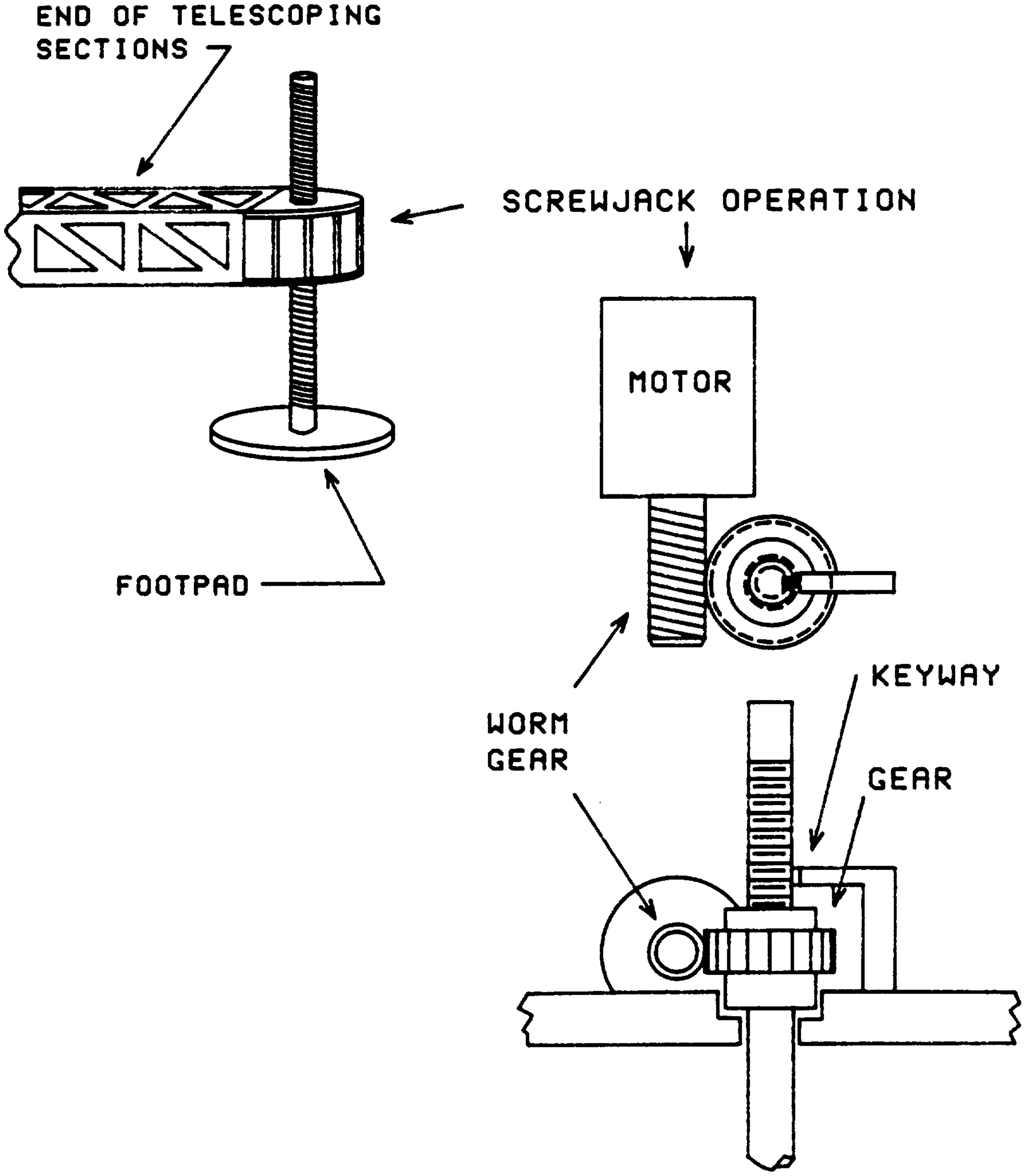


Figure 3.7: OUTRIGGER FOOTPAD DETAIL

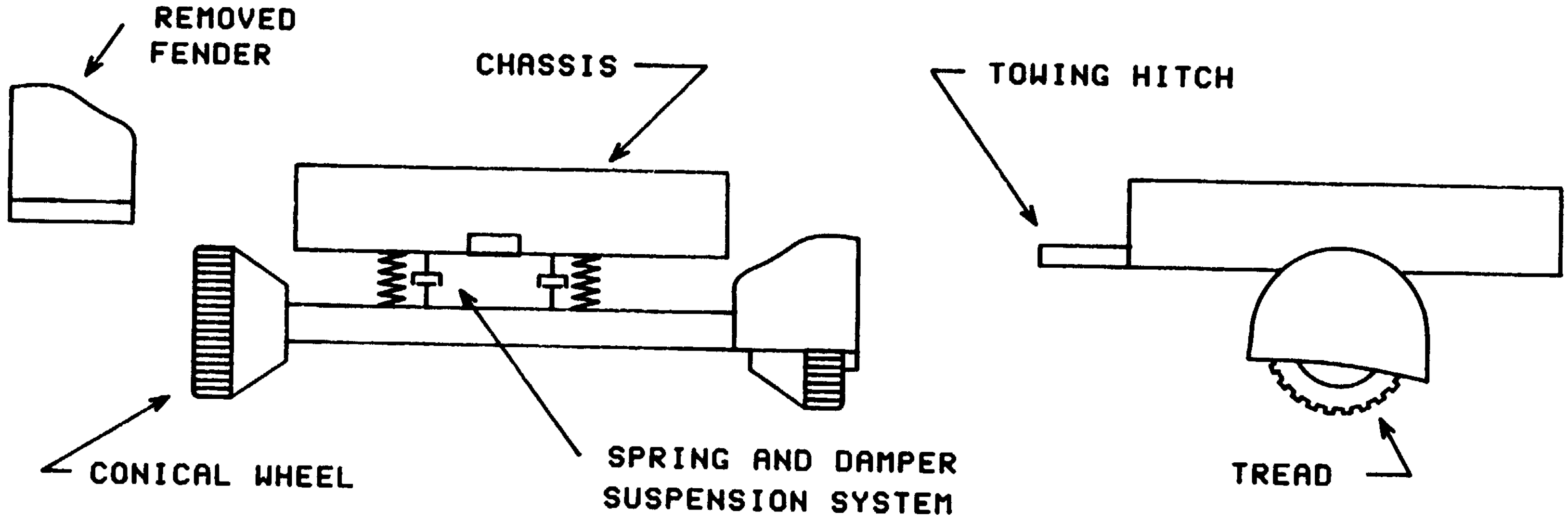


Figure 3.8: WHEELS AND SUSPENSION

horsepower and is capable of lifting cargo at a rate of one meter per second. The other motor/generator powers the boom. It has an output of 5 horsepower and is capable of lifting the boom at an average rate of one half a degree per second.

