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UNIVERSITY of MARYLAND

WALKING ROBOT:

A DESIGN PROJECT

for

UNDERGRADUATE STUDENTS

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ABSTRACT

The design and construction of the University of Maryland walking machine was completed during the 1989-1990 academic year. It was required that the machine be capable of completing a number of tasks including walking in a straight line, turn to change direction, and maneuver over an obstacle such as a set of stairs. The machine consists of two sets of four telescoping legs that alternately support the entire structure. A gear-box and crank-arm assembly is connected to the leg sets to provide the power required for the translational motion of the machine. By retracting all eight legs, the robot comes to rest on a central "Bigfoot" support. Turning is accomplished by rotating the machine about this support. The machine can be controlled by using either a user operated remote tether or the on-board computer for the execution of control commands. Absolute encoders are attached to all motors (leg, main drive, and Bigfoot) to provide the control computer with information regarding the status of the motors (up-down motion, forward or reverse rotation). Long and short range infrared sensors provide the computer with feedback information regarding the machine's relative position to a series of stripes and reflectors. These infrared sensors simulate how the robot might sense and gain information about the environment of Mars.

INTRODUCTION

The University of Maryland walking machine, Prototerp IV, was designed to be a Martian Planetary Rover. Among the design requirements were that the machine be able to support itself on a set of movable legs and not depend on rollers or wheels for its maneuverability. In addition, it was required that the machine be able to "walk" in a straight line and turn to change the direction of motion. These requirements allows the machine to follow any path as well as walk over an irregular surface. The University of Maryland Planetary Rover has the capability to obtain control feedback information regarding its immediate environment thus the machine has the ability to autonomously compute any desired and obtainable path.

The machine was designed and built by the senior Mechanical and Electrical Engineering students of ENME 408 over the two semester period of the 1989-1990 academic year. The motivation behind building Prototerp IV was to provide the students with practical experience so they may improve and refine their engineering skills by combining their talents as they work toward a common goal. In addition, It is the purpose of this project to provide an environment where the students learn about robotic systems and apply their creativity toward the construction of their walking machine.

Prototerp IV required two semesters to evolve. The machine was designed in the Fall of 1989, and construction was completed in the Spring of 1990. For both semesters, the students were divided into groups which were to address a particular aspect of the project.

In the first semester, the students proposed the initial design. There were four groups: (i) the chassis group, which was responsible for the chassis, drive-line, and the Bigfoot (ii) the leg group, which was responsible for the designing of the legs, (iii) the control group, which was responsible for the control hardware and software as well as the selection of all motors, and (iv) the sensors group, which was responsible for the selection of rotation, position and vision sensors.

In the second semester, the students were responsible for the actual construction of the walking machine. As in the first semester, the students were split into groups which were responsible for reviewing the design proposal of the previous semester and to suggest changes to improve the overall design of the machine. There were five groups involved during the second semester: (i) the chassis and Bigfoot group, (ii) the leg group, (iii) the drive-line group, (iv) the control hardware group, and (v) the control software group.

CHASSIS AND BIGFOOT

The chassis of Prototerp IV provides a rigid support to which all other components are attached. Primary considerations for the chassis design include durability, functionality, weight, balance, and safety (Appendix A).

Many materials were considered for the design of the chassis. Preliminary calculations indicated that the robot would weigh approximately 150 pounds. In order to prevent bending or flexing along the length or width of the chassis, it was determined that a 2" X 3" 1024 aluminum box channel would be best suited to fulfill the requirements (Shigley, 1989). The advantages of using aluminum include its high strength-to-weight ratio and the ease with which it can be machined to proper dimensions.

The overall shape of the body resembles a composite I-beam. To allow for the placement of the gearbox, crank assemblies, computer, and power-packs, the web of the composite I-beam is made of two sections of box channel separated by a distance of 11" . Mounted on the outer edge of each web section, near the center, are two leg assembly slider rod support brackets (Fig. 1) .Initially, these support brackets were to be a single piece of aluminum channel that bisected the web at the midpoint. This effectively cut the chassis into two pieces. It was then determined that this design would significantly reduce the rigidity of the robot which could result in buckling and failure. Upon review, it was decided that the best approach was for the web sections to be continuous, and have the slider rod support brackets and slider rods mounted directly to them.

It is important that the chassis remains properly aligned with 90 degree angles at each corner. Further, a crucial requirement for the leg assembly slider rods is that they should be parallel to one another to reduce drag during each stride (Fig. 2). To ensure that these conditions are met, connections between the sections of the chassis need to remain rigid. Therefore, a 3" X 3" aluminum angle was used as a brace at the inside of each section with four bolts at each leg of the brace. The junctions were tested with a design factor of safety of five to ensure that the supports would hold under the repetitive torsional and bending loads (Willems, et al., 1981).

There are many components which will ride on the chassis including the on-board computer, main-drive gearbox, Bigfoot motor, eight leg motors, photo-interrupter, encoders, infrared sensors and battery-packs. The gearbox is the heaviest component and is located as close as possible to the center of gravity. The remainder of the free floating parts are positioned carefully to distribute the weight as evenly as possible throughout the chassis and to locate the center of gravity of the robot close to the ground for stability. For safety in the design, all components are securely fastened to the chassis and all sharp edges are rounded off. The powerful crank arms and gearbox are covered with a plastic shell to prevent them from catching anything as they move the connecting rods.

The design of Prototerp IV incorporates the use of a centrally located "Bigfoot" on which the robot pivots when executing a turn. Due to this design feature, the body is required to be symmetric about the centroidal axes to ensure balance and reduce friction. This Bigfoot consists of a fixed shaft on which a geared collar rotates. The "legs" of the Bigfoot are two 1/2" square 2' long pieces of aluminum channel which are connected directly to the bottom of the collar. At the ends of each channel are threaded posts that act as "feet". They have rubber caps attached at the ends so provide a non slip contact with the floor as the robot is turning. The Bigfoot motor shaft is geared directly to the Bigfoot assembly by a collar. The Bigfoot is capable of turning the robot 90 degrees in five seconds.

DRIVE-LINE

It is the function of the drive-line to provide the forward locomotive force for Prototerp IV. Several different designs were considered throughout the evolution of the machine. The final design consists of a gearbox and crank-arm assembly that transmit force from a single motor to the leg groups (Appendix B).

The prime mover of the drive-line is the gearbox assembly. The driving force of the gearbox is provided by a 1/20 hp. electric motor. This motor operates on 12 volts DC, and has a built in 36.7 to 1 gear reduction transmission. Attached to the output shaft of the motor is a 3", 72 tooth spur gear which meshes in line with two identical spur gears. The second and third gears were each connected by a shaft and key to a chain sprocket (Fig. 3).

A length of chain was used to transmit the motive force from the gearbox to the 5.41" long crank-arms through the use of sprockets. Using this configuration, it was possible to create opposing rotation of the crank-arms. Connecting rod were then attached between the crank arms and each of the forward,innermost leg support brackets. This design translates the rotational motion of the crank-arm to linear motion of the legs (fig.4).

To achieve the goal of moving the eight legs in two groups of four, a series of connecting rods, pulleys and cables was used. The connecting rods were attached between forward and rear leg brackets in such a way that the inner and outer sets of legs move independently, but in tandem. Cable was then routed around pulleys so that the inner group of legs on one side of the robot was connected to the outer group of legs on the other side (Fig 5).

LEGS

Prototerp IV's leg assembly has been designed around the premise that the machine will always be resting on four of its eight legs while walking (Appendix C). This approach to the walking problem provides excellent stability during all phases of maneuvering. During a typical walk maneuver, the first set of the machine's four legs are supporting all of the weight while the second set of four legs is transitioning to the next position . Once this position is reached, the second set of legs support the machine while the first set then moves to the next position. Since all eight legs are coupled together, and are horizontally translated by one motor, the horizontal motion of the machine is continuous.

The transitioning set of legs remain above the supporting set of legs due to the vertical telescoping leg design. This vertical telescoping motion is adjusted by a single motor that is attached to the top of each leg. The vertical and horizontal drive mechanisms achieve the lift and translate motion that enable the machine to walk.

The following description contains the basic sequence that constitutes a step. The typical walk cycle has the machine initially supported by one set of legs. The other set is moving horizontally relative to the body at a level of about three inches above the floor. When the machine reaches the desired horizontal position, the transitioning legs are lowered and the supporting legs are then raised and begin to transition to the next desired horizontal position (Fig 6).

Vertical translations of the legs are made possible by a telescoping design that incorporates the lower, keyed part of the leg to be driven either into or out of the upper, slotted part of the leg. A motor fixed to the top of the leg rotates a ball screw through a worm gear assembly. The ball screw, supported by bearings, drives a ball nut vertically along the screw. This ball nut is fixed to the lower portion of the leg, the inner tubing, which is keyed to fit into the slotted upper portion of the leg. The key, a delrin strip fixed to the lower part of the leg, and slot, the linear bearing of the upper leg, allow for the ball nut to remain fixed with respect to the ball screw. Thus, the leg is driven in a telescoping fashion.

The figure showing the exploded diagram of the entire assembly illustrates the mechanisms that are involved in the above process (Fig. 7). At the top of the assembly, a Pitman motor, operating at 12 V, drives the worm. A an aluminum couple joins the motor shaft to the worm shaft. The other end of the worm shaft is supported by a bearing that is mounted on the inside of the aluminum gear box. The gear box is screwed to the top of the bearing housing. The worm drives a worm gear that is fixed to the ball screw and is supported by two bearings that are contained in the aluminum bearing housing. This bearing housing is screwed inside the top of the outer tubing. The smaller inner tubing of the lower leg holds a linear bearing which forms a slot in which the delrin key of the lower leg slides. This key/slot of the upper and lower parts of the leg prevents rotation with respect to the upper and lower parts of the leg as the ball screw rotates. This allows the ball screw attached to the lower leg to move vertically as the ball screw rotates. The ball screw is attached to the lower part of the leg via an aluminum couple. And finally at the bottom of the lower leg is the foot which holds the contact sensors.

CONTROL HARDWARE

The Prototerp IV walking robot control system is based on the 87C196KB 16-bit embedded micro-controller from Intel. The system is comprised entirely of high speed CMOS (Complementary Metal Oxide Semiconductor) integrated circuits (Appendix D). The advantage to using these circuits is that they require less current for operation and therefore conserve power. The control hardware utilizes a power source separate from that which supplies the motors. This prevents a possible voltage fluctuation from affecting the operation of the chips. The need for a separate power source is due to the fact that when a motor initially starts, it could cause a large power drain which in turn could cause the voltage to drop to an unacceptable level (below 3.7 volts).

The control system has the capability of obtaining information as to the robot's current configuration through the use of closed-loop feedback. This monitoring capability is achieved through a wide variety of sensors placed in several locations throughout the robot .The types of sensors used include encoders, short and long range infrared sensors, photo-interruptors, and switches (Fig. 8). Encoders are connected to each motor. They provide information pertaining to the configuration of specific components such as the height of each leg or the position of the crank-arms. Infrared sensors provide information as to the position of the robot relative to a specific object. This is achieved when the emitted infrared beam is reflected back to the sensor. Leg position is determined through the use of a photo-interruptor. A photo-interruptor directs a light beam toward a sensor and sends a signal to the computer any time the beam is crossed. On the robot, the photo-interruptors activated any time a leg crosses a certain position. This provides a means with which to count the number of strides taken. Finally, double position (momentary on-off) switches are located at the bottom of each leg and are used to sense when a leg makes contact with the floor.

The information from all of the sensors is gathered by the 87C196KB processor. This information is used to analyze the current status of the robot and its surroundings. Once the analysis has been completed the control system directs the machine to make any necessary adjustments.

It is the purpose of the control system to vary the robot's motors according to specific demands; to operate in either direction, at a certain speed, or to shut down. The voltage for the motor is controlled by a pulse width modulated (PWM) wave which is created by the control system. An illustration of a pulse width modulated wave form is shown below (Fig. 9).

The PWM hardware achieves the variable speed control of a motor by adjusting the time on, time off ratio of each period of the wave form. these adjustments are repeated thousands of times per second. As the motor is incapable of reacting to these fluctuations, it interprets the signal as a percentage of the maximum voltage where the percentage is proportional to the on time of the PWM wave form.

CONTROL SOFTWARE

It is the purpose of control software to regulate all motors of the robot (Appendix E). These motors include: (i) the main drive motor, (ii) the Bigfoot motor, and (iii) each of the eight leg motors.

An absolute encoder is mounted onto each motor to provide positional information about the motor. The resolution of each encoder varies from motor to motor (the resolution is 2400 counts per inch of movement of the telescoping legs, 1024 counts per revolution of the main drive motor, and 365 counts per revolution of the Bigfoot). This is an important consideration as far as control software is concerned. The different encoder resolutions imply separate yet interactive software routines for integrated operation of all motors.

Their are four separate software routines designed to control the motors and coordinate their operation to perform various tasks that a planetary rover might need such as walking, turning or climbing.

The first level routine is the most basic of the four. Its function is to control the operation of the motors. This is accomplished by varying the cycle time of the Pulse Width Modulators. The PWM can be varied from 0% (totally off) to 100% (full speed operation).

The second level routine is dedicated to the interpretation of the closed loop feedback information. This feedback information is provided through all of the sensors including the infrared sensors, the motor encoders, and the leg stride photo-interruptor. Information from these sensors will be used to determine motor regulation.

The third level routines are dedicated to the execution of the walk routines. This software incorporates all information gathered by the sensors (second level software) and coordinates the operation of the motors (first level software).

The fourth and final level of software is designed to operate the robot during autonomous operation. This routine has programmed into it a series of commands that shall allow the robot to walk through a figure eight or walk up stairs thus demonstrating autonomous roving possibilities.

As previously stated, the robot walks on two groups of four legs. At any one time, only four legs are in contact with the ground. As each leg is mechanically linked to the drive motor, the horizontal leg location is a function of the angular position of the crank-arms. The positional information of the crank arms, and thus the horizontal position of the leg assembly, is provided by the main drive motor encoder and the information regarding the vertical position of the foot is provided by the leg motor encoders. Therefore, the vertical and horizontal position of the base of the legs can be calculated at any time.

The path of the leg foot as it transitions from the non-supporting return stroke to the supporting walk stroke was designed to follow a form based on a second degree equation (Fig. 10). There are benefits to using a second order equation for the travel path of the leg feet. At some point all feet are simultaneously on the ground and by using an asymptotic approach trajectory for the foot as it finishes the return stroke, a smooth transition between stride changes is assured. Since the leg groups travel with different relative velocities most of the time, it becomes important to keep the time spent on the ground by all legs at a minimum. A second order decay fulfills two requirements: (i) the vertical foot positioning is at ground level for the transition, (ii) the vertical foot velocity is at a minimum when contact is made.

The control of the Bigfoot turning motor incorporates a slightly different approach to that of the legs. A proportional feedback system acts to determine the appropriate Bigfoot motor speed based on the actual and ideal robot position. By calculating the maximum angular acceleration and deceleration of the robot as it is turning, it is possible to calculate the time required to power the Bigfoot motor to achieve the desired rotational acceleration. Then, proportional feedback is used to calculate the time when the polarity of the Bigfoot motor is to be reversed so as to decelerate the robot and stop rotation at the desired angular position.