3.3 OTHER DESIGN CONSIDERATIONS

3.3.1 Protection System

The lifter is protected from the harsh lunar environment (e.g. thermal effects and micrometeorite bombardment) by a protection system (see Figure 3.9). This protection system is intended for short term exposures. For long term storage of the lunar lifter, a protective shelter is assumed to be available. A possible material for the protection system is multilayered insulation covered with layers of aluminized mylar. This protective material was chosen by the NASA team working on the design of a micrometeorite and thermal protection system. The protection system covering the boom, outriggers, and boom lifting cable is of an accordion design to allow for boom extension and retraction and is capable of being opened at the seam to allow for maintenance of the boom. The chassis, wheels, and outriggers are also protected by nearly the same protection system as the boom. The only major difference is that this protection system lacks the accordion design.

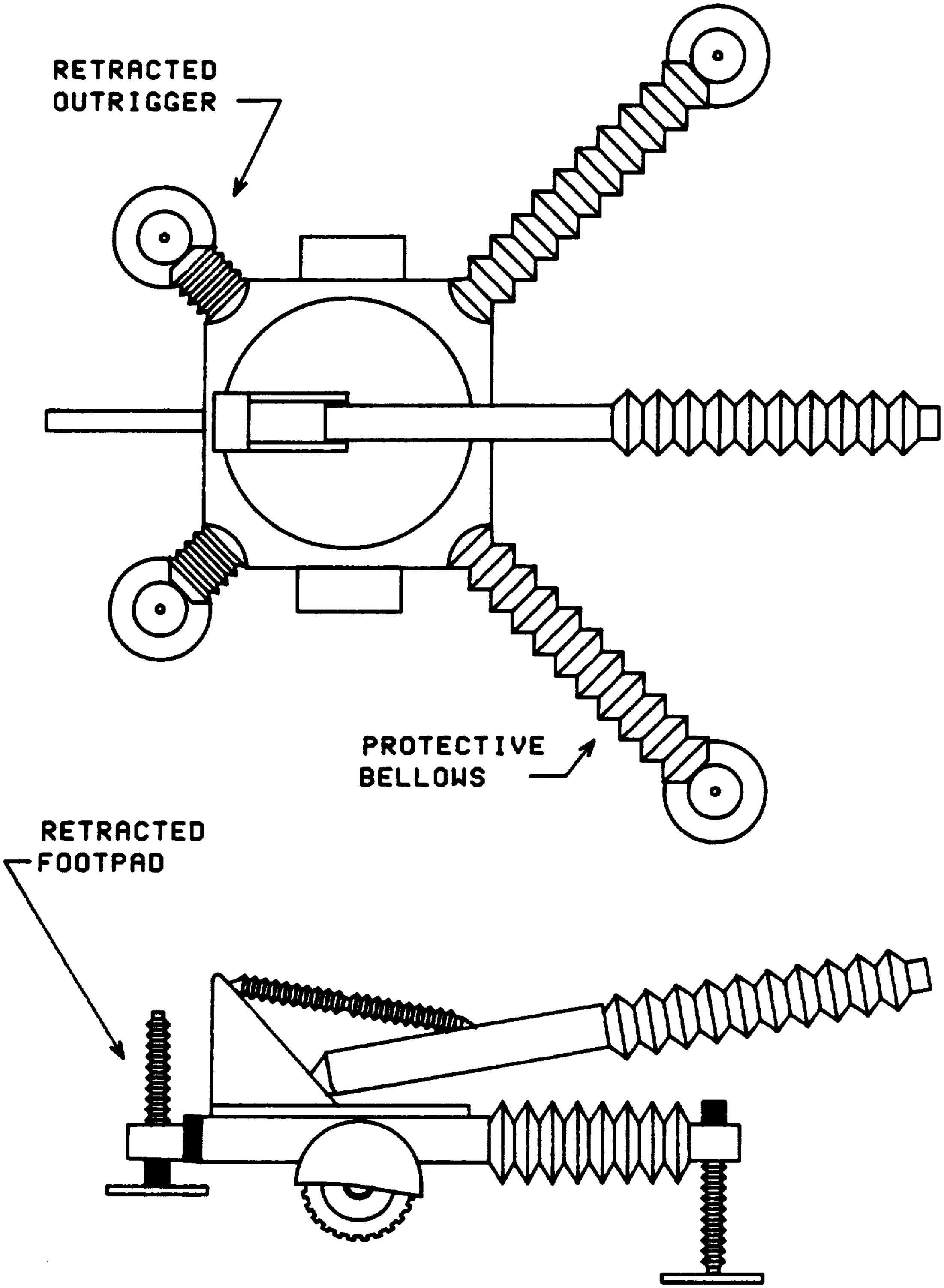


Figure 3.9: PROTECTION SYSTEM

3.3.2 Teleoperation System

In compliance with the design criteria, the lifter is controlled by teleoperations by a person either in a pressurized vehicle, in a extravehicular activity (EVA) suit, or at the lunar base. All teleoperations are performed via a control pad and radio network (see Figure 3.10). The control pad is a device separate from the lifter that contains joysticks. By movement of the joysticks, a crew member is able to control the operations of the lunar lifter. Separate joysticks control each component of the lifter. The radio network transmits the commands induced by the joysticks to a radio receiving network located within the lifter. The radio receiving network transmits the commands to the separate lifter components.

3.3.3 Dismount from Lander

The lunar lifter will be one of the first pieces of equipment sent to the moon. Without a lunar lifter already present on the lunar surface, the lifter must be capable of dismounting itself from the lunar lander. The lifter will dismount on a ramp incorporated onto the lander (see Figure 3.11). The robot arm is used in conjunction with the tag lines to lower the lifter down the ramp to the lunar surface.

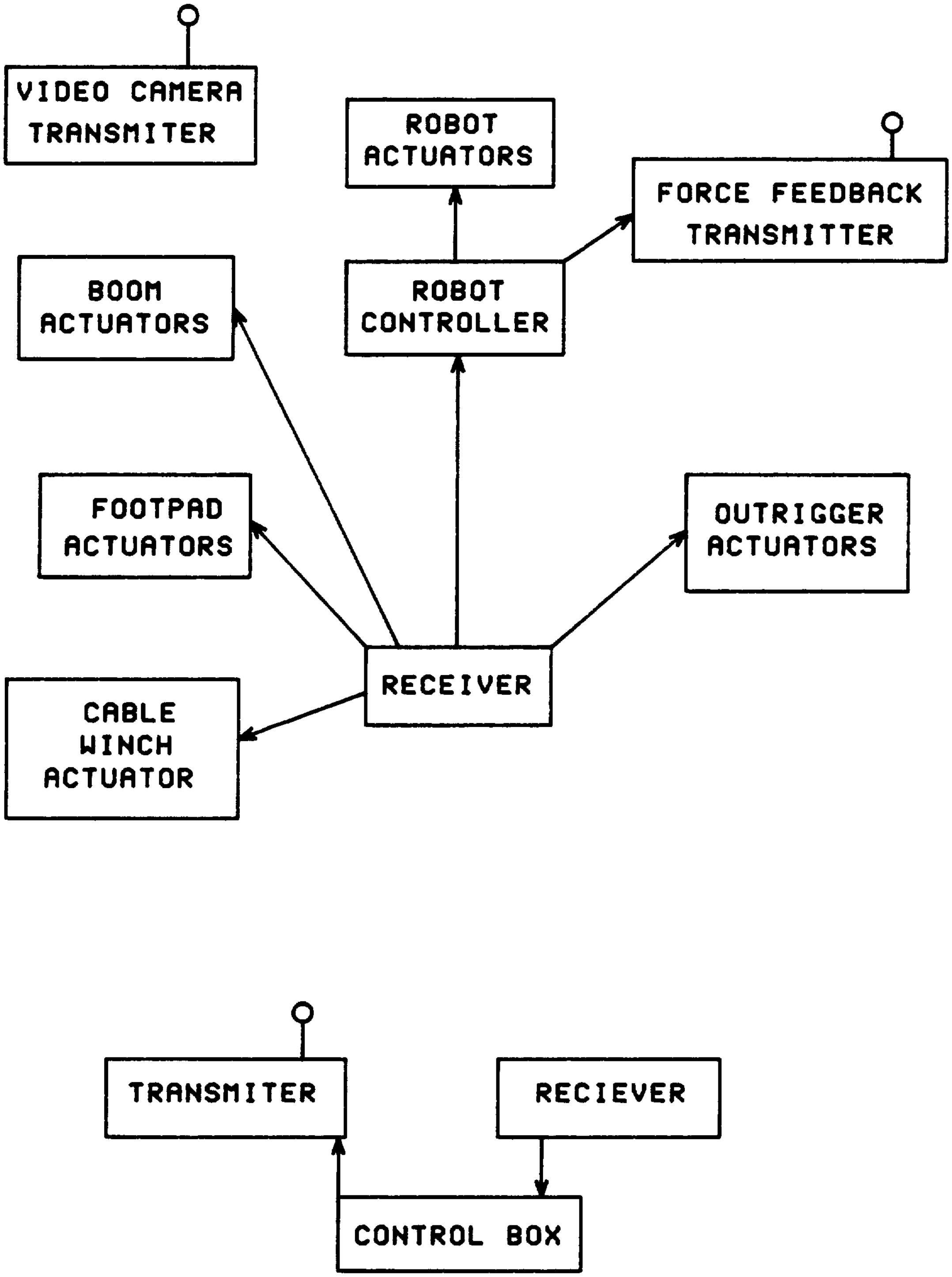


Figure 3.10: TELEOPERATIONS SCHEMATIC

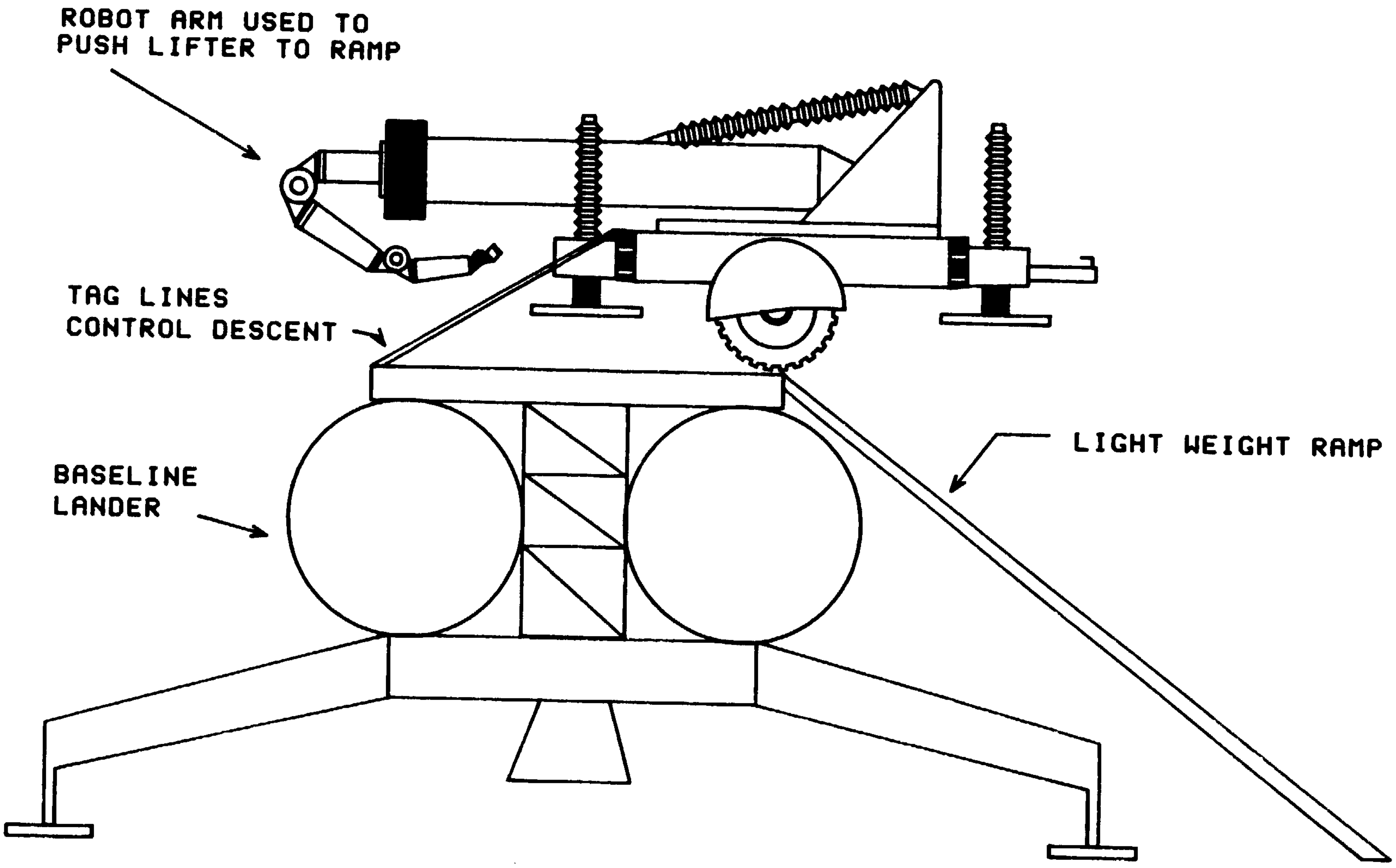


Figure 3.11: DISMOUNT FROM LANDER

3.4 SUMMARY OF DESIGN SOLUTION

Resulting from the decision matrices, the team selected an overall design as well as its major components. The overall design is a variable angle crane and the major components are the telescoping boom, the robotic arm with three jaw gripper, the cable with hook, the stabilizing outriggers, the conical wheels, and the motor/generator. The specifications for the lunar lifter and its components are in Appendix E.

CONCLUSION AND RECOMMENDATIONS

USRA and NASA are sponsoring the development of specialized equipment that will assist in the establishment of a manned lunar base. Our design team was asked to design a versatile lifting machine for lunar base operations. The team developed several alternate designs for the overall configuration of the lifting machine and for its major components.