Upon testing the machine, a back-driving problem was encountered with the telescoping legs. Because the legs can move freely in the vertical direction when no driving voltage is applied, the leg motors tend to spin backwards under the weight of the robot and the machine falls to the ground. Software control had to backdrive the legs in order to keep the vertical motion steady during the walk routines. Located in the foot of each leg is a switch that closes when it comes in contact with the floor. The status of the contact switches and the intended leg speeds developed in other routines are considered by the software routines before control voltages are sent to the motors. If the situation warrants backdriving the motors, then the lowest level routines instruct motor control hardware circuits to send sufficient voltage so as to prevent the backdriving of the motors.

CONCLUSION

The experience of designing and building Prototerp IV was unique for every person involved in the project. From the initial conception of the machine, through all phases of the design, and clearly up to the final details of construction, Prototerp IV has proven to be both challenging and rewarding. As an interdisciplinary avenue for the students, this project has excelled. It has provided an excellent opportunity for Electrical Engineering students to learn about mechanics, and for Mechanical Engineering students to further their knowledge of electronics. The project has given these students a glimpse of the real world with all of the joys and sorrows that await them as the enter the job market as junior Engineers. This experience has also shown the students the value of working harmoniously in groups; arguments don't get the job done! In addition, during the course of construction, it was required that each group deal with vendors for supplies. We often were required to plead for quick delivery or barging for donated parts; a new experience for many of the students. In short, every member of the Prototerp IV team was required to learn and grow along with the robot.

ACKNOWLEDGEMENTS

Support for the University of Maryland Walking Machine project was given through a grant from USRA/NASA Advanced Design Program. This support is gratefully acknowledged. The students of EMNE 480 would also like to thank Bob Anders, of the University of Maryland Engineering Machine shop, and Bob Lincoln, of the University of Maryland Electronics Laboratory, for their technical advice and unending support of our efforts. Finally, we would like to thank Mark Uebel, our teaching assistant during this project, for without his direction, concern, and all those sleepless nights toward the end, Prototerp IV would not be a reality.

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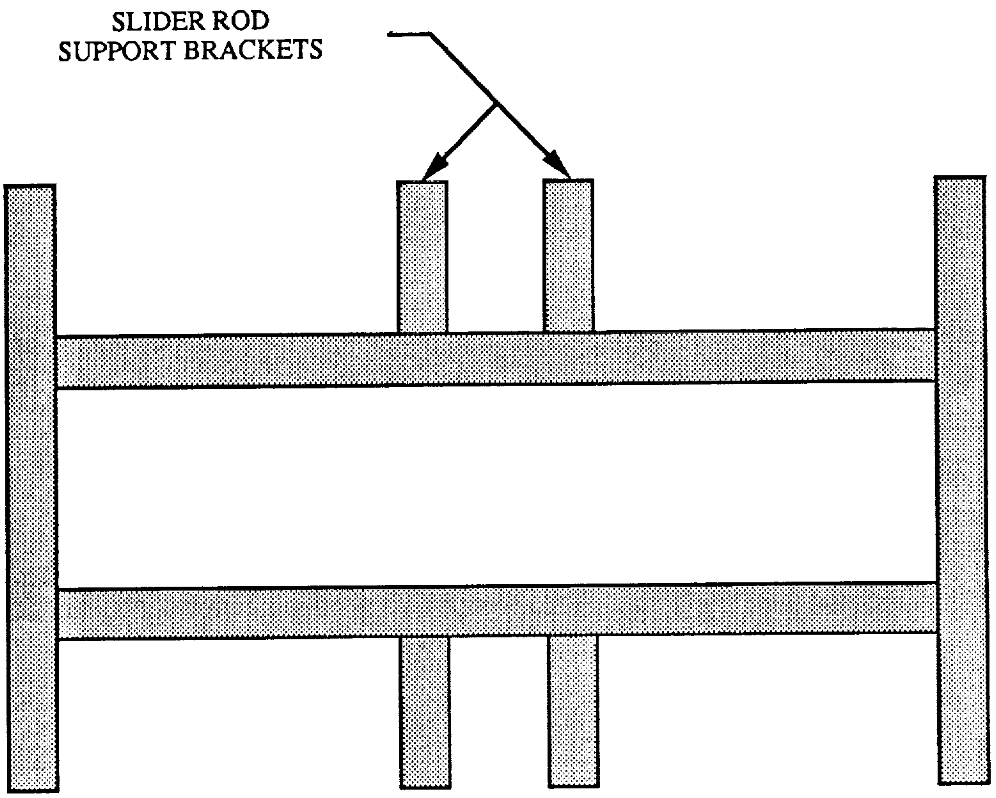