The final chosen design is a variable angle crane with a compactable, telescoping boom. This final design meets the stated design requirements and criteria as explained below.

The crane is capable of lifting heavy loads by a cable and hook suspended from the end of the boom. The crane is also capable of light, dextrous lifts by a robot arm with a three jaw gripper. The robot arm has a camera to give visual feedback to the operator. Two conical shaped wheels attached to the chassis allow the crane to be towed on the lunar surface by a separate vehicle. Power for the lifter is supplied by a separate energy source.

Four retractable outriggers extend from the chassis to stabilize the crane during lifting operations. The outriggers, as well as the boom and chassis, are truss structures to minimize weight and to increase accessibility of internal components for maintenance or repair. Motor/generators are used to minimize power consumption. The lifter is teleoperated by one person using joysticks and a video monitor.

The design team has developed an overall design for the lunar lifter and its components. The structural sizes determined by the design team are approximate. Further analysis is needed to determine the optimum design dimensions of the lifter and its components.

The design team recommends that following steps for further design of the lifter and its components:

1. detailed stress analysis,
2. materials selection process,
3. design or selection of suitable teleoperations hardware,
4. design of a protection system,
5. design of a suspension system,
6. selection of more precise motor sizings,
7. gear train analysis,
8. design of the robot arm,
9. development of motion programming, and
10. development of a force feedback control system.

BIBLIOGRAPHY

1. "Lunar Base Environment Report", Eagle Engineering Incorporated; Kennedy Space Center, July 1989.

2. "Design of a Lunar Colony", University of Houston, MSC and Rice University; NASA/ASEE System Design Institute, 1972.

3. Gere, James M., Mechanics of Materials, second edition, PWS Engineering, Boston, Massachusetts, 1984, pp. 200-210, 350-390.

4. "Lunar Lander Conceptual Design", Eagle Engineering, Inc., Houston, Texas, NASA Contract NAS9-17878.

5. Land, Peter, "Lunar Base Design", Lunar Bases and Space Activities of the 21st Century, Mendell, W.W. (ed), Lunar and Planetary Institute, Houston, TX, 1985.

6. Eismann, P.H., Farrell J.D., Karlen, J.P., Thompson, J.M., Vold, H.I., "A 17 Degree of Freedom Anthropomorphic Manipulator", Robotics Research Corporation.

7. Bryant, C., Davis, G.W., Hooker, M., Lebigot, N., Wordtvedt, B., "The Lunar Split Mission: A Robot Constructed Lunar Base Scenario", NASA/USRA Advanced Space Design Program, August, 1988.

8. Freeman, R., Professor of Mechanical Engineering, The University of Texas at Austin, (512) 471-6546.

9. Gere and Timoshenko, Mechanics of Materials. second edition, Brooks/Cole Engineering Division, 1984.

10. Robotics Research Group, "The Development and Demonstration of a Class of Modular, Dextrous, Medium Capacity, Force Reflecting Manipulator Structures", The University of Texas at Austin, August, 1989.

11. Kogan, Josef, Crane Design Theory and Calculations of Reliability, John Wiley and Sons, New York, 1976.

APPENDICES

APPENDIX A

PHYSICAL CHARACTERISTICS OF THE EARTH AND MOON

PHYSICAL CHARACTERISTICS OF THE EARTH AND MOON

CHARACTERISTICS	MOON	EARTH
Diameter	3476 km	12756 km
Mass	7.4×10^{22} kg	6.0×10^{24} kg
Density	3.34 g/cm^3	5.11 g/cm^3
Gravity	1.62 m/s^2	9.81 m/s^2
Escape Velocity	2.38 km/s	11.18 km/s
Length of Day	27 days, 7 hrs, 27 min	23 hrs, 56 min
Mean Surface Temp.	108° C (day) -150°C (night)	22° C
Magnetic Field	negligible	0.5 gauss
Seismic Energy	2×10^6 joules/yr	5×10^7 joules/yr

APPENDIX B

DECISION MATRICES

DECISION MATRIX CRITERIA WEIGHTING FACTORS

CRITERIA CONSIDERED	TALLY MARKS	TOTAL	WEIGHTING FACTOR
RELIABILITY	********	8	8/45 = 0.1778
COMPACTNESS	*	1	4/45 = 0.0222
WEIGHT	*****	5	5/45 = 0.1111
SAFETY	*********	9	9/45 = 0.2000
SIMPLICITY OF OPERATION	***	3	3/45 = 0.0667
SIMPLICITY OF DESIGN	*	1	1/45 = 0.0222
ENERGY EFFICIENCY	****	4	4/45 = 0.0889
DURABILITY	*	1	1/45 = 0.0222
VERSATILITY	******	6	6/45 = 0.1333
REPAIRABILITY	*******	7	7/45 = 0.1556
		45 TOTAL	SUM = 1.000

OVERALL DESIGN DECISION MATRIX

		DESIGN PARAMETERS		
DESIGN CRITERIA ↓	WEIGHTING FACTORS ALTERNATES →	VARIABLE ANGLE	GANTRY	TOWER
RELIABILITY	.178	.707 6.0	.942 8.0	.707 6.0
COMPACTNESS	.022	.200 9.0	.067 3.0	.133 6.0
WEIGHT	.111	.667 6.0	.444 4.0	.556 5.0
SAFETY	.200	1.60 8.0	2.00 10.0	1.00 5.0
SIMPLICITY OF OPERATION	.022	.178 8.0	.222 10.0	.200 9.0
SIMPLICITY OF DESIGN	.067	.534 8.0	.667 10.0	.600 9.0
ENERGY EFFICIENCY	.022	.200 9.0	.222 10.0	.200 9.0
DURABILITY	.089	.711 8.0	.445 5.0	.711 8.0
VERSATILITY	.133	1.33 10.0	.400 3.0	.667 5.0
REPAIRABILITY	.156	.934 6.0	.467 3.0	.937 6.0
SUM OF PRODUCTS	1.000	7.062	5.876	4.773

BOOM DECISION MATRIX

		DESIGN PARAMETERS			
DESIGN CRITERIA ↓	WEIGHTING FACTORS ALTERNATES →	TRUSS	FOLDING	TELESCOPING	TONG
RELIABILITY	.118	1.602 9.0	1.424 8.0	1.424 8.0	1.424 8.0
COMPACTNESS	.022	.022 1.0	.089 4.0	.133 6.0	.178 8.0
WEIGHT	.111	.889 8.0	.778 7.0	.667 6.0	.556 5.0
SAFETY	.200	1.800 9.0	1.400 7.0	1.800 9.0	1.600 8.0
SIMPLICITY OF OPERATION	.022	.200 9.0	.155 7.0	.178 8.0	.133 6.0
SIMPLICITY OF DESIGN	.067	.600 9.0	.600 9.0	.534 8.0	.534 8.0
ENERGY EFFICIENCY	.022	.200 9.0	.178 8.0	.178 8.0	.178 8.0
DURABILITY	.089	.800 9.0	.711 8.0	.622 7.0	.711 8.0
VERSATILITY	.133	.133 1.0	.933 7.0	1.200 9.0	1.200 9.0
REPAIRABILITY	.156	1.089 7.0	.934 6.0	.622 4.0	.778 5.0
SUM OF PRODUCTS	1.000	7.336	7.202	7.357	7.290