FIG 1: CHASSIS

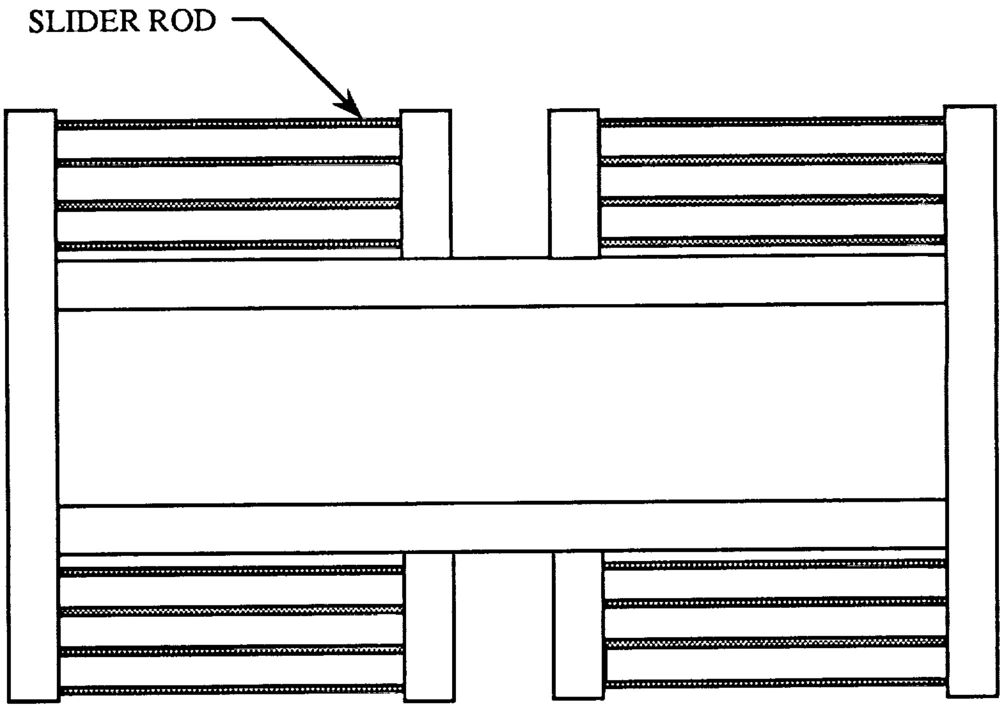


FIG 2: SLIDER RODS

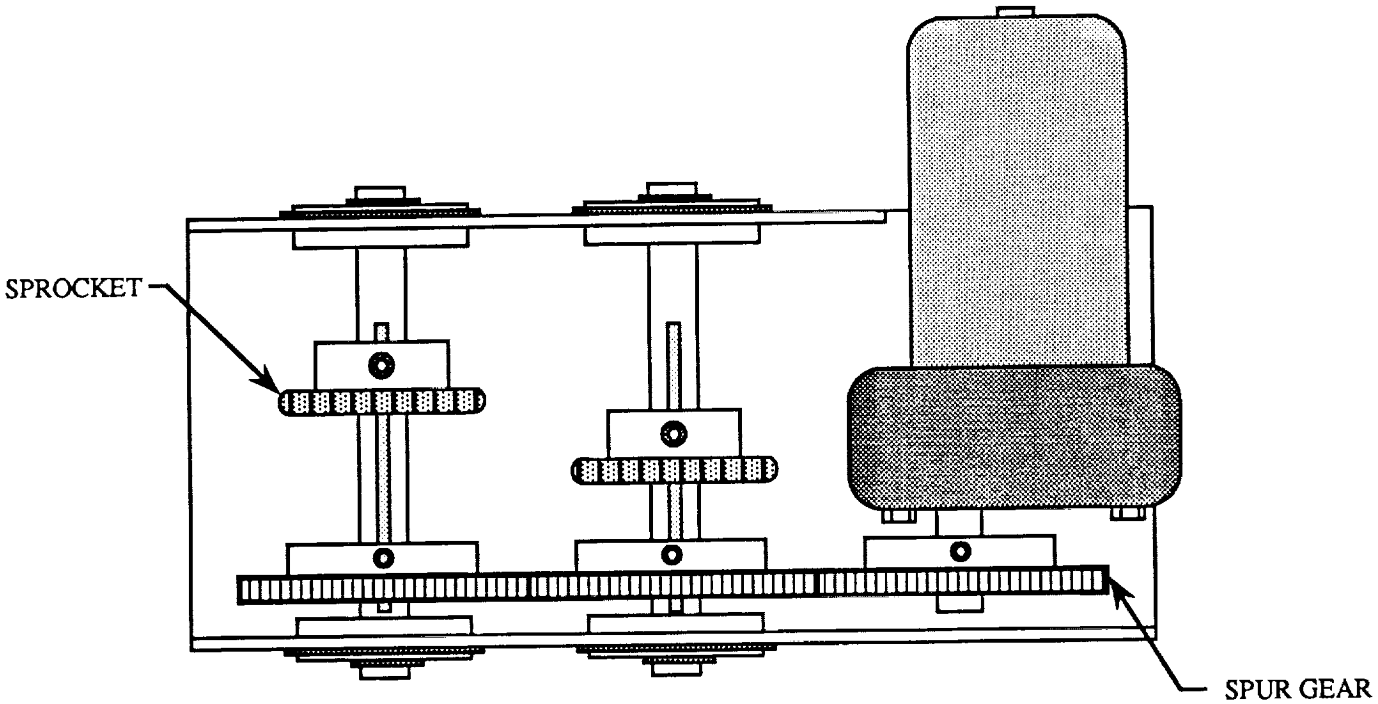


FIG 3: GEARBOX

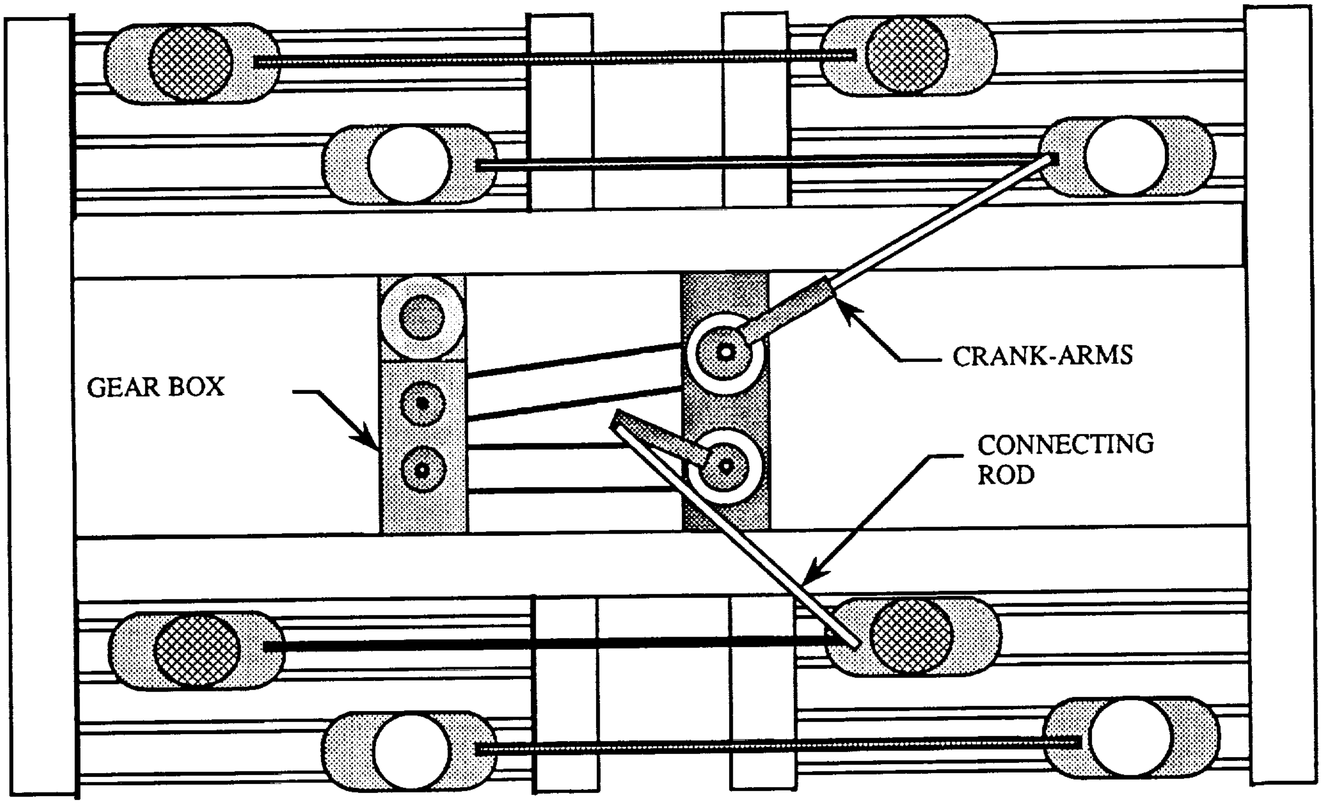


FIG 4: CRANK ARM AND CONNECTING ROD PLACEMENT

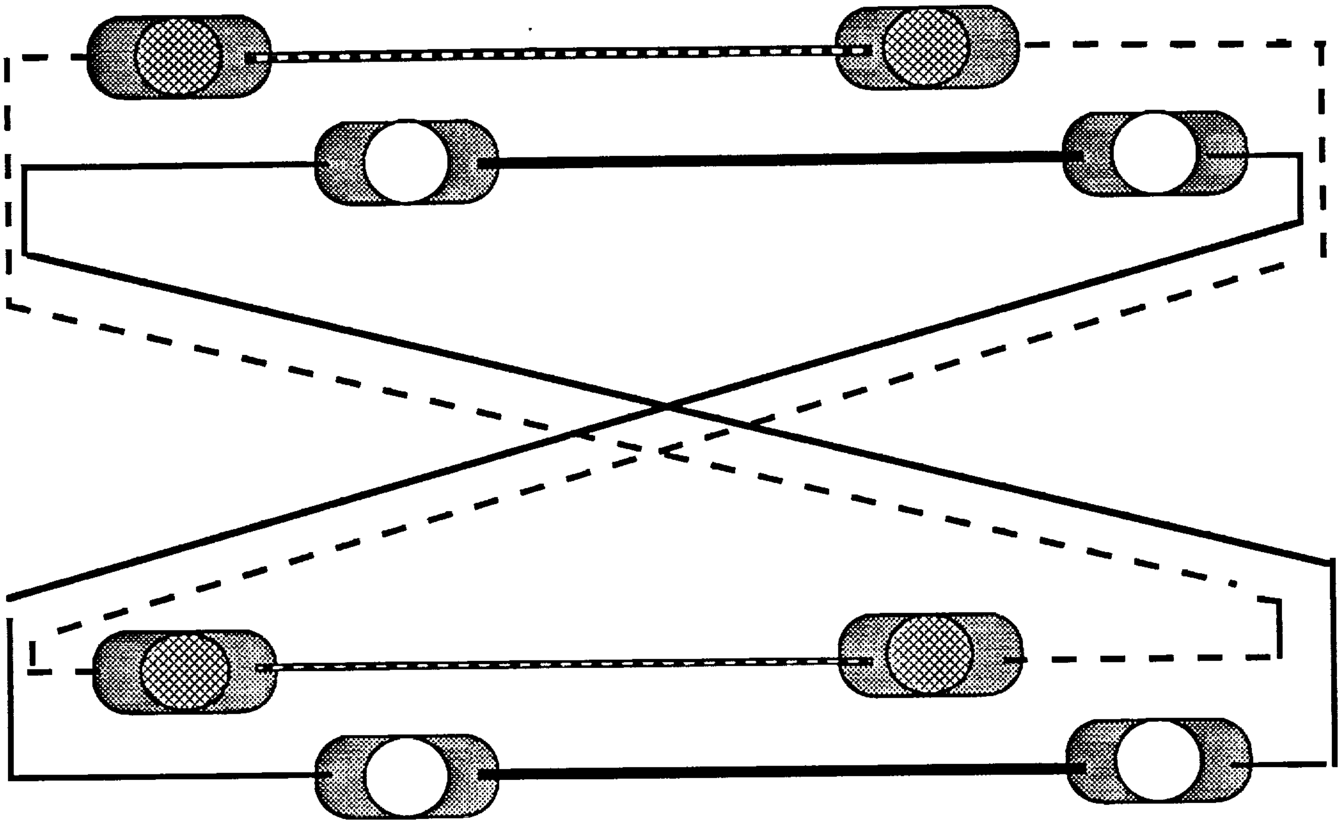


FIG 5: PULLEY ARRANGEMENT

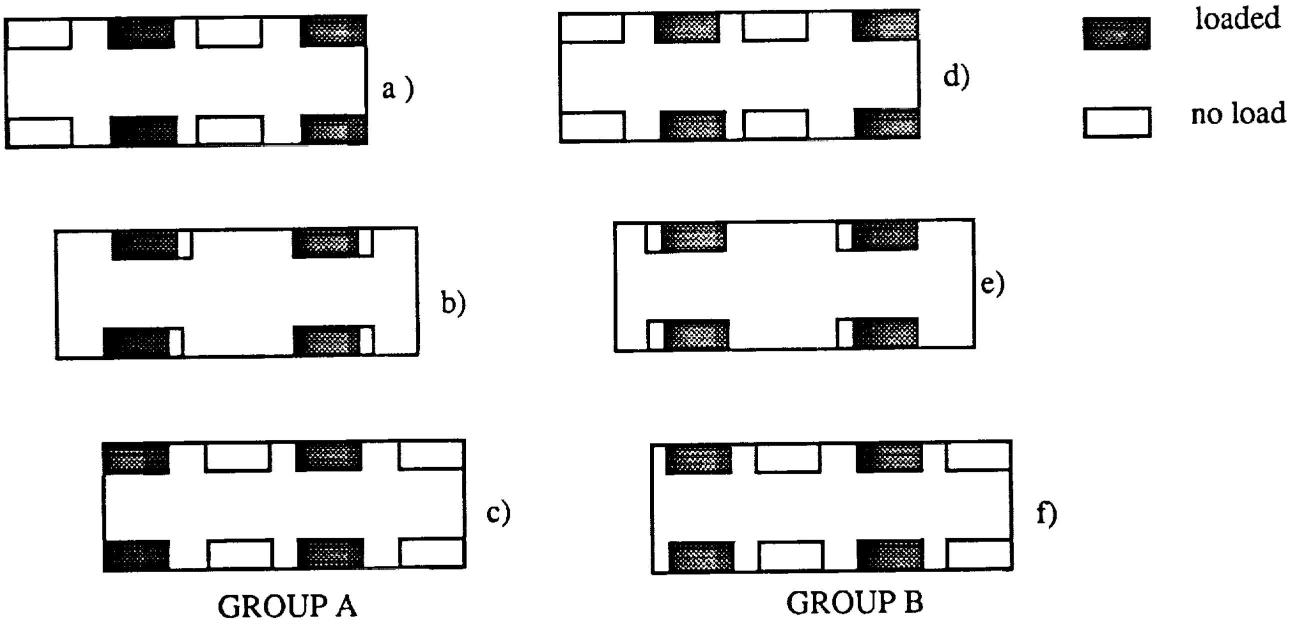


FIG 6: WALK ROUTINE

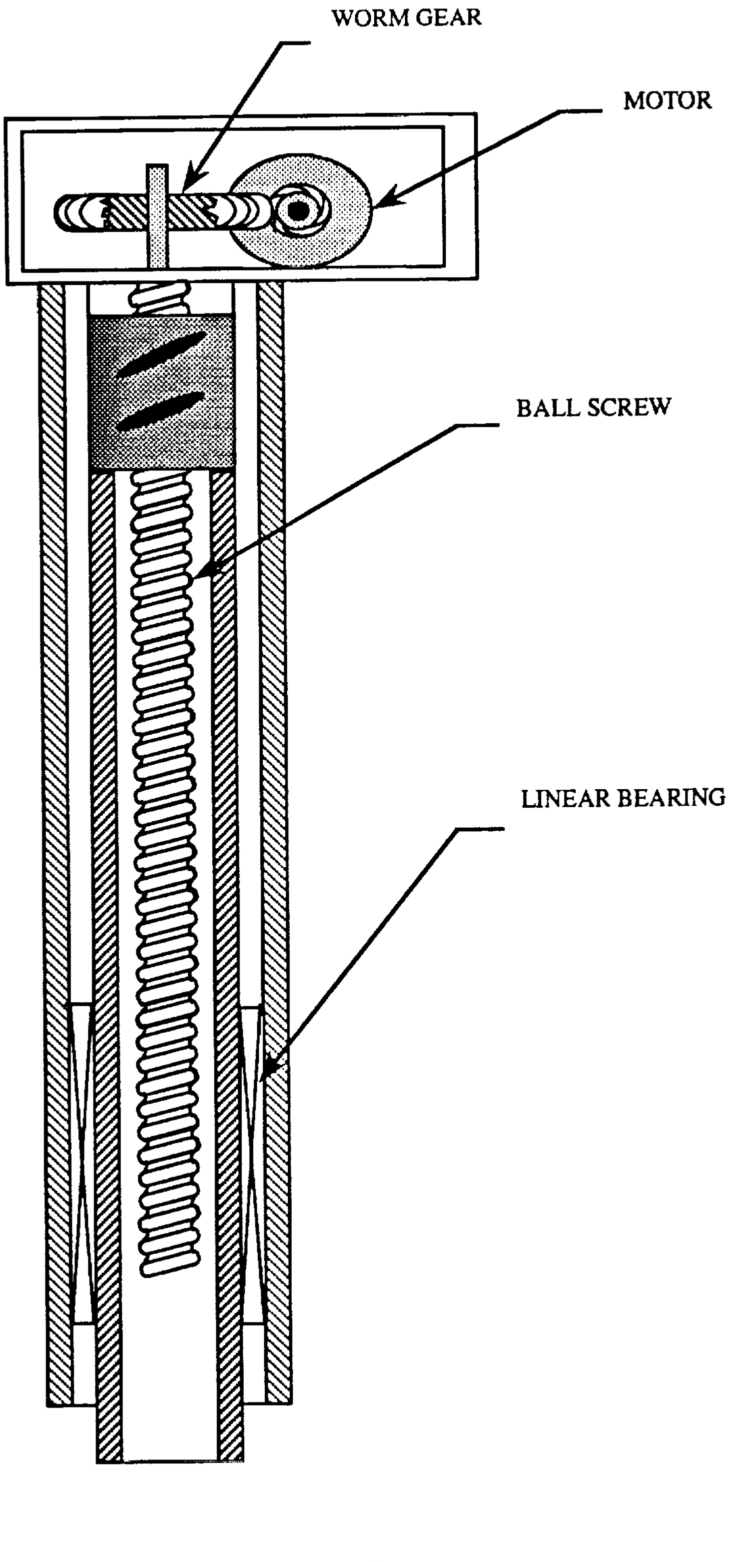


FIG 7: LEG ASSEMBLY

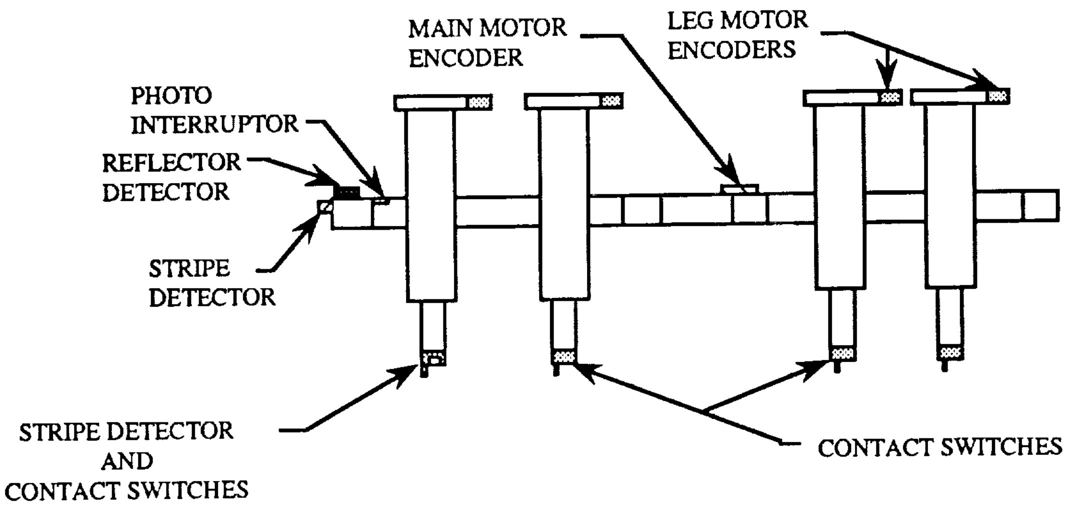
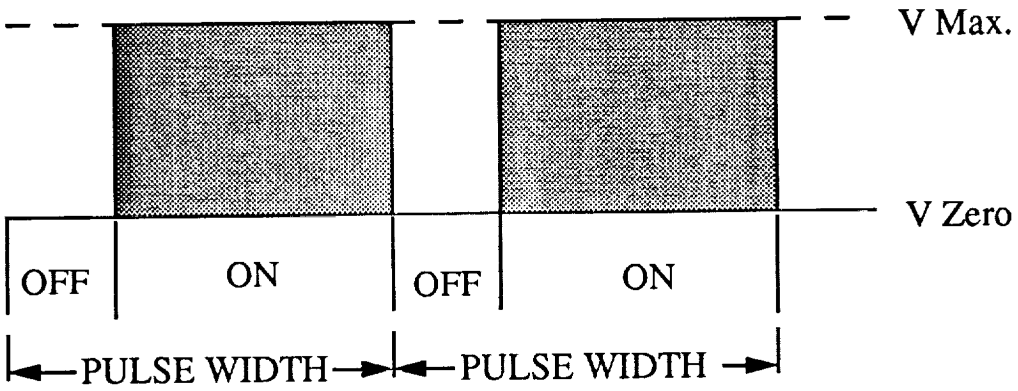
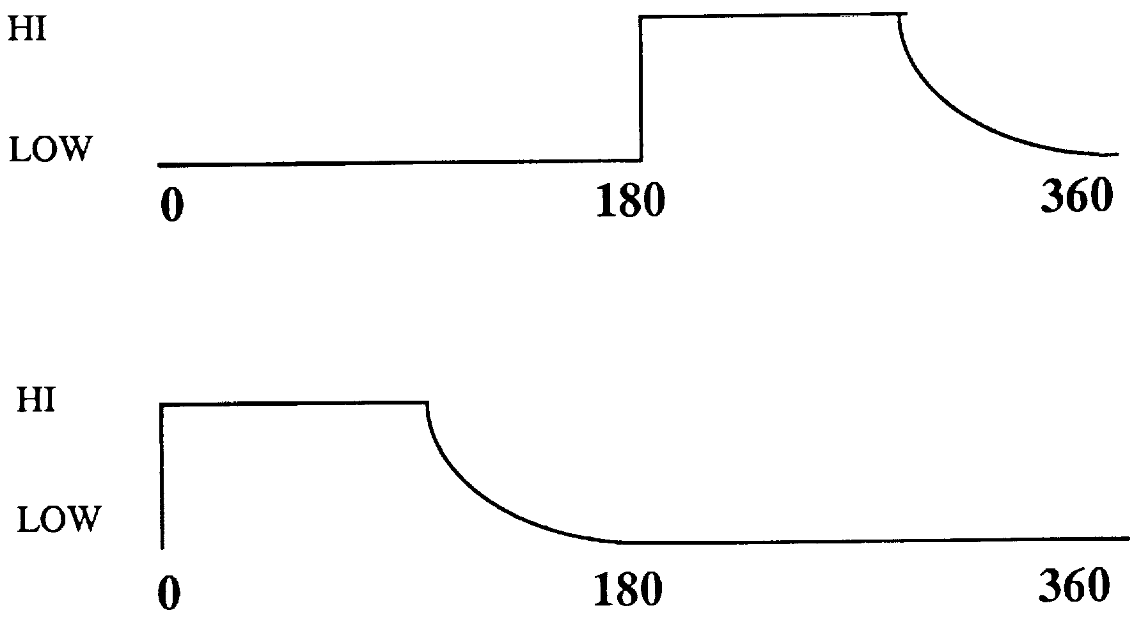


FIG 8: SENSOR LOCATION



PROPORTIONAL VOLTAGE = [1- (time off/time on)] x V Max

Fig. 9: PWM Waveform



y = H x (1 - x/l)^2   H = max height   Velocity= 0 @ x = l
l = decay stride length

Fig . 10: Leg Height versus Angular Position of Crank Arm

APPENDIX A:

CHASSIS & BIGFOOT

DESIGN AND CONSTRUCTION OF THE CHASSIS AND BIGFOOT

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5-7-90

INTRODUCTION

The duties of the spring semester of the walking robot class were to construct, based on designs from the students in the fall semester, the walking machine Proto Terp IV for competition in the 1990 Society of Automotive Engineers (SAE) Walking Robotic Machine Decathlon. All facets of construction were based on the feasibility of the design, availability of materials, and time constraints.

The responsibility of the chassis and bigfoot group were to review the fall semester design, propose modifications (which were needed, see design evolution section), and construct the article. These tasks were accomplished in the set time period of 11 weeks. This doesn't mean that it was a smooth transition from design proposal to construction. There were many instances where alternative design proposals had to be incorporated well into the construction stage. This was basically for strength-to-weight optimization of the chassis towards the end of the construction stage.

The fabrication of the chassis and application of a previous "bigfoot" involved many hours of design consideration, procurement of materials, and machine shop labor to come into fruition. The result was a significant contribution to the waking robotic machine Proto Terp IV as a foundation for driveline, legs, and computer hardware.

Design Evolution

Starting with the design proposed by the Fall 1989 semester of the walking robot class, the Chassis and Bigfoot group of Spring of 1990 made several design modifications to improve the functionality and expedite the construction of Proto Terp IV. The Fall 1989 design proposal also included the drive mechanism, which was not assigned to the Chassis and Bigfoot group of Spring of 1990. Therefore, modifications included in this report do not refer to drive mechanisms (except Bigfoot), which were assigned to a different group.

From the first proposed design of the chassis (Fall of 1989), the design team and advisors believed that the aluminum blocks used to hold the rods to the chassis were too heavy and that the rods could be held in place by plates fastened to extended aluminum tubing (see fig. 1). This design revision used all the same dimensions and was essentially a materials revision. From here the chassis was revised three more times. Design revision 2 was the same basic idea as revision 1, but due to materials available from the physics shop at that time (2"x3" channel as opposed to 1.5"x2") the design was modified to accommodate the availability of these materials. However, due to further investigation as to why the dimensions of the chassis were chosen, which was for SAE Walking Robotic Machine event

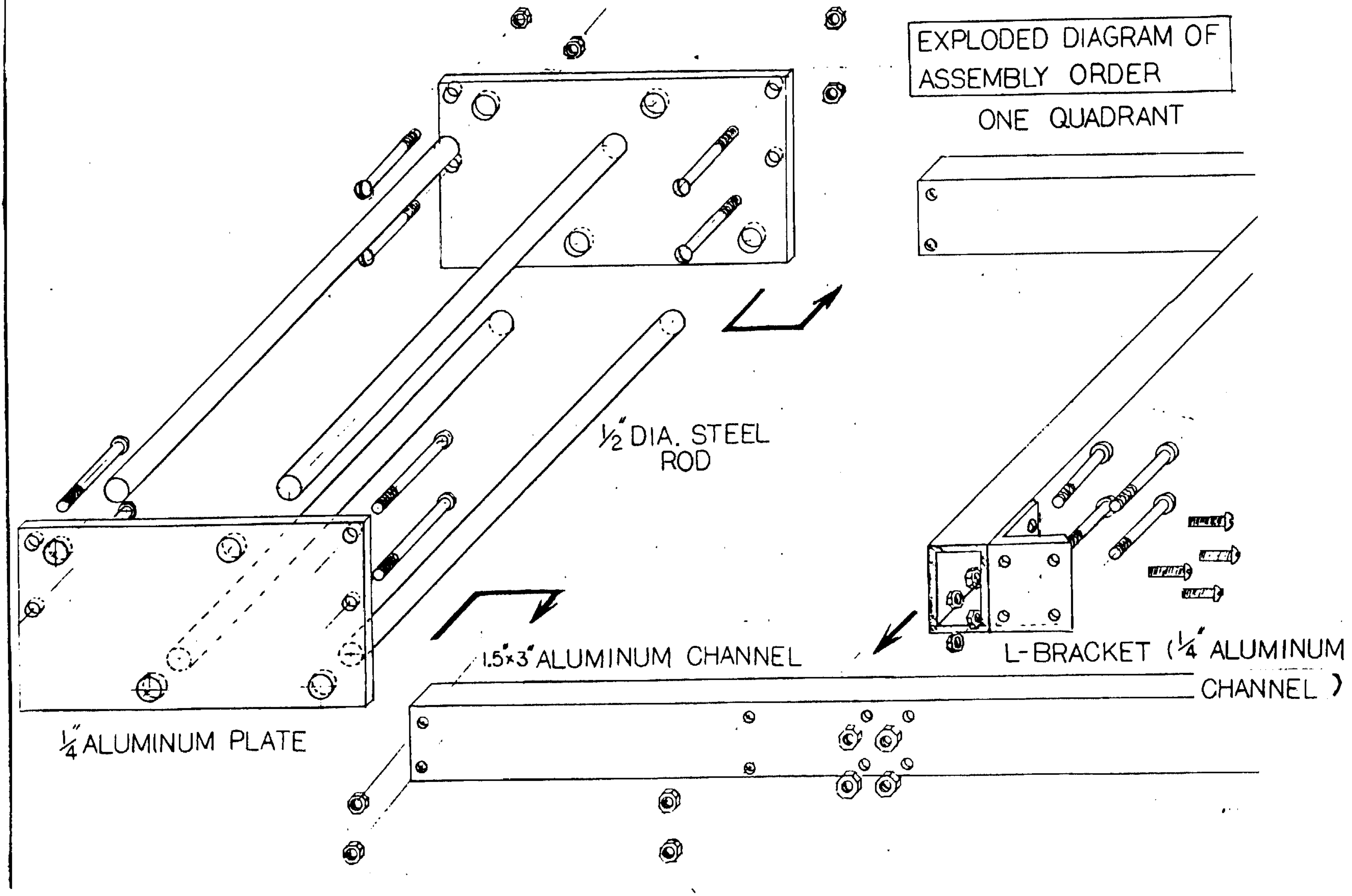


Figure 1 - Plates fastened to aluminum tubing

three, foot placement, the design was revised a third time. The event states:

"Starting at Area 6, the Walking Machine must walk across the contest area and cross line F. No foot of the Walking Machine may at any time completely cross line L or line R. Four stripes, each 20 cm wide and parallel to lines S and F, will be placed completely across the walking path. The second stripe will be placed 1 meter after the first stripe, the third 0.5 meters after the second, and the last stripe 1.5 meters after the third. The Walking Machine must step over the stripes and not touch any of the four stripes with any of its feet (see fig. 2, stripes not shown)."

The original distance, proposed by the Fall of 1989, between the legs of 21.75 inches would not allow clearance of the first stripe by the second set of legs on the second stride. The minimum distance required between the legs is 27.5 inches to have the legs clear the first stripe (see fig. 3). The distance between the legs could have also been less than 19.5 inches, but that would have caused stability problems and altered the stride length, which had to remain fixed at 30 cm. So the overall dimensions had to be changed to accommodate this latest revision. The chassis was lengthened to 49.75" and this in turn dictated that the rod lengths would need to be lengthen to 21.875". This

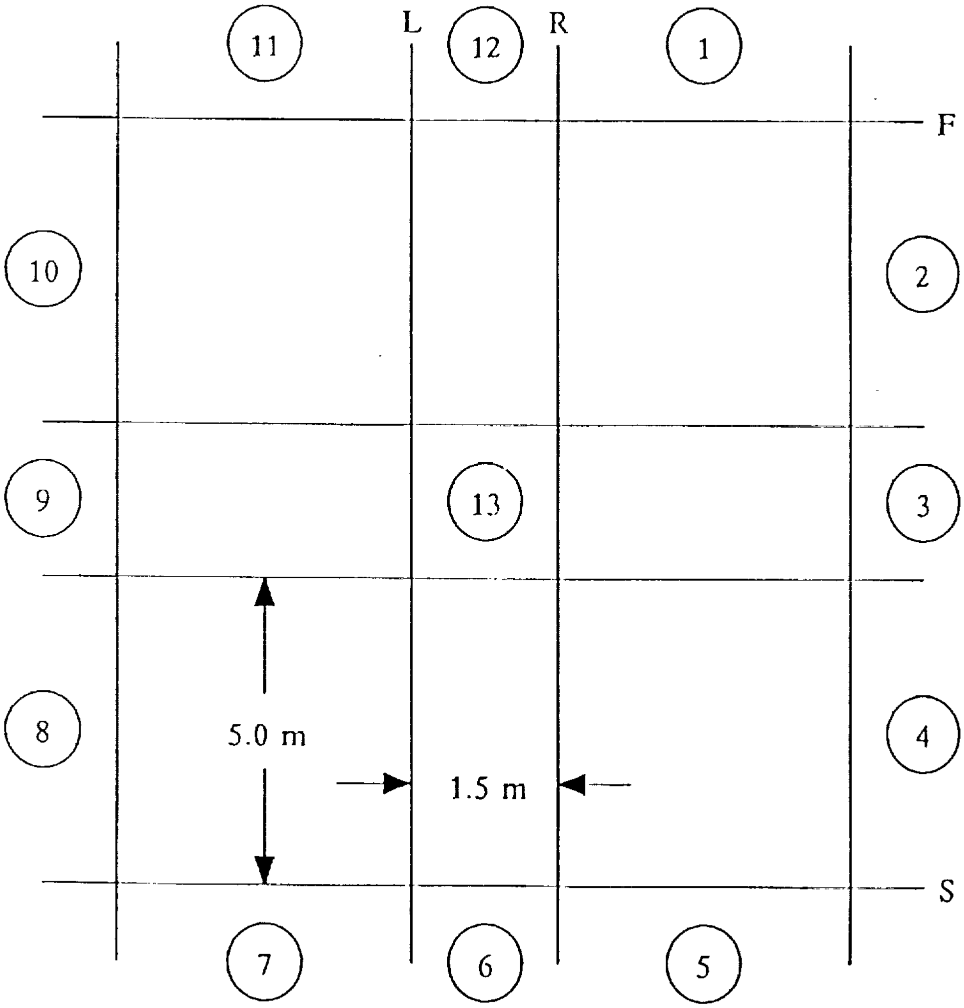
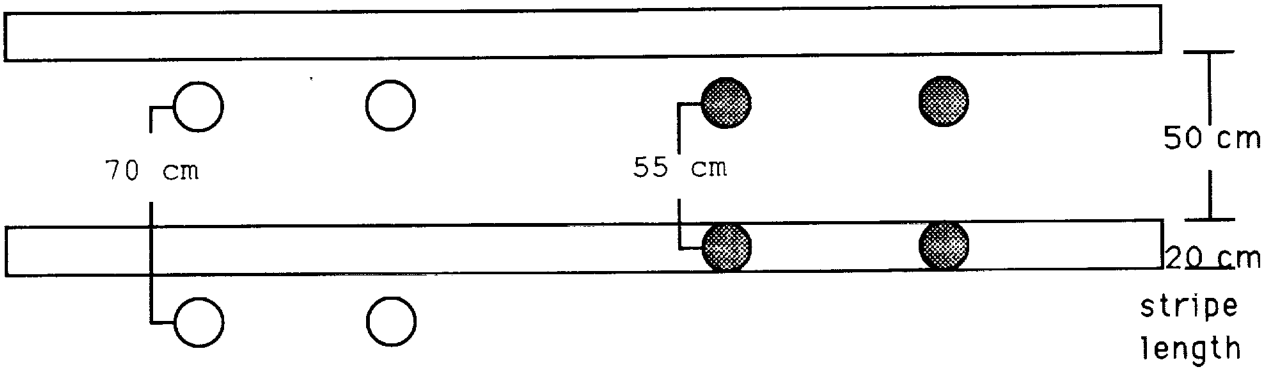


Figure 2 - Competition Area

The Lengthening of the Chassis is required to allow the four feet to be set down on either side of the first two stripes and maintain stability. The old design did not permit the feet to fit within the 50cm zone or straddle the stripe (70 cm total distance).



With chassis design revision 4, the 4 feet may be put down after the stride is completed without touching any of the stripes.

With the original design, the feet would not clear the stripe.

Figure 3 - Stripe Placement

lengthening of the rods would cause a greater deflection, which is theoretically related by the length cubed:

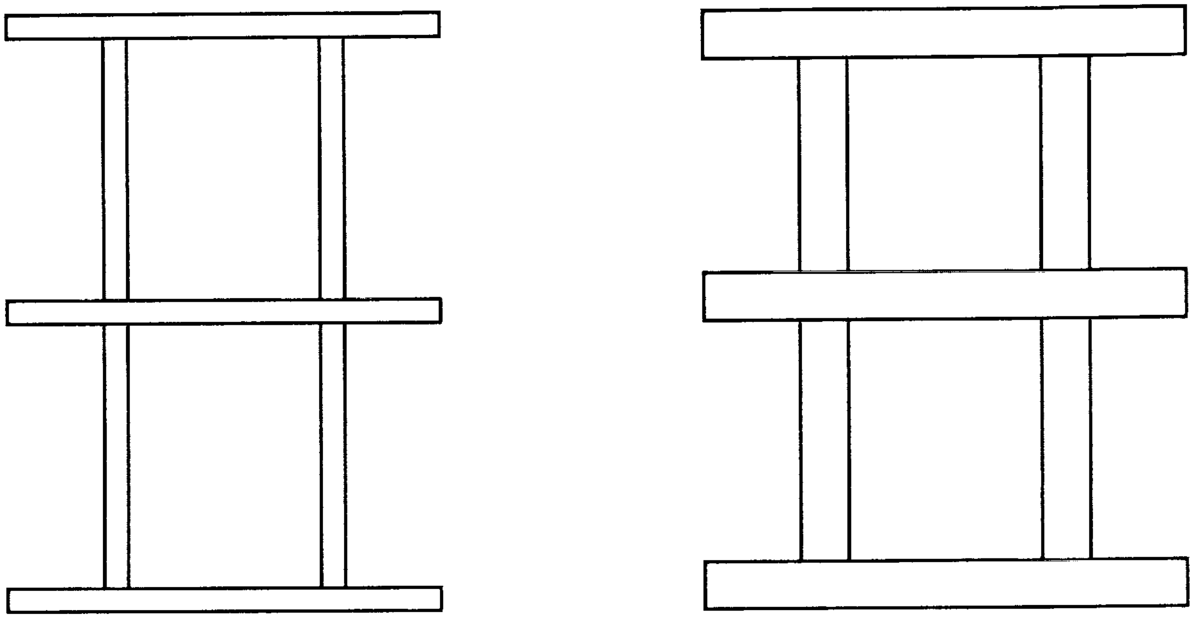
$$Y = (PL^3)/48EI$$

A reduction in the length of the rods was necessary, so design revision 4 was incorporated. By taking up slack in the rods in the middle of Proto Terp IV the deflection would be reduced. The new rod lengths would be 17.375" as opposed to 21.875".

Figures 4 shows the design evolution of the Proto Terp IV chassis including the optimize, final chassis.