ROBOT END EFFECTOR DECISION MATRIX

		DESIGN PARAMETERS		
DESIGN CRITERIA ↓	WEIGHTING FACTORS ALTERNATES →	PARALLEL	THREE JAW	BAYONET
RELIABILITY	.178	1.246 7.0	1.424 8.0	1.602 9.0
COMPACTNESS	.022	.178 8.0	.178 8.0	.178 8.0
WEIGHT	.111	.889 8.0	.889 8.0	.778 7.0
SAFETY	.200	.600 3.0	1.600 8.0	1.800 9.0
SIMPLICITY OF OPERATION	.022	.178 8.0	.155 7.0	.200 9.0
SIMPLICITY OF DESIGN	.067	.467 7.0	.400 6.0	.600 9.0
ENERGY EFFICIENCY	.022	.178 8.0	.178 8.0	.178 8.0
DURABILITY	.089	.622 7.0	.533 6.0	.800 9.0
VERSATILITY	.133	.400 3.0	1.200 9.0	.267 2.0
REPAIRABILITY	.156	1.089 7.0	1.089 7.0	.311 2.0
SUM OF PRODUCTS	1.000	5.846	7.646	6.713

CABLE END EFFECTOR DECISION MATRIX

		DESIGN PARAMETERS		
DESIGN CRITERIA ↓	ALTERNATES → WEIGHTING FACTORS	HOOK	BALL	ELECTROMAGNET
RELIABILITY	.178	1.78 10.0	1.45 8.0	.890 5.0
COMPACTNESS	.022	.178 8.0	.178 8.0	.089 4.0
WEIGHT	.111	1.00 9.0	.889 8.0	.333 3.0
SAFETY	.200	1.80 9.0	1.80 8.0	1.00 3.0
SIMPLICITY OF OPERATION	.022	.222 9.0	.200 9.0	.200 5.0
SIMPLICITY OF DESIGN	.067	.667 10.0	.534 9.0	.334 9.0
ENERGY EFFICIENCY	.022	.222 10.0	.222 8.0	.022 5.0
DURABILITY	.089	.800 10.0	.800 10.0	.622 1.0
VERSATILITY	.133	1.20 9.0	1.07 9.0	.933 7.0
REPAIRABILITY	.156	1.09 7.0	1.09 7.0	.311 2.0
SUM OF PRODUCTS	1.000	8.958	8.202	4.734

STABILIZER DECISION MATRIX

		DESIGN PARAMETERS				
DESIGN CRITERIA ↓	ALTERNATES → WEIGHTING FACTORS	COUNTERBALANCE	OUTRIGGERS	ANCHORS	HOOK TO LANDER	TROUGH
RELIABILITY	.178	1.42 8.0	1.42 8.0	.890 5.0	1.42 8.0	1.42 8.0
COMPACTNESS	.022	.089 4.0	.178 8.0	.178 8.0	.200 9.0	.155 7.0
WEIGHT	.111	.444 4.0	.889 8.0	1.00 9.0	.889 8.0	.889 8.0
SAFETY	.200	1.20 6.0	1.80 9.0	.400 2.0	1.60 8.0	1.40 7.0
SIMPLICITY OF OPERATION	.022	.089 4.0	.200 9.0	.155 7.0	.178 8.0	.133 6.0
SIMPLICITY OF DESIGN	.067	.534 8.0	.467 7.0	.467 7.0	.400 6.0	.600 9.0
ENERGY EFFICIENCY	.022	.178 8.0	.178 8.0	.178 8.0	.178 8.0	.111 5.0
DURABILITY	.089	.711 8.0	.711 8.0	.800 9.0	.711 8.0	.800 9.0
VERSATILITY	.133	1.07 8.0	1.20 9.0	.267 2.0	.800 6.0	.400 3.0
REPAIRABILITY	.156	.934 6.0	1.25 8.0	.778 5.0	1.25 8.0	1.25 8.0
SUM OF PRODUCTS	1.000	6.668	8.290	5.112	7.624	7.158

TRANSPORT MEDIA DECISION MATRIX

		DESIGN PARAMETERS				
DESIGN CRITERIA ↓	WEIGHTING FACTORS ALTERNATES →	CONVENTIONAL	CONED	TRACK	WALKING/TRAILER	TRISTAR
RELIABILITY	.178	1.42 8.0	1.42 8.0	.534 3.0	.890 5.0	1.25 5.0
COMPACTNESS	.022	.200 9.0	.200 9.0	.111 5.0	.133 6.0	.155 7.0
WEIGHT	.111	1.00 9.0	1.00 9.0	.222 2.0	.556 5.0	.778 7.0
SAFETY	.200	1.60 8.0	1.60 8.0	1.60 8.0	1.40 7.0	1.40 7.0
SIMPLICITY OF OPERATION	.022	.200 9.0	.200 9.0	.200 9.0	.089 4.0	.200 9.0
SIMPLICITY OF DESIGN	.067	.600 9.0	.600 9.0	.400 6.0	.467 7.0	.534 8.0
ENERGY EFFICIENCY	.022	.178 8.0	.178 8.0	.178 8.0	.155 7.0	.178 8.0
DURABILITY	.089	.711 8.0	.711 8.0	.533 6.0	.622 7.0	.711 8.0
VERSATILITY	.133	.933 7.0	.933 7.0	.933 7.0	1.20 9.0	1.07 8.0
REPAIRABILITY	.156	1.09 7.0	1.09 7.0	.778 5.0	.934 6.0	1.25 8.0
SUM OF PRODUCTS	1.000	7.935	7.935	5.489	6.445	7.513