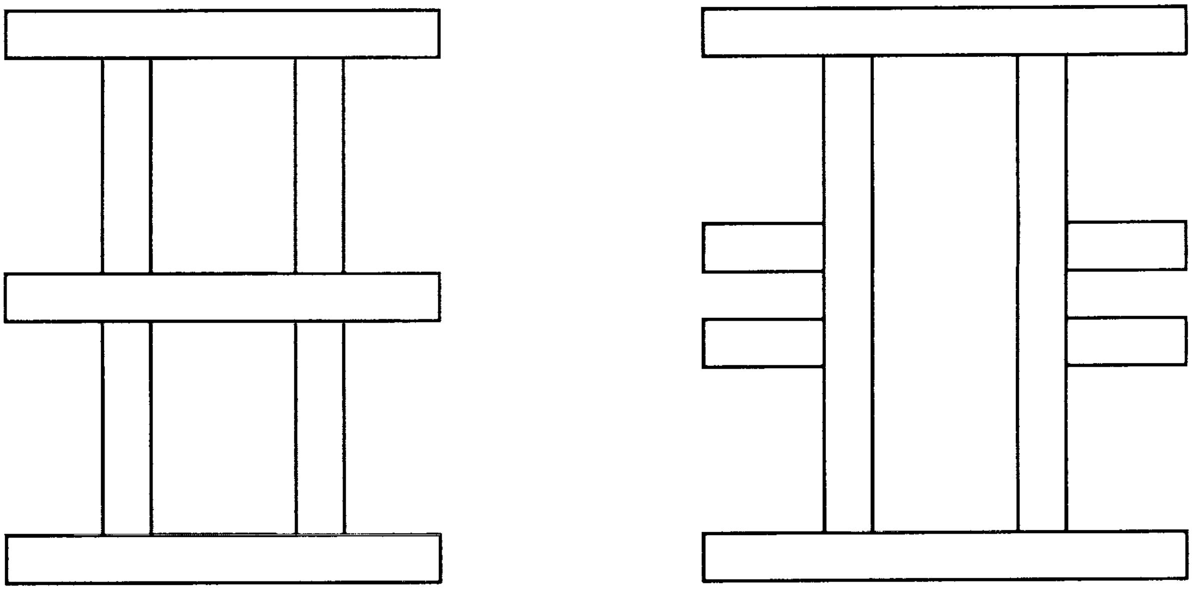
The use of the actual bigfoot collar constructed by the 1988 walking robot team at Maryland eliminated the need for a design. However, the Fall of 1989 design was quite similar to this already fabricated piece. The only new design modification was the lengthening of the shaft which would need to be fixed underneath the top plate which was mounted by the driveline group (see fig. 5). The lengthening of the shaft was accomplished by using a length of all-thread with a 0.75 inch dia. aluminum shaft (bored, not tapped) fitting over it to the proper length (approximately 3.5") to have it fixed to the top plate for greater stability.

The original motor proposed for Bigfoot in the Fall 1989 design was a Brevel 12 v DC 20 in-lb at full load and @ 4.6 rpm. This was later changed to the proposed drive motor, a



Design revision 1, replaces aluminum box and solid aluminum blocks.

Design revision 2, same as 1 but 2"x3" channel instead of 1.5"x2".



Design revision 3, same as 2 but chassis lengthened to 49.75"

Design revision 4, changed to accomodate the deflection in the slider rods. length, 49.75"

Figure 4 - Design Evolution

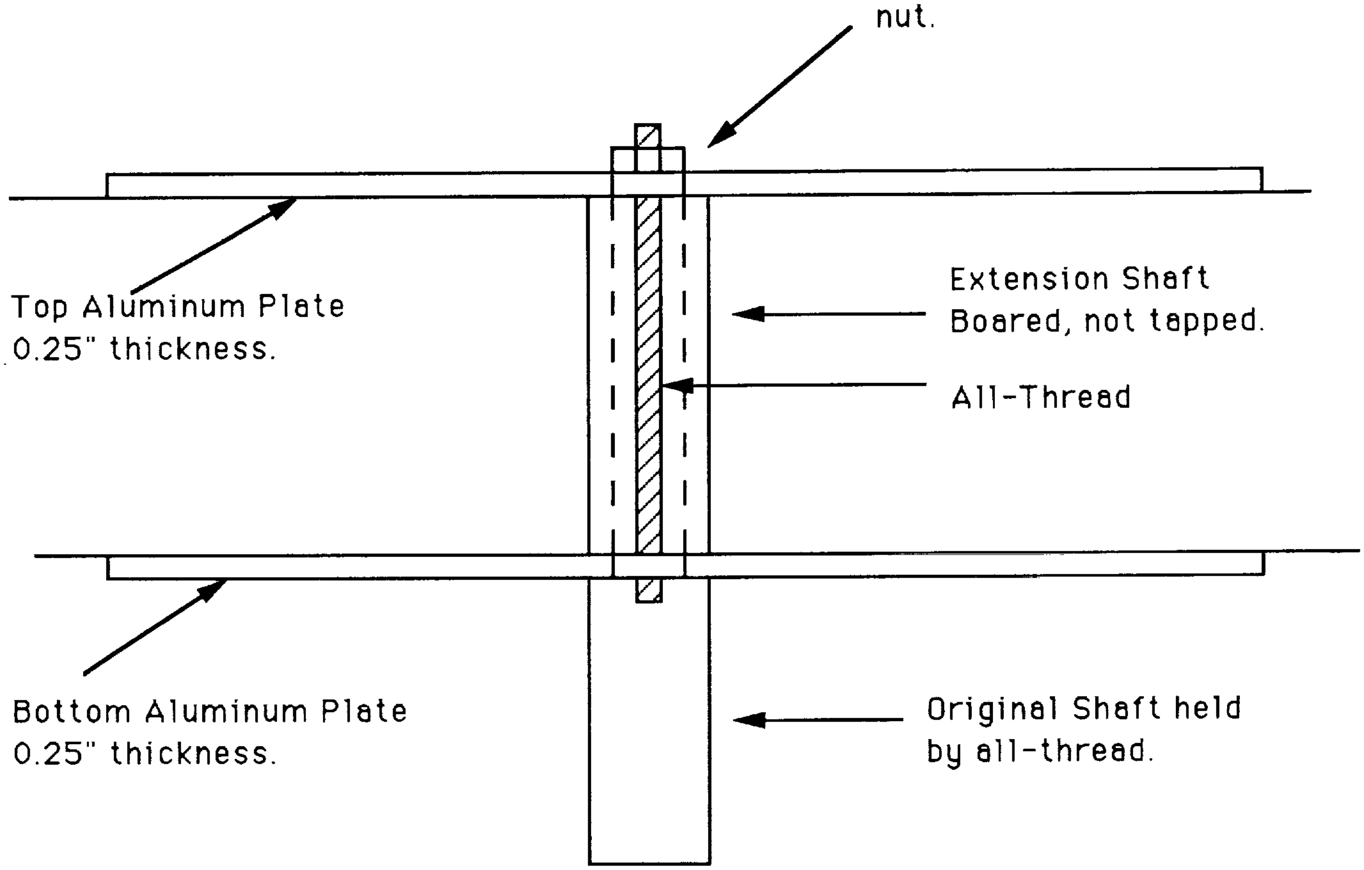


Figure 5 - Mounting of Bigfoot Shaft

Von Weise 12 v DC 8 in-lb @ 200 rpm and full load. This motor had a 14:1 gear reduction, and would operate unloaded at 108 rpm. Project advisors recommended that the Bigfoot motor should obtain a $\dot{\Theta}$ of 30 rpm in 90° of polar displacement. An angular acceleration of 0.047 rad/sec^2 was calculated from an estimated mass moment of inertia (see calculations in Appendix). The calculations reinforced theoretically that the Von Weise motor would be sufficient, but an experimental test rig was constructed to verify this information. With a much smaller mass moment of inertia simulated by free weights placed at various distances from the centroidal axis, motor operation with the Von Wiese not only showed very high start-up current draw (sometimes 14 amps), but also enough wear on the plastic gear reduction to render the motor inoperable. After attempts to reduce the opposite end of the Von Wiese were considered, another motor was ultimately chosen for the Bigfoot motor, with selection made by the driveline group.

The same gear reduction that was used on the 1988 Bigfoot was used on the 1990 Proto Terp IV.

The final design was design revision 4 with modifications to save weight and reduce the overall width by 2.25". Additional plates mounted by the driveline group gave the chassis further stability.

Construction of Chassis

The chassis for the 1990 walking robot was mostly constructed of 2"x3"x.125" aluminum channel. The frame, or channel portion, of the chassis was constructed first. We cut the channel sections on the Do-All saw and machined them to the exact length using the milling machine. Next, we cut the angle brackets for the corners using the Do-All and, for safety, we deburred the edges by hand. Angle brackets were used for the corners for two reasons. First, the angle brackets provided the strength and stability needed to hold the joints together. Second, they simplified construction by guaranteeing perfectly square connections (see Fig. 1).

The angle brackets were attached to the channel sections by drilling the holes through both pieces at the same time on the drill press. This turned out to be quite a job, since the angle bracket hit the drill chuck, and the drilling procedure turned into a complex process of clamping, drilling, disassembling, drilling, and reassembling, etc. The pieces of the frame were custom fit to a specific location, even though they could be interchanged. Once the frame was assembled, we carefully and explicitly identified the location and orientation of each piece, so that when the frame had to be taken apart, it could easily be reassembled.

The next part of the chassis to be constructed was the slider-rod assembly. The slider rod assembly was the most critical part of the chassis. The rods had to be perfectly parallel, or the linear bearings of the legs would not work smoothly. In addition, the rods had to be perfectly aligned so that the robot would walk in a strait line.

The first step of the construction of the slider-rod assembly consisted of cutting-out all the plates using the band saw. Once the plates were cut out, we used the milling machine to cut them all to exactly the same size. We used a fly-cutter bit to cut all of the pieces at the same time. Once the plates were cut out, we pinned them together and drilled them in pairs, so that the rods would be exactly parallel. The holes for the rods were drilled using the milling machine for exacting precision.

Once the holes for the slider-rods were drilled, the plates were mounted on the frame, and the rod lengths were measured and cut. The rods were custom fit to their exact location. This was necessary so that they would not slip out once they were installed. The upper rods were held in place by the channel, and the lower rods were held in place by snap-rings. The grooves for the snap-rings were cut right at the inside edges of the plates, so that the rods would not slip out.

The slider-rods proved to be difficult parts to obtain.

The slider-rods were the only non-aluminum components of the chassis. They were case-hardened steel drill rods, .500" in diameter. The first set of rods, obtained from the physics shop, turned out to be .002" to large for the linear bearings. The second set of rods, obtained at Thompson and Cook, were too soft and grooved under the sliding action of the legs. The snap-ring grooves in the this set of rods were cut by Mr. Bob Anders of the shop, since they were so hard it required special tools and techniques to cut them. The third set of rods were the right diameter and they were hard enough to not deform when loaded by the linear bearings. When Mr. Anders tried to cut the grooves in these rods, he was unable to do so because they were to hard. We had to heat up the last .5" of each end with an acetylene torch. After heating up the ends, we cooled them very slowly. This altered the material properties enough that Mr. Anders was able to cut the grooves for the snap rings. This process did not affect the material properties of the center portion of the rods.

Once the grooves were cut, we put together the slider-rod assemblies, and installed them on the chassis. This completed the basic chassis configuration. At this point, it was obvious that the robot overall was much too heavy. In order to help lighten it, some chassis revisions were made. Most significantly, we reduced the overall width of the robot. Next we cut the plates and the ends of the frame along the angle formed by the slider-rods (see Fig. 6). This also greatly improved the cosmetic appearance of the robot. We obtained weight savings of approximately 10 lbs. by taking these steps.

The final part of our assignment was to construct a secure, protective, stable crate to use to transport the robot. The crate was constructed out of donated 2"x4" lumber and was custom fitted to exactly fit the robot. The crate protects the robot from low impact on all sides and holds the robot of the ground approximately 1".

Conclusion

In conclusion, the chassis of the 1990 University of Maryland Walking robot, Proto Terp IV, was the end result of many design revisions, changes due to construction difficulties and constraints, material demands, and weight requirements. The main thrust of the chassis was to provide a geometrically exact, structurally sound, stable, light weight base upon which to mount all of the other components of the robot. We succeeded in obtaining these goals and providing such a platform upon which to assemble the robot.

APPENDIX B:

DRIVELINE

ENME 408
Prototerp IV Walking Robot
Driveline Group Report

May 7, 1990

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Group Members:

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Morad Hekmat
Dave Russell
Hossein Tavakoli
Gary Young

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Introduction

Overview

Prototerp IV is a walking machine designed and built by University of Maryland students in the class ENME 408. The University of Maryland began offering ENME 408 four years ago for the purpose of allowing students in mechanical and electrical engineering to work together in a team environment to study state-of-the-art robotics, and to design and build a functional walking machine.

Each year, a machine has been entered into a decathlon sponsored by the Society of Automotive Engineers. The decathlon is a nationwide collegiate competition with 10 events designed to exploit the abilities of the walking machines.

Prototerp IV was designed largely with the rules of the competition in mind. However, the intent of the rules was used as a guideline, rather than the actual rules themselves. Therefore, our robot was designed to conform to many applications, not just the decathlon.

The following goals were set for the design of the machine:

1) The machine should be able to walk straight quickly. Walking is defined as a mobile machine supported discontinuously and propelled by articulated mechanisms (the legs). Each leg must have one or more joints or hinges by which it moves relative to all legs or the frame. A leg may pivot, slip or slide on the supporting surface during walking motion, but it may not roll.

2) The machine should be able to turn quickly.

4) The machine should be able to walk with a variable stride length.

5) The machine should be able to walk over a small staircase (with a minimum size defined by the decathlon rules).

6) The machine should be able to push a hockey puck with a stick attachment.

7) The machine should be able to "see" by sensing retroreflective material.

8) The machine must be able to be programmed to do any of the above functions autonomously, and in combination.

The last requirement is very important, because it allows our machine to be called a "robot". Part of the RIAA definition of a robot is "a reprogrammable, multifunctional manipulator". Our machine fits this definition, in that it can manipulate a hockey puck (or any object placed on it) in any way defined by the software programming.

The project was split over two semesters. The first semester students designed the robot on paper and submitted a design report. The second semester students made initial modifications to the design and built the robot, with minor changes along the way.

The design and manufacturing of the robot was divided into five groups: (1) Leg and hockey, (2) Chassis and Bigfoot, (3) Driveline, (4) Control-Software, and (5) Control Hardware. This report details the work done by Driveline group, from original design through the entire manufacturing process.

Driveline Group Responsibilities

The robot was designed with 8 legs which slide horizontally relative to the chassis. At any moment during walking, four legs rest on the ground, driving the chassis forward, while the other four legs are returning to the front of the robot. The legs were all linked mechanically, so that they do not slide independently in the x-direction (horizontally). However, each of the legs can extend in length, allowing the robot separate x- and y-degrees of freedom. The driveline team was responsible for all of the parts propelling the robot in the horizontal direction. This included a gearmotor and gearing mounted in a gearbox, chains and sprockets necessary to transfer the motor power, an offset crank mechanism used to convert the rotational motion to translational motion, and the physical connection between legs including wire, pulleys and tubing.

Design Considerations

Many factors were accounted for in the driveline design. These factors were governed by the following:

1) Goals of the overall robot design
2) Power requirements
3) Simplicity of design
4) Weight considerations
5) Stress considerations
6) Ease of manufacture
7) Ease of maintenance
8) Esoterics

Past University of Maryland robots and other universities' robots were studied to optimize the design, and a great deal of forethought preceded the final design. The following is a summary of the design steps taken to adhere to the above guidelines:

The robot was based on an x- y- degree of freedom system. The separation of the x-direction motion from the y-direction motion provided flexibility of motion, while simplifying the driveline. The horizontal drive mechanism is simplified by the fact that it need not supply power to support the weight of the robot. The only work done by the driveline is to accelerate the robot in the horizontal direction. This allows for a high speed robot with relatively little driveline power.

The driveline was driven by one motor. This allows a simple control scheme, but does not interfere with any of the requirements of the robot. The variable stride requirement is taken care of by leg motors unrelated to the driveline. Using one motor prevents timing problems prevalent in multiple motor systems, and made manufacture and maintenance easier.

A quick-return slide mechanism was used. The driveline was designed with a linkage which returned the legs to the driving position faster than it drove the legs moving the robot. This improves the uniformity of the robot's velocity. The quick return allows the legs on the return stroke to start moving in the direction of the drive stroke before they touch the ground. In other words, there is a slight overlap of strides, much in the way a human walks.

The drive motor runs continuously in one direction during walking. By using the crank-slider mechanism, the drive motor need not reverse to drive the legs back and forth. This makes for a faster robot, since the motor need not overcome the inertia developed once it has started moving. It also prevents alternating stresses in shafting and other mechanical parts. This allowed for sizing components smaller, thereby reducing weight.

Frictional losses were minimized. This was accomplished in part by designing the gearbox with spur gears as opposed to bevel gears. This has the added benefit of allowing looser tolerances in manufacturing the gearbox. Pulley angles were kept large, high-quality bearings and pulleys were used, and using hardened steel rods were used for the legs to slide on. In addition, the angle of the offset crank mechanism was minimized to prevent excessive friction (see Theory and Design section).

The drive motor and main gearing were assembled in a gearbox. This modular design allowed for the driveline to be assembled and tested separately from the chassis. This makes manufacture and maintenance easier. It also allowed for flexibility of placement of the driveline on the chassis, which was necessary since other components' designs were not solidified until several weeks into manufacture.

Chains were used to link the gearbox to the chassis-mounted drive components. This avoided having to tolerance the gearbox mounting precisely; slots were machined to allow for removing slack in the chains during gearbox mounting.

Theory and Design:

As mentioned before, Prototerp IV implements the use of a single drive motor to translate rotational motion to the translational motion of the eight sliding legs. It has been decided earlier that a crank-slider mechanism would be the means for the transformation of these motions. It is still necessary however, for the primary drive of a main motor to be translated outwards to two vertically mounted shafts in a predetermined location such that their direction of spin is opposing one another.

A separate gearbox has been built which has within itself two adjacent shafts where sprockets have been mounted to drive a dual chain system outwards to the two outer "crank-shafts". The gearbox works such that the spins of the two internal shafts are opposing. This creates identical spins at the cranks. On top of the crank shafts are mounted crank arms which are the circular motions of the crank slider model. The connecting rods attach to the ends of the crank arms and follow out the leg slider blocks. This completes the description of the drive mechanisms which propel two opposing legs on either side of the robot (fig.1).

Gearbox

The gearbox was built totally separate from the robot, was installed after construction of the chassis, and remains an adjustable, removable component of the robot. It is constructed from a large C-channel which houses the motor and all internal driveshafts. The initial design consisted of a horizontally mounted gearmotor which sat on top of the channel. The horizontal motor coupled up with a shaft with a bevel gear translating to a vertical shaft. The vertical shaft drove an adjacent shaft, producing again the opposing spin (fig.2). One problem in the use of bevel gears are their difficulty alignment during assembly. It was decided that a simpler approach would be to use spur gears in the meshing of the drive motor and the first shaft. The final design was a slight modification to the earlier concept in that the drive motor was mounted vertically in the aluminum channel housing with its drive shaft parallel and adjacent to the first shaft (fig.3). With this setup, the strict use of identically sized spur gears allowed for a much more forgiving design in the construction aspect. The bearings used in the gearbox came with snaprings installed in the outer race which allowed for a sandwich type fit when an entire shaft is installed in the housing. On the two vertically mounted shafts sprockets were installed which drive the two sets of chains to the outer cranks.

The advantage in having a totally separate gearbox on the robot is that it can be adjusted backwards and forwards in its mountings to create ample chain tension. In other words, the gearbox was mounted with bolts to a bottom plate which had slots machined in it. This was a very simple method for creating and maintaining a certain tension in a chain drive system that cannot allow for any looseness in the final walk of the robot.

Outer Drivetrain (Crank End)

One advantage in a chain drive system is the option to change the reduction in the drive at any stage in the robot. The chain drive built used identically sized sprockets throughout which gave the same angular velocity of the final cranks with respect to the drive motor. Through the operation of the robot, it was unnecessary to change this drive reduction since the torques required of the system were sufficiently met with the capability of the drive motor. If the need were there to change, different sized sprockets at the gearbox were supplied to allow for a 1/2 reduction overall from the gearbox to the crank arms.

The previous design of the crank assembly was to have steel shafts with aluminum crank arms (fig.4). Since it is impossible to weld or bond two dissimilar metals, it would be necessary to bolt one to the other. One change that was made to this is to make everything out of steel including the crank arm. In this case, it was possible to weld the steel shaft to a steel flange, which was bolted to the steel crank arm. The reason for the separate plates is so the crank arm can be adjusted with respect to the crank shaft to obtain very small angular increments which will give a fine tune adjustment of one set of legs with respect to the other. Every time a small angular adjustment is made a separate set of holes were drilled through the arm and the flange, then they were through-bolted when the proper setting was gained. The bearings used for the crankshafts were the same as for the gearbox because the same stresses are present in all four shafts. The connecting rods were attached to the ends of the crank arms (fig.5).

Connecting Rods and Cables

The purpose of the connecting rods are to translate pure compressive and tensile forces from the rotation of the end of the crank arm to the translation of the leg sliders. A very simple design for this is to use rod end bearings, which connect to the end of a rod and attach to a fixed post while allowing for angular deformations. This uses a ball and socket type device. For a connection of the rod end bearing to the rod, the rod needed to be threaded. 3/8 inch aluminum rod was very lightweight and useful for this application. One modification that was made to the connecting rods was that the height difference between the top of the crank arms and the top surface of the leg slider block had to be accounted for by creating a bend (fig.6).

The drive system described to this point includes whatever necessary to propel two opposing legs. The robot has however, eight legs. For this reason, the motion of each directly driven leg must be mimicked by the other three legs which will create two sets of four legs. To connect all sets of legs which are in front and back of each other, solid connecting rods were used to pair them up. A cable system was used to move the set of legs on the opposite side of the robot than the directly driven side (fig.7). In order to route the cables throughout the robot, small pulleys were used. Friction was cut to a minimum by using ball bearing sheaves. A previous design was to mount the sheaves in the cross section of the chassis tubing by putting shafts inside. A modification to this was to place the sheaves on the underneath surface of the tubing (fig.8).

The routing of the cables throughout the robot must be done so as not to obstruct any of the other moving components. Fortunately, by placing the entire cable setup underneath the chassis, the only thing it must pass by is the shaft for the bigfoot mounting. This was a very simple problem to overcome by the placement of the rear two sheaves further inward. By doing this, the intersection of the two sets of cables is behind the bigfoot shaft. The connections and tensioning of the cables was made possible by using mini-turnbuckles and cable clamps. Although being very small and detailed components, they proved to be absolutely necessary in the use of a mini cable system and fine adjustment of all legs could not have been made without their use.

Crank and Slider Mechanism

It has been determined to this point that a combination of a gearbox and its' connected chain drive would be most advantageous for this particular Robot design. The task at this point is to size all of the interrelated components for the best overall weight and performance. To be able to do this however, the amount of power being transmitted through the drivetrain must be calculated. For this reason, the final crank arm torque and RPM must be specified such that the Robot will have the desired stride and velocity that will be competitive.

The geometry of the crank and slider was chosen to give a walking stride of approximately 30 cm (fig.9). The offset was chosen arbitrarily so that there would be enough quick return action to give an observable advantage in uniform velocity but not so much that there would be tremendous frictional forces in the slider mechanism when large angles in the connecting rod with respect to the slider rod are produced.

By examining that if a full revolution of the crank takes place, two full strides will occur because each half turn of a crank arm is propelling a set of legs which drives the Robot forwards. This holds true if a desired Robot velocity is 30 cm/sec and a half a revolution per second is required. The approximation for a 30 cm stride is probably very accurate because the actual horizontal travel of the sliding legs from fig.9 is 30.37 cm and the feet will not be placed on the ground exactly at the ends of the travel but rather a little further in from the ends.

The task is to now determine the maximum torque required at the crank arm to propel the Robot at a velocity of 30 cm/sec and at a crank angular velocity of 30 RPM. The major reasoning in determining the torque at the crank will be due to the acceleration and deceleration of the entire Robot because of the non-uniform velocity of the crank-slider throughout a revolution; hence, a plot will be needed of torque with respect to all other variables including the angles associated with the geometry of the crank-slider. To do this, some equation will be needed to explain the kinematic motion of the crank-slider. From fig.9b, the position equation of the slider with respect to angles theta and phi can be calculated (eq.1). When time is introduced into this equation, then differentiated, a velocity profile is obtained as (eq.2). When differentiated again, the linear acceleration is obtained (eq.3). The angle between the horizontal and the connecting rod can be found (eq.4). When differentiated, its' angular velocity can be found (eq.5). A previous groups task was to make a plot of the torque, linear velocity and acceleration with respect to the angles involved using a Lotus Program Spread Sheet to find the point throughout a revolution at which the maximum torque occurs. When this was performed, the point of maximum torque corresponded to values of (eq.6). This value for maximum torque however, does not correspond to the value for maximum acceleration. The reason for this is the characteristic of a mechanical crank. In other words, the point of maximum acceleration is at the endpoint of its' motion, and this also happens to be at the point of the crank's maximum mechanical advantage. So there is no torque on the crank arm at this instantaneous moment. So the point of the maximum torque will be at some short moment of time after it has reached its' maximum horizontal extension, which is exactly what this mathematical model has shown.

The torque can be directly calculated as follows: A mass must be approximated for the robot and the torque accounted for will be accelerating this mass. Using this assumption, Newton's law can be used to find the horizontal force exerted on the legs (eq.7). At an angle of 9.55 degrees from the horizontal, the force in the connecting rod can be calculated (eq.8). From fig.9c, the acting radius of the torque can be calculated and then the torque (eq.9). With a factor of safety of 3 to account for frictional forces, additional forces created in returning legs, or any miscalculation in assuming a robot mass, a safe calculation for the torque can be determined which corresponds to an angular velocity of 30 rpm (eq.10). Now that the torque and RPM requirements of the crank arm are determined, a suitable drive motor can be chosen according to the power requirement. The power required for the motor with
a sizable factor of safety can be found (eq.11).

All components of the entire drivetrain system can be sized accordingly with the correct power transmission in mind. An attempt to find a main drive gearmotor with an output shaft geared to the same speed and torque requirement of the final crank made the process simpler because it was simpler to create this one-to-one reduction throughout. In other words, all spur gears in the gearbox were of identical size which gave the same rpm for the internal gearbox shafts as the gearmotor. The primary choice for the sprockets in the gearbox and out at the cranks were also all identical. Sizing these spur gears, the sprockets, and all shaft bearings for the system was then a simple task because similar torque and power was being transmitted throughout.

All drive shafts in the system were made of plain carbon steel rod at 1/2 inch in diameter which suited a standard size for the inner bore of all components. The crank arms were sized using the previously calculated maximum torque as the limiting bending moment. Assuming a rectangular cross section of stock 6061 aluminum, the theoretical maximum bending moment can be calculated (eq.12). This value for theoretical bending moment should be very oversized compared to the actual maximum transmitted torque to account for any twisting action or flexing occurring in the arm. A final modification to this calculation as previously mentioned was to make the entire crank assembly out of steel. An additional calculation was not necessary to perform since steel is stronger and stiffer and a larger cross section of steel was used than the calculation for aluminum.

To determine the maximum compression that the connecting rod would experience, the overall maximum robot acceleration must be taken and using Newton's Law and the mass of the robot, the horizontal force on the slider calculated (eq.13). At this point of maximum acceleration, at the angle of the connecting rod with the horizontal, the actual maximum force in the connecting rod was calculated with a factor of safety (eq.14). This force was compared to the theoretical critical load for column buckling assuming a 1/4 inch 6061 aluminum rod (eq.15). A major change that was undertaken in the construction was that the connecting rod had to be purposely bent to accommodate a difference in height between the crank arms and the slider blocks to which they connected. The aluminum rods used were also upgraded to thicker 3/8 inch diameter aluminum. Although the intentional bend in the rods promote premature buckling, having an increased diameter and sufficient testing have ensured that their strength was ample.

Manufacturing

The first step in manufacturing Prototerp IV was to construct a timeline outlining what would be built when. The timeline proposal is included in Appendix D. The timeline was relatively closely adhered to during the semester, but minor setbacks and changes were encountered along the way. The following is an account of the manufacturing processes and problems encountered resulting in deviations from the schedule.

Manufacturing processes utilized

The following operations were performed on each component:

Gearbox

L-Brackets: Cut to length with aluminum saw; reamed bearing holes; drilled and countersunk connecting holes; bolted together with additional plate. Mounted bearings and shafts with components.

Gearbox shafting: Cut to length with band saw; turned one down on lathe for encoder mounting. Cut keyways with broaching tool on milling machine; cut and sanded keys. Cut snap ring grooves with lathe.

Sprockets: Cut keys with broaching tool; mounted on shafts.

Gears: Mounted on shafts.

Motor: Bolted to channel; mounted with strap.

Encoder mount: Cut channel to length; drilled mounting holes; cut spacers; bolted channel to gearbox; mounted encoder to shaft with setscrews, to channel with machine screws, nuts.

Crank Mechanism

Crank shaft discs: Cut with band saw; sanded; drilled center hole; ground down on lathe after welding; drilled finetune holes.

Crank shafts: Cut to length; weld discs on; clean up weld on lathe; cut keyways with broaching tool on milling machine; cut and sanded keys; cut snap ring grooves; drilled; countersunk and tapped center hole. Mounted crankarm with machine screws; washer; and nuts.

Crank arms: Cut to size with band saw; sanded; drilled holes. Finetune holes drilled. Mounted connecting rods with bolt; washer; and rod-end bearing.

Connecting rods: Cut to length; threaded ends with die; mounted rod-end bearings; cut spacers from aluminum tubing on grinder; tapped leg sliders; bolted to leg sliders.

Component Mounts

Bottom plate: Cut with aluminum saw; reamed holes for crankshaft bearing, bigfoot shaft and motor mount; drilled mounting holes; mounted bearings and shafts. Milled holes under gearbox bearings, slots for gearbox, weight reduction holes. Mounted plate to chassis with machine screws and nuts.

Top plate: Reamed holes for bigfoot shaft and crankshaft bearings; drilled mounting holes. Milled holes for weight reduction. Mounted plate to chassis with machine screws and nuts.

Pulley and Cable System

Cable: Cut to length; attached to legs with cable clamps; cut holes in rod mounting plates for cables to run; ran cables around sheaves; tightened with turnbuckles.