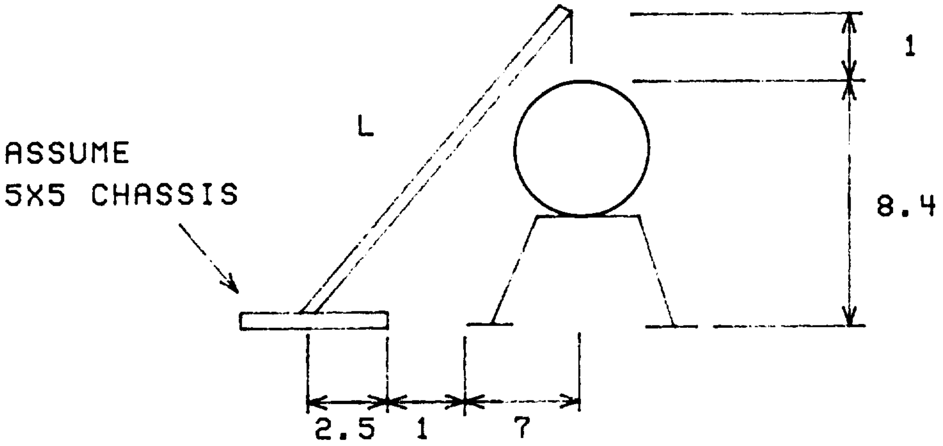
ENERGY CONVERSION DECISION MATRIX

	ALTERNATES →	DESIGN PARAMETERS			
DESIGN CRITERIA ↓	WEIGHTING FACTORS	MOT/GEN	FLYWHEEL	DUAL BOOM	SPRING
RELIABILITY	.178	1.60 9.0	1.25 7.0	1.42 8.0	1.42 8.0
COMPACTNESS	.022	.200 9.0	.155 7.0	.111 5.0	.178 8.0
WEIGHT	.111	.889 8.0	.667 6.0	.444 4.0	1.00 9.0
SAFETY	.200	1.80 9.0	.800 4.0	1.40 7.0	.800 4.0
SIMPLICITY OF OPERATION	.022	.178 8.0	.133 6.0	.155 7.0	.200 9.0
SIMPLICITY OF DESIGN	.067	.534 8.0	.400 6.0	.334 5.0	.600 9.0
ENERGY EFFICIENCY	.022	.178 8.0	.178 8.0	.178 8.0	.178 8.0
DURABILITY	.089	.711 8.0	.711 8.0	.622 7.0	.711 8.0
VERSATILITY	.133	1.07 8.0	.667 5.0	1.07 8.0	.667 5.0
REPAIRABILITY	.156	1.09 7.0	.778 5.0	.934 6.0	.622 4.0
SUM OF PRODUCTS	1.000	8.252	5.739	6.668	6.376

APPENDIX C

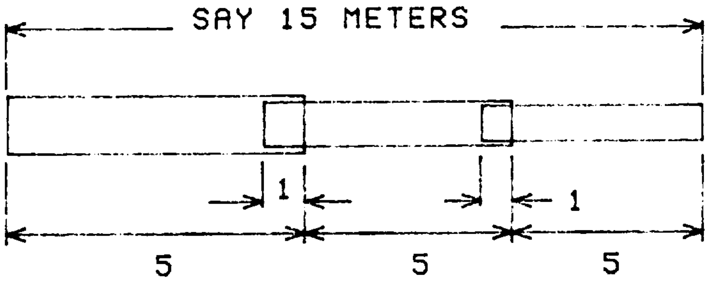
BOOM ANALYSIS

BOOM LENGTH

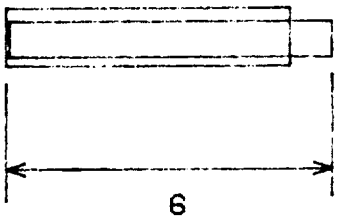


$$L = \sqrt{10.5^2 + 9.4^2}$$

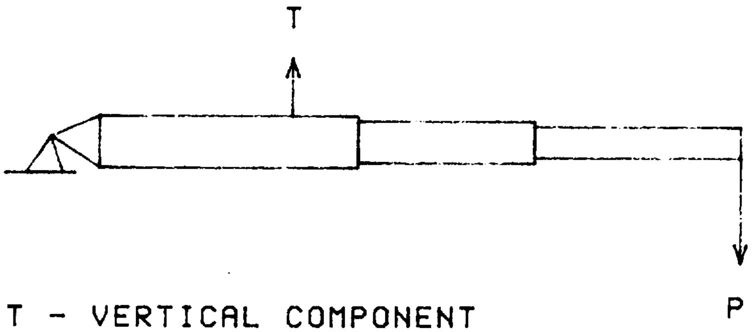
$$L = 14 \text{ m}$$



COMPACTED



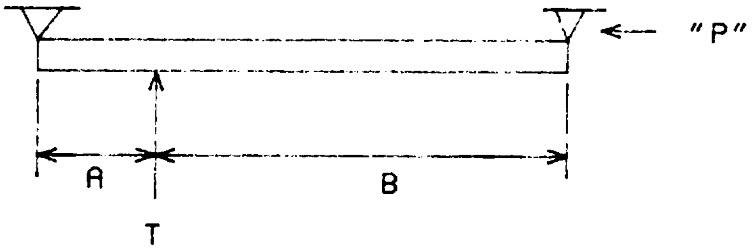
BOOM LOAD ANALYSIS



T - VERTICAL COMPONENT OF CABLE FORCE

P - WEIGHT OF LIFTED CARGO

TO SIMPLIFY CALCULATIONS THE BOOM WAS CONSIDERED TO BE ONE SECTION LOADED AS SHOWN



THE MAXIMUM DEFLECTION IN THE BOOM IS DETERMINED BY THE FOLLOWING FORMULA:

$$\delta = \frac{PB(L^2 - B^2)^{3/2}}{9\sqrt{3}\,LEI}$$

E - YOUNGS MODULUS
I - MOMENT OF INERTIA

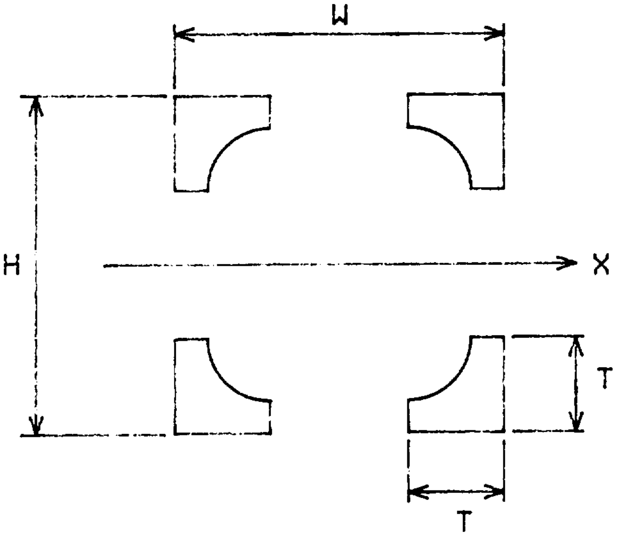
P CAN BE DEFINED IN TERMS OF T BY SUMMING THE MOMENTS ABOUT THE LEFT END.

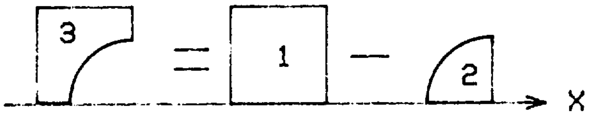
$P = TA/L$ L - OVERALL LENGTH

ESTIMATION OF MOMENT OF INERTIA FOR THE TRUSS STRUCTURE BOOM.

THE MOMENT OF INERTIA OF A CROSS SECTION OF THE BOOM WAS DETERMINED BY USING THE METHOD OF COMPOSITES AND THE PARALLEL AXIS THEOREM.

BOOM CROSS SECTION IGNORING ANGLED MEMBERS OF TRUSS (CONSERVATIVE)





$$I_{3x} = I_{1x} - I_{2x}$$

$$= \left(\frac{BH^3}{12} + AD^2\right) - \frac{1\pi R^4}{16}$$

$$= \frac{T^4}{3} - \frac{\pi R^4}{16}$$

SHAPE 3 IS THEN MOVED BY PARALLEL AXIS THEOREM

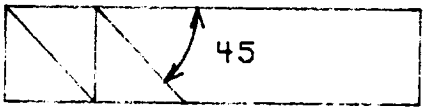
$$I_3 = \left(\frac{T^4}{3} - \frac{\pi R^4}{16}\right) + AD^2$$

$$= \left(\frac{T^4}{3} \quad \frac{\pi}{16}^{4}\right) + \left(T^2 - \frac{\pi R^2}{4}\right)\left(\frac{H}{2} - T\right)^2$$

$$I_{TOTAL} = 4\, I_3$$

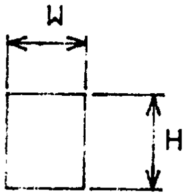
ESTIMATION OF MASS OF BOOM

ASSUME: ANGLED MEMBERS OF TRUSS ARE AT 45 DEGREES



ANGLED MEMBERS
= LX4/H

VERTICAL MEMBERS
= LX4/H



SECTION AA

FOR THE WEIGHT ESTIMATION THE BOOM WAS CONSIDERED WHOLE (NOT IN SECTIONS) WITH THE ABOVE LISTED NUMBER OF MEMBERS.

FOR LEGTHWISE MEMBERS:

$$VOLUME= LT^2-\pi R^2 L$$

FOR ANGLED AND VERTICAL MEMBERS:

$$VOLUME=LXWXT$$

THE MASS OF THE BOOM IS THEN THE TOTAL VOLUME OF MATERIAL TIMES ITS DENSITY

FOR THE ESTIMATION, ALUMINUM WAS CHOSEN.
A BASIC PROGRAM WAS WRITTEN TO DETERMINE THE MAXIMUM DEFLECTION AND THE MASS OF THE BOOM.

```
5 REM   PROGRAM TO CALCULATE DEFLECTION AND MASS OF BOOM
6 REM
10 CLS
20 CW=.06                               REM: WIDTH OF ANGLED AND VERTICAL
MEMBERS
30 P=25000*9.8/6                    REM: BOOM LOAD IN NEWTONS (HABITATION
MOD)
40 PI=3.145
50 E=7E+10                        REM: YOUNGS MODULUS FOR ALUMINUM
60 INPUT"WIDTH OF BOX SECTION";W
70 L=15                           REM: BOOM LENGTH
80 A=5                            REM: DISTANCE TO CABLE CONNECTION
90 B=L-A                           REM: DISTANCE FROM CABLE TO END
100 INPUT"HEIGHT OF BOX SECTION";H
110 INPUT"WIDTH OF ANGLE BEAM";T
120 INPUT"RADIUS OF ANGLED BEAM";R
130 TC=P*L/A                        REM: TENSION IN CABLE FOR GIVEN LOAD
140 I3=(T^4/3-PI*R^4/16)+(T^2-PI*R^2/4)*(H/2-T)^2
150 I=4*I3                        REM: TOTAL MOMENT OF INERTIA
160 DMAX=(TC*B*(L^2-B^2)^(3/2))/(9*3^.5*L*E*I)
170 PRINT"MAX DEFLECTION="; DMAX
180 SIGMA=P*B*(H/2)/I              REM: MAXIMUM STRESS
190 PRINT"SIGMA=";SIGMA
195 REM   MASS CALCULATIONS
196 REM
200 V1=104*H*(T-R)*CW          REM:VOLUME OF VERTICAL MEMBERS
210 NANGLE=(L/.75)*4          :REM NUMBER OF ANGLED MEMBERS
220 V2=92*H/COS(45)*(T-R)*CW  REM:VOLUME OF ANGLED MEMBERS
230 NVERT=(L/.75)*4           :REM NUMBER OF VERTICAL MEMBERS
240 VANGLE=NANGLE*H/.707*(T-R)*CW  :REM VOLUME OF ANGLED MEMBERS
ON SIDES
250 VANGLE2=NANGLE*W/.707*(T-R)*CW:REM VOL OF ANGLED MEMBERS ON
TOP AND BOT
260 VVERT=NVERT*H*(T-R)*CW          :REM VOLUME OF VERT MEMBERS ON
SIDES
270 PRINT"MASS=";MASS
```

USING THIS PROGRAM, ITERATION OF THE CROSS SECTION DIMENSIONS WERE PERFORMED UNTIL A DESIREABLE DEFLECTION AND MASS WAS OBTAINED.

THE FOLLOWING VALUES WERE CHOSEN:

H = 0.75 m
W = 0.5 m
T = 0.08 m
R = 0.075 m

THESE VALUES RESULTED IN THE FOLLOWING:

MAX DEFLECTION = 0.14 m
MAX STRESS = 2.13 X 10^8 Pa
MASS = 420 Kg

THE RESULTING DEFLECTION WAS ACCEPTED FOR TWO MAIN REASONS:

1. IT IS SMALL COMPARED TO THE LENGTH
2. THE ACTUAL DEFLECTION WOULD BE LESS SINCE THE ESTIMATED MOMENT OF INERTIA IS BELIEVED TO BE LOWER THAN THE ACTUAL

APPENDIX D

OUTRIGGER ANALYSIS

OUTRIGGER SIZING

IN ORDER TO PERFORM THE OUTRIGGER SIZING CALCULATIONS, THE OVERALL WEIGHT OF THE LIFTER HAD TO BE ESTIMATED.

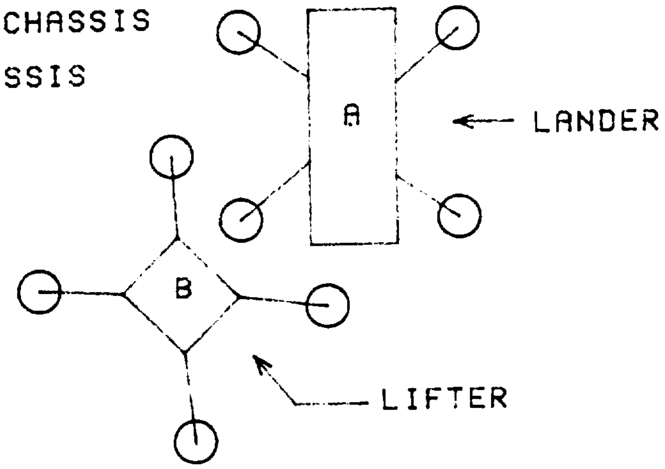
BELOW ARE APPROXIMATE VALUES OF MASS FOR SEVERAL COMPONENTS.