Sheaves: Made spacers; drilled holes in chassis; mounted sheaves with machine screws and nuts; attached aluminum sheet metal with screws.

Deviations from the timeline and original design

Deviations from the timeline and design occurred for a few reasons. First, all of the necessary materials (rod-end bearings, bolts, washers, etc.) were not always available to complete the tasks. To subvert this, other tasks were started, or redesign was necessary. For example, the gearbox channel was originally designed as a C-channel. However, as this was not available, another design utilizing L-brackets was utilized. This turned out advantageously, since we were able to ream both top and bottom bearing holes at once by placing the brackets back to back.

Unexpected problems accounted for some slowdown. For example, the gearbox shaft for the optical encoder mount was turned down too far, resulting in a broken encoder.
Upon purchase of a new encoder, a new shaft was machined, but had to be built back up due to the extremely tight tolerance required by the encoder (less than 0.0005 " on diameter).

In addition, upon mounting the motor, it was found to flex away from the mounting plate. This was solved simply by attaching a small steel band around the motor to hold it in place.

Timeline deviations also occurred because precautions were taken. To insure that the crank mechanism would fit in with the chassis, it was decided to machine the connecting rods long, thread more than necessary, and wait until the leg sliders were manufactured. This turned out to be an intelligent decision, since the rods needed to be bent so the bearings would not be acting at an angle.

Similarly, the pulley placement design was intentionally not solidified until well into production, since other components' placements were unclear. When the other design was definite, the pulley placement was designed for minimum frictional losses.

Recommendations for Mars Exploration

In order for the driveline mechanism to function properly on the surface of Mars, certain design changes and additions are essential. The atmospheric and surface conditions on Mars were studied, and in conclusion temperature variations, dust storms, surface characteristics, and gravitational effects would have the greatest impact on the driveline performance.

On Mars, the lowest temperatures occur at the south pole during winter, where they fall as low as 150 K and the highest temperatures are at the southern midlatitudes in the summer, when midday temperatures reach as high as 300 K. Where the robot lands geographically makes a lot of difference as far as atmospheric conditions are concerned, therefore the worst situation is the best design criteria. Because of such large temperature variations, ductility/brittleness and expansion/contraction characteristics of the material (aluminum and steel in prototerp IV) used to build the driveline assemblies will be important. It is recommended to research further and test other suitable materials such as composites, ceramics, plastics, and other types of metals for use on the driveline mechanism.

The use of lubricants is also affected by temperature and the amount of outgassing. Since lubricating the chains and gears reduces a lot of friction, it can not be ignored. Ordinary grease, like the one used on prototerp IV can not be used on Mars because of complicated thermo-physical reasons beyond the scope of this paper. Instead, it is best to use a NASA approved and tested synthetic lubricant for aerospace applications called TRIBOLUBE 15. Coating all gears and driveline components such as the rolling ball bearings with a double layer of teflon will help in significantly reducing friction without the use of too much TRIBOLUBE 15 (costs approximately $600.0 per lb). See Appendix E for specifications of TRIBOLUBE 15.

According to data and observations collected in recent years, dust storms occur regularly on the surface of Mars. Most of these storms move with velocities of 14-35 m/s. These storms are caused by high velocity wind patterns picking up fine grains of sediment. Knowing this important fact, we would have to cover all bearings (including the ones on the pulleys) with a cap made of special rubber to stop the fine grains from getting in between the rolling balls, thus destroying their function. It would also be of benefit to cover and seal tight the entire midsection of the robot, including the two crank arms, their connecting rods, and the gearbox with a thin aerodynamic thermal barrier made from light material. This barrier would not only reduce turbulence caused by high velocity winds, but that it would also protect the power transmission plant from excessive dust and sand. Since the temperatures get extremely cold, addition of an electric resistance heater inside the mentioned barrier would help in maintaining the stability and performance of the motor. This heater shall utilize the existing robot main battery. As the crank arms rotate, the connecting rods translate along the sides of the robot, and the best way to cover them is through the use of a flexible canvas covered with a layer of special rubber (DANDUX,as supplied to NASA by CR Daniels INC.), similar to the conventional manual transmission shift boot installed on most cars.

The final concern for the driveline mechanism would be the gravitational effects. These effects all depend on the magnitude of the gravitational force, since the robot has to stay on the ground in order for it to walk. The gravity on Mars is relatively lower than that on earth, hence we might be able to reduce the factors of safety associated with the design of our components, keeping in mind the extra shocks and vibrations due to the take-off and landing of the mother spacecraft. This can be done, as mentioned before, by using alternate materials with stronger, yet lighter characteristics.

In conclusion, it is important to note that all original specifications are to be incorporated, unless otherwise indicated in this paper. To reiterate the basic specifications, the electric motor will have 1/20 HP operating on 12 volts with a 36.7 to 1 gear reduction transmission and all gears will be the same as now (i.e. attached to motors shaft, a 3" diameter, 72 tooth spur gear meshing in line with two identical spur gears, which are connected by a shaft and key to a chain sprocket).

Conclusions

The driveline of Prototerp IV was completed ahead of schedule, allowing the members of the group to help with other groups. There were no mechanical failures, and the drive mechanism ran smoothly. Upon powering up the robot, it was apparent that the drive motor was well sized, since the robot's weight was easily accelerated.

In retrospect, the driveline group learned a great deal about design work and project engineering. There are several guidelines which the group feels are important in future walking machine project work:

1) **Keep the design simple.** On any project with a specific deadline, complexity adds to the probability of error, and makes troubleshooting easier. Although our driveline design was relatively simple, there were still minor problems that were unaccounted for which slowed progress.

2) **Draw up a parts list early and order parts ahead of time.** Lack of components can slow down progress. Shipping time should also be accounted for.

3) **Know the complexity of machine shop processes before you design the robot to use them.** In this case, specialized tooling and expertise was necessary to machine some driveline components, and one process involved tighter tolerances than our machinery was capable of.

4) **Design for low weight from the outset.** The driveline group made modifications to parts along the way to reduce weight. This possibly could have been averted slightly if the original design was more weight-conscious.

Overall, the driveline group project was a success. Hopefully the work done by this year's group can be used to help advance the field of robotics, and help future University of Maryland students design and construct successful walking robots.

Appendix A
Figures

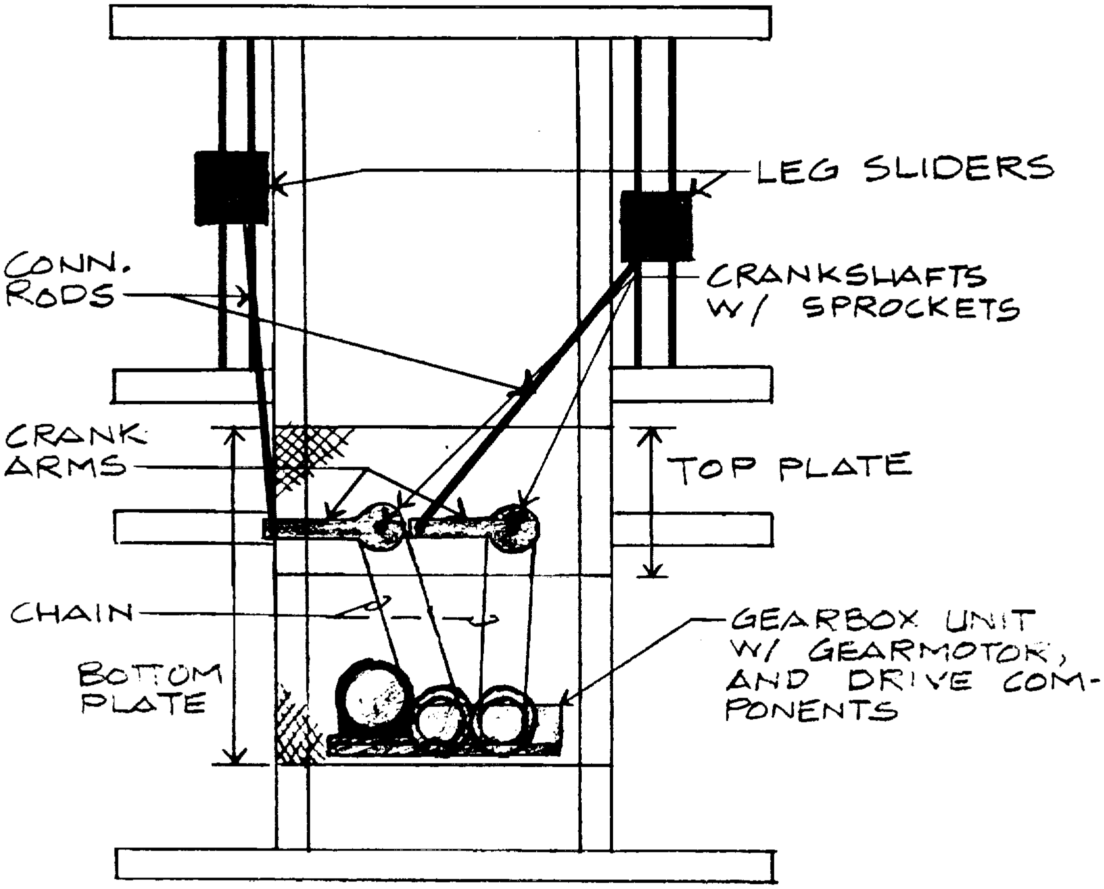


FIG. 1
LOCATION OF DRIVE COMPONENTS ON CHASSIS

-NOTE - GEARBOX WILL BE MOUNTED TO BOTTOM PLATE OF ROBOT IN SLOTTED HOLES.

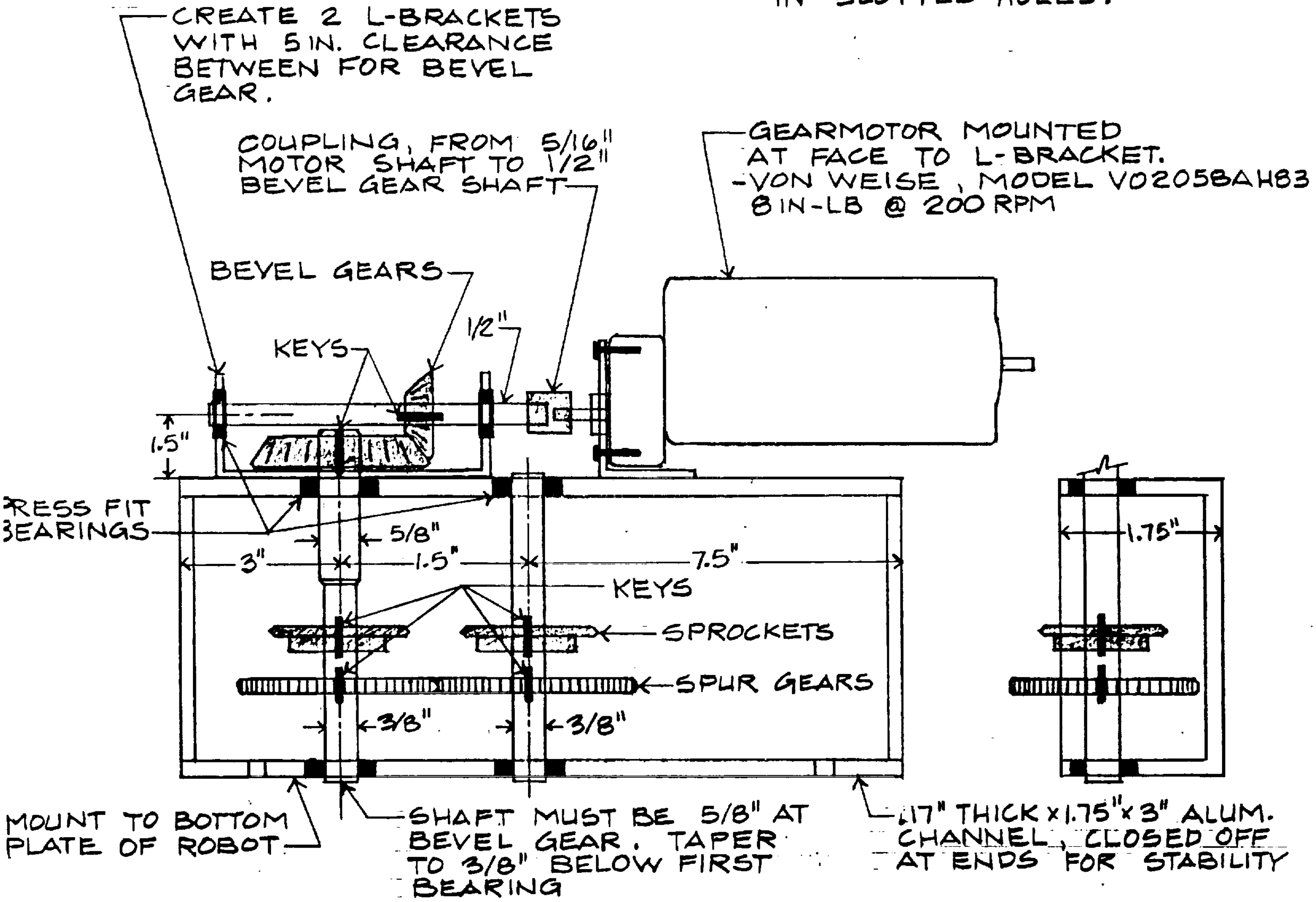
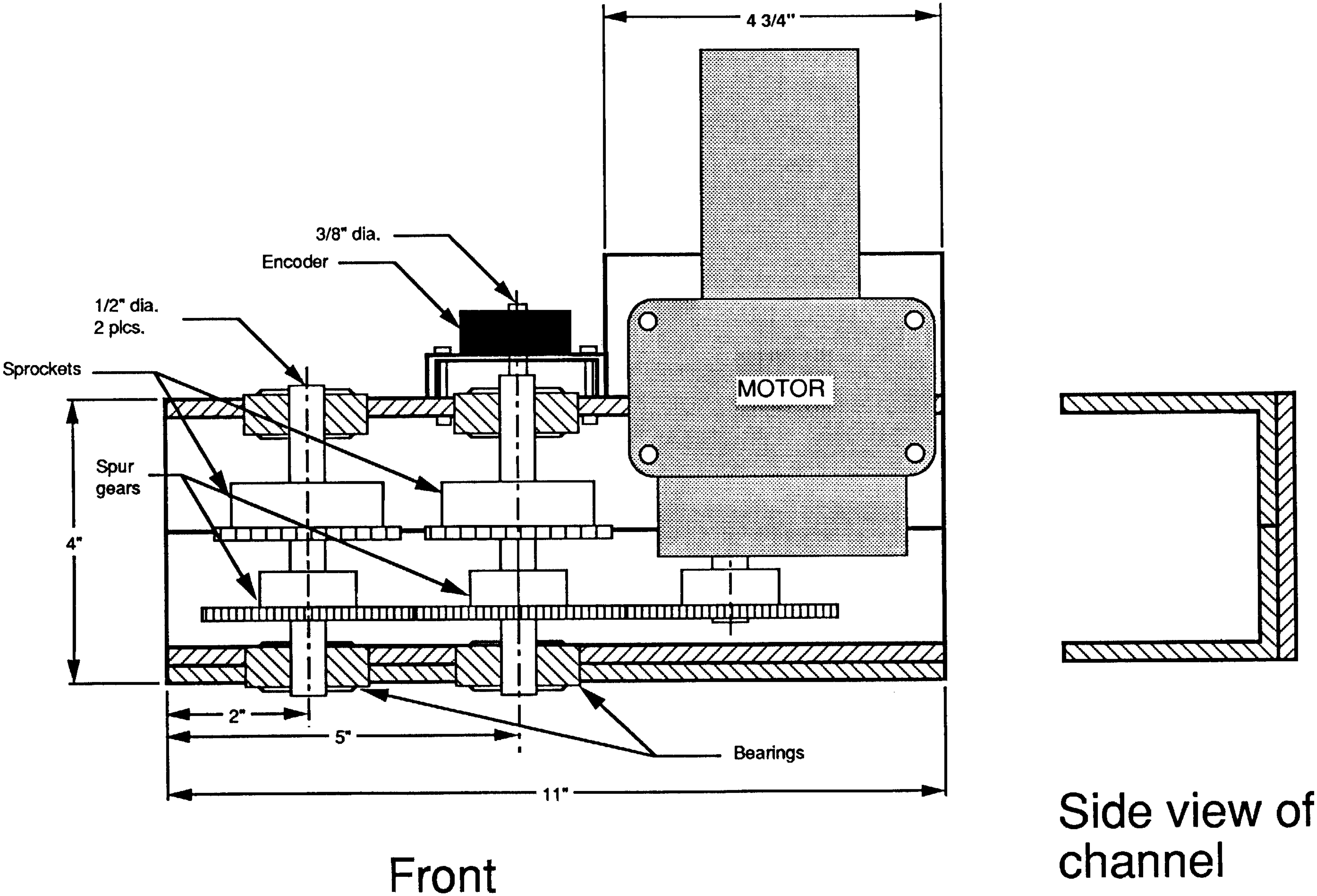