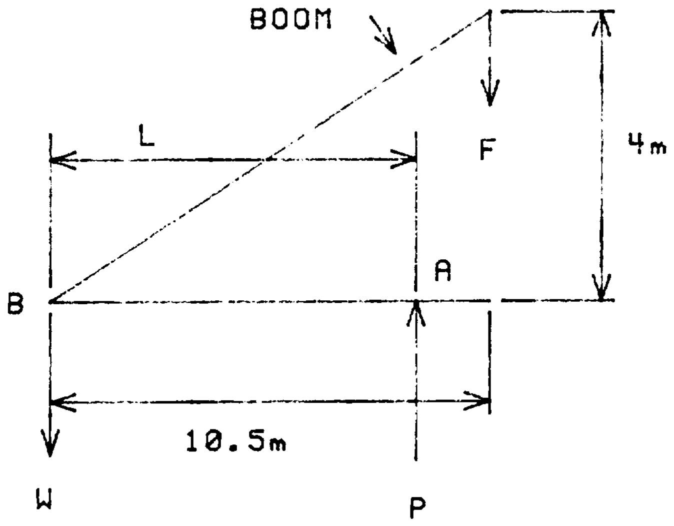
BOOM AND ITS RIGGING	600 Kg
CHASSIS	600 Kg
OUTRIGGERS & FOOTPADS	2400 Kg
ALL MOTORS	300 Kg
TURNTABLE	200 Kg
WHEELS	200 Kg
ROBOT ARM	100 Kg
TOTAL MASS	4400 Kg

ASSUMING THE CENTER OF GRAVITY TO BE IN THE GEOMETRIC CENTER OF THE LIFTER, THE ANALYSIS IS AS FOLLOWS:

TO MINIMIZE MOMENT LOADING, THE LIFTER IS POSITIONED AS CLOSE AS POSSIBLE TO LANDER.

THE DISTANCE FROM A TO B IS ABOUT 10.5 m GIVEN A 5m SQUARE CHASSIS AND 1m CLEARANCE BETWEEN LIFTER CHASSIS AND LANDER FOOT.





W - WEIGHT OF LIFTER
P - REACTION AT FOOTPAD
L - DISTANCE TO FOOTPAD
F - WEIGHT OF HABITATION MODULE

SUMMING THE MOMENTS ABOUT PT A. AND B.

L = 10.5F/(W+F)   P = 10.5F/L

ATUAL OUTRIGGER LENGTH BY GEOMETRY IS:

$$L/COS(45)-\underset{\text{1/2 CHASSIS DIAGONAL}}{3.5}$$

THE CROSS SECTIONAL SHAPE OF THE OUTRIGGERS WAS CHOSEN TO BE THE SAME AS THE BOOM.

INITIAL CALCULATIONS REVEALED THE OUTRIGGERS WOULD EXTEND AS FAR AS TEN METERS. THEREFORE, THEY WERE DESIGNED TO TELESCOPE AS THE BOOM.

```
10 REM ************* PROGRAM TO ANALYZE OUTRIGGERS ***********
20 CLS
30 F=25000*9.8/6
40 PI=3.145
50 E=7E+10                    :REM: YOUNG MODULUS FOR ALUMINUM
60 INPUT"MASS OF LIFTER ";MASS
70 WEIGHT=MASS*9.8/6
80 INPUT"WIDTH OF BOX SECTION";W
90 INPUT"HEIGHT OF BOX SECTION";H
100 INPUT"WIDTH OF ANGLE BEAM";T
110 INPUT"RADIUS OF ANGLED BEAM";R
120 L=10.5*F/(WEIGHT+F)          :REM DISTANCE FROM CENTER OF LIFTER TO
FOOTPAD
130 LO= L*1.414-2.5             :REM LENGTH OF OUTRIGGER
140 P=10.5*F/L                  :REM REACTION AT OUTRIGGER
150 I3=(T^4/3-PI*R^4/16)+(T^2-PI*R^2/4)*(H/2-T)^2
160 I=4*I3
170 DMAX=P*LO^3/(3*E*I)
180 PRINT"LENGTH OF OUTRIGGER =";LO
190 PRINT"MAX DEFLECTION="; DMAX
200 SIGMA=P*LO*(H/2)/I          :REM MAX STRESS IN BEAM
210 PRINT"SIGMA=";SIGMA
220 REM       WEIGHT ESTIMATE
230 NANGLE=(LO/.75)*4           :REM NUMBER OF ANGLED MEMBERS
240 NVERT=(LO/.75)*4            :REM NUMBER OF VERTICAL MEMBERS
250 VANGLE=NANGLE* H/.707*(T-R)*CW:REM VOLUME OF ANGLED MEMBERS
ON SIDES
260 VANGLE2=NANGLE*W/.707*(T-R)*CW:REM VOLUME OF ANGLED MEMBERS
ON TOP & BOTTOM
270 VVERT=NVERT*H*(T-R)*CW          :REM VOLUME OF VERTICAL MEMBERS
ON SIDES
280 VVERT2=NVERT*W*(T-R)*CW         :REM VOLUME OF VERTICAL MEMBERS
ON TOP & BOT
290 LV=4*(LO*T^2-PI*R^2*LO/4)      :REM VOLUME OF LENGTHWISE MEMBERS
300 VOL=VANGLE+VANGLE2+VVERT+VVERT2+LV:REM TOTAL VOLUME
310 MASS=VOL*2710
320 PRINT"MASS=";MASS
```

BECAUSE THE SIZE OF THE OUTRIGGERS AFFECTS THE OVERALL MASS OF THE LIFTER, THE CALCULATIONS FOR THE OUTRIGGER LENGTH WERE ITERATIVELY PERFORMED BY A BASIC PROGRAM. (LISTING ON NEXT PAGE)

AS WITH THE BOOM, THE OUTRIGGERS WERE NOT CONSIDERED AS SECTIONED.

THE OUTRIGGERS WERE MODELED AS A CATILEVER BEAM LOADED AT THE END.

THE RESULTING OUTRIGGER DIMENSIONS AND LOAD RESPONSE ARE AS FOLLOWS:

LENGTH	9 m
CROSS SECTION HEIGHT	0.75 m
CROSS SECTION WIDTH	0.5 m
FLANGE WIDTH (T)	0.1 m
MAXIMUM DEFLECTION	0.1 m

THE RESULTING DEFLECTION WAS ACCEPTED FOR THE SAME REASONS AS MENTIONED IN THE BOOM ANALYSIS IN APPENDIX D.

APPENDIX E

LIFTER SPECIFICATIONS

LIFTER SPECIFICATIONS

LIFTING CAPACITY	41,000 NEWTONS
MASS	4400 Kg
EXTENDED BOOM LENGTH	15 METERS
RETRACTED BOOM LENGTH	6 METERS
BOOM CROSS SECTION HEIGHT	0.75 METERS
BOOM CROSS SECTION WIDTH	0.5 METERS
CHASSIS LENGTH	5 METERS
CHASSIS WIDTH	5 METERS
CHASSIS DEPTH	0.85 METERS
EXTENDED OUTRIGGER LENGTH	10 METERS

OPERATION TERRAIN

DEPENDENT UPON WEIGHT AND ELEVATION OF CARGO

NO LOAD: LIFTER WILL SLIDE BEFORE TIPPING

FULLY EXTENDED BOOM

LIFTING 41,000 N OFF A LANDER: FLAT TERRAIN