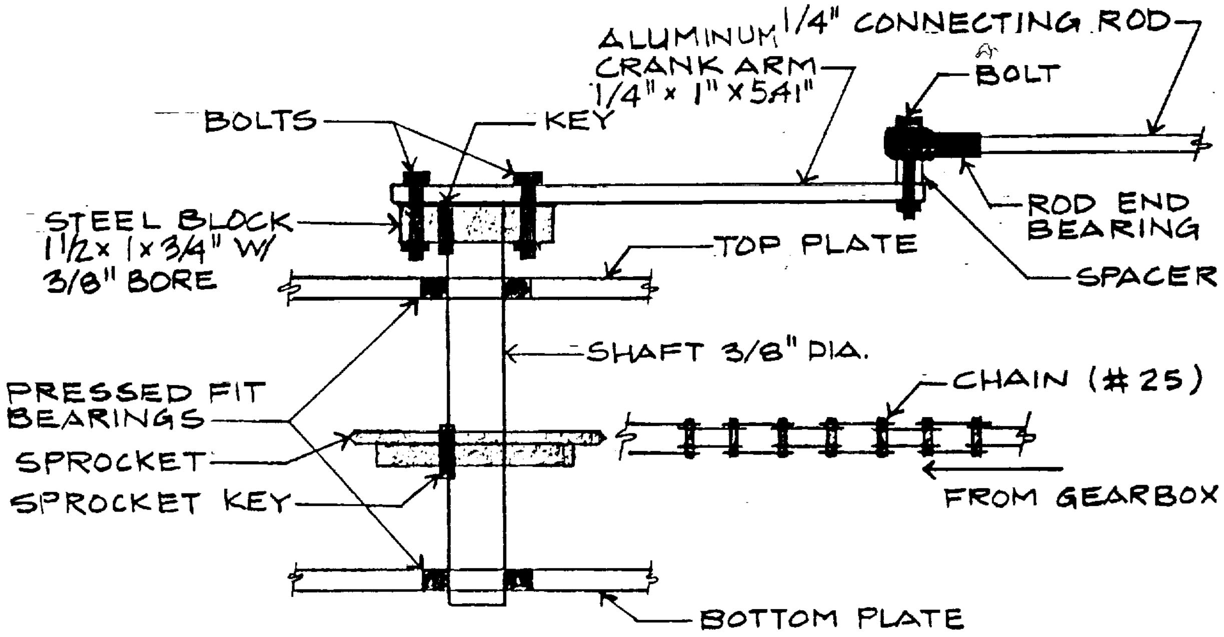
FIG. 2 - GEARBOX ASSEMBLY (FACE AND SIDE VIEW)
NO SCALE



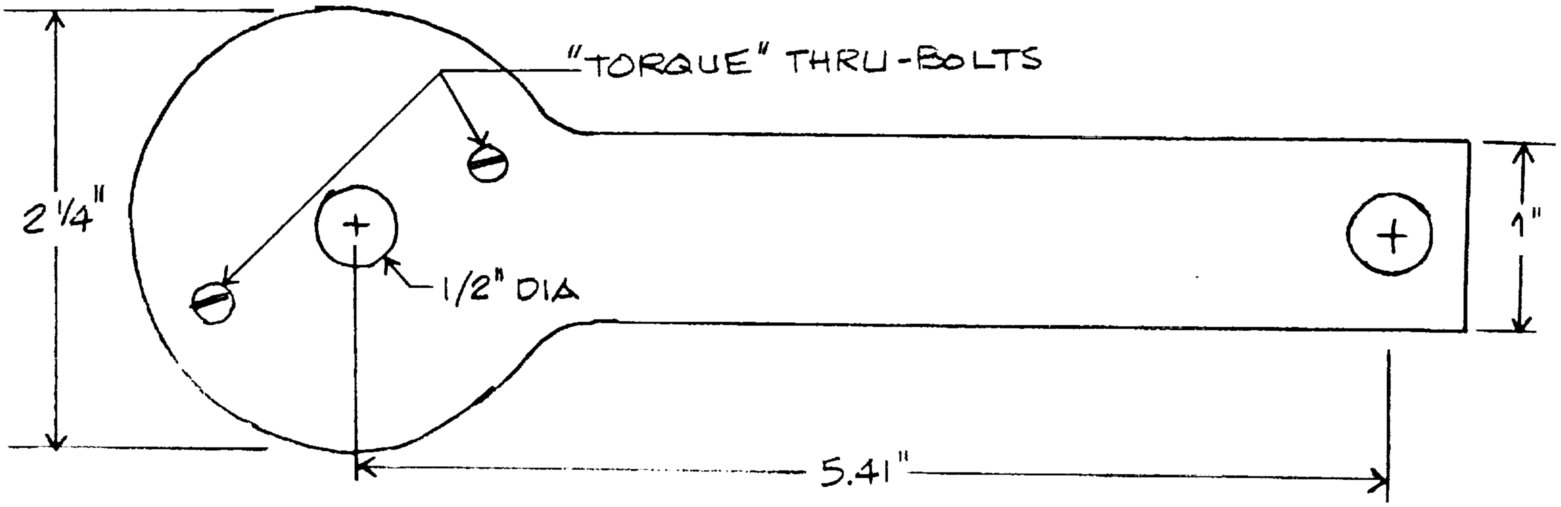
Front

Side view of channel

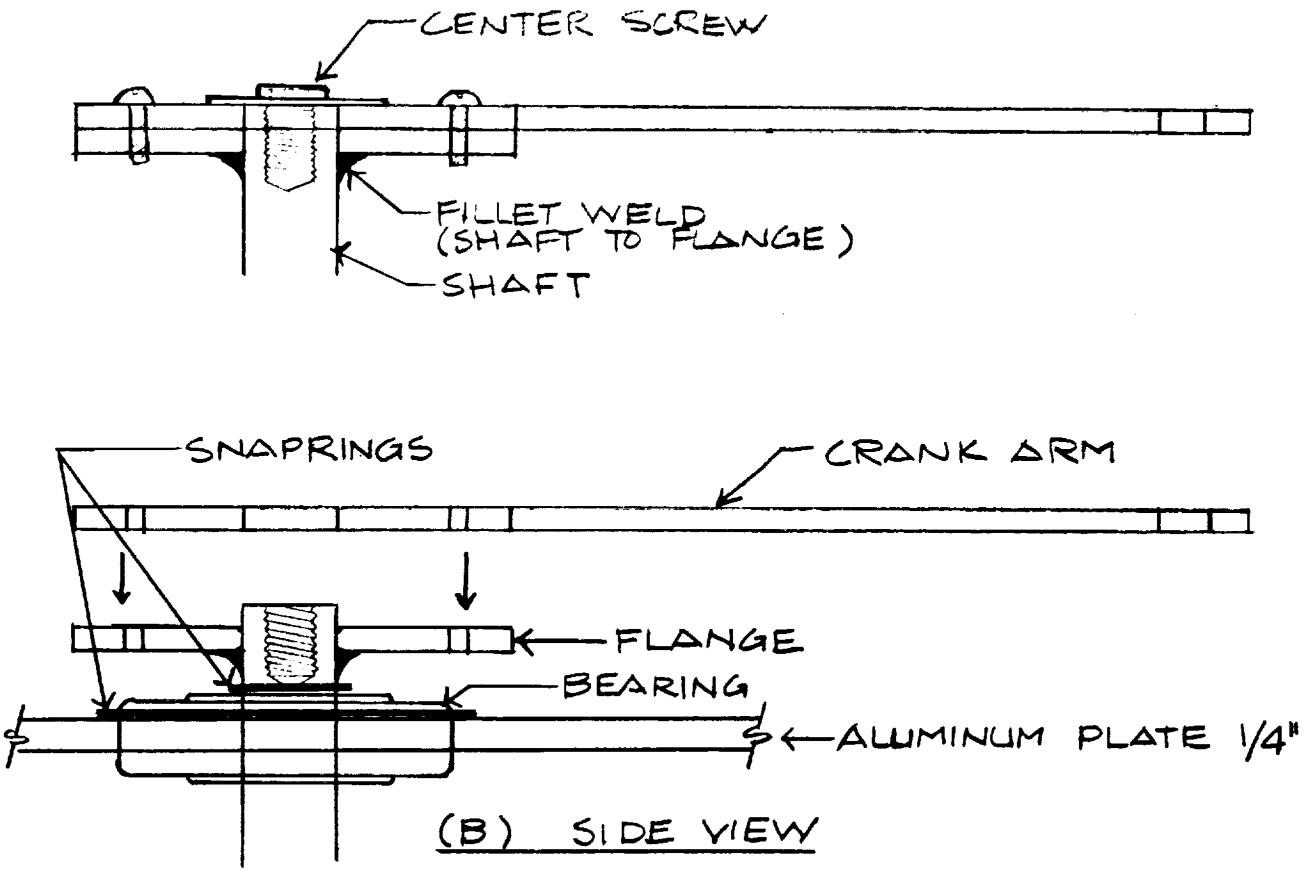
Fig. 3- Gearbox Assembly (Modified)



<u>FIG. 4 - DRIVETRAIN DIAGRAM (CRANK END)</u>

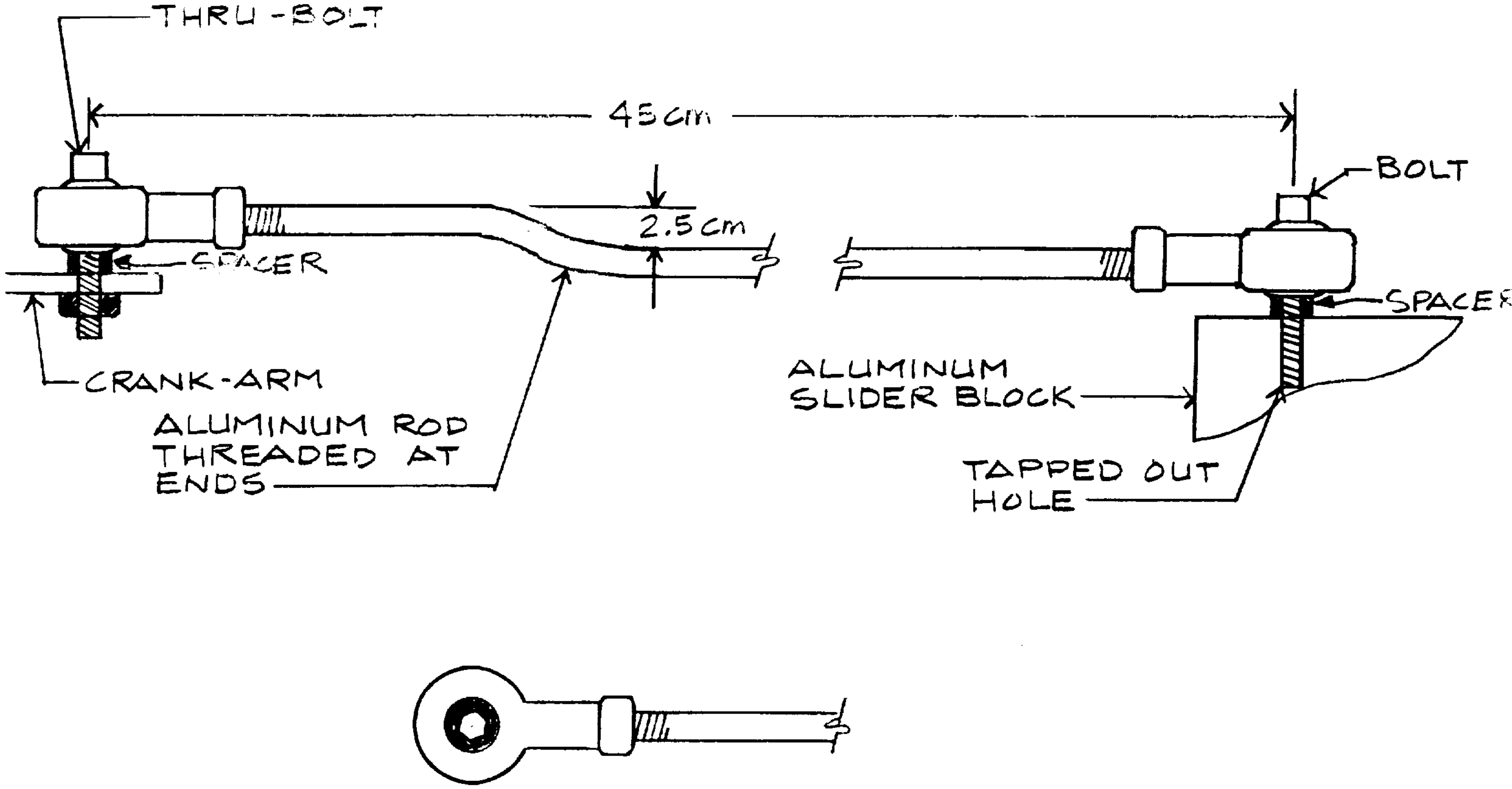


(A) TOP VIEW



(B) SIDE VIEW

FIG. 5 - CRANK ASSEMBLY (STEEL)



TOP VIEW - ROD END BEARING

FIG 6 - CONNECTING RODS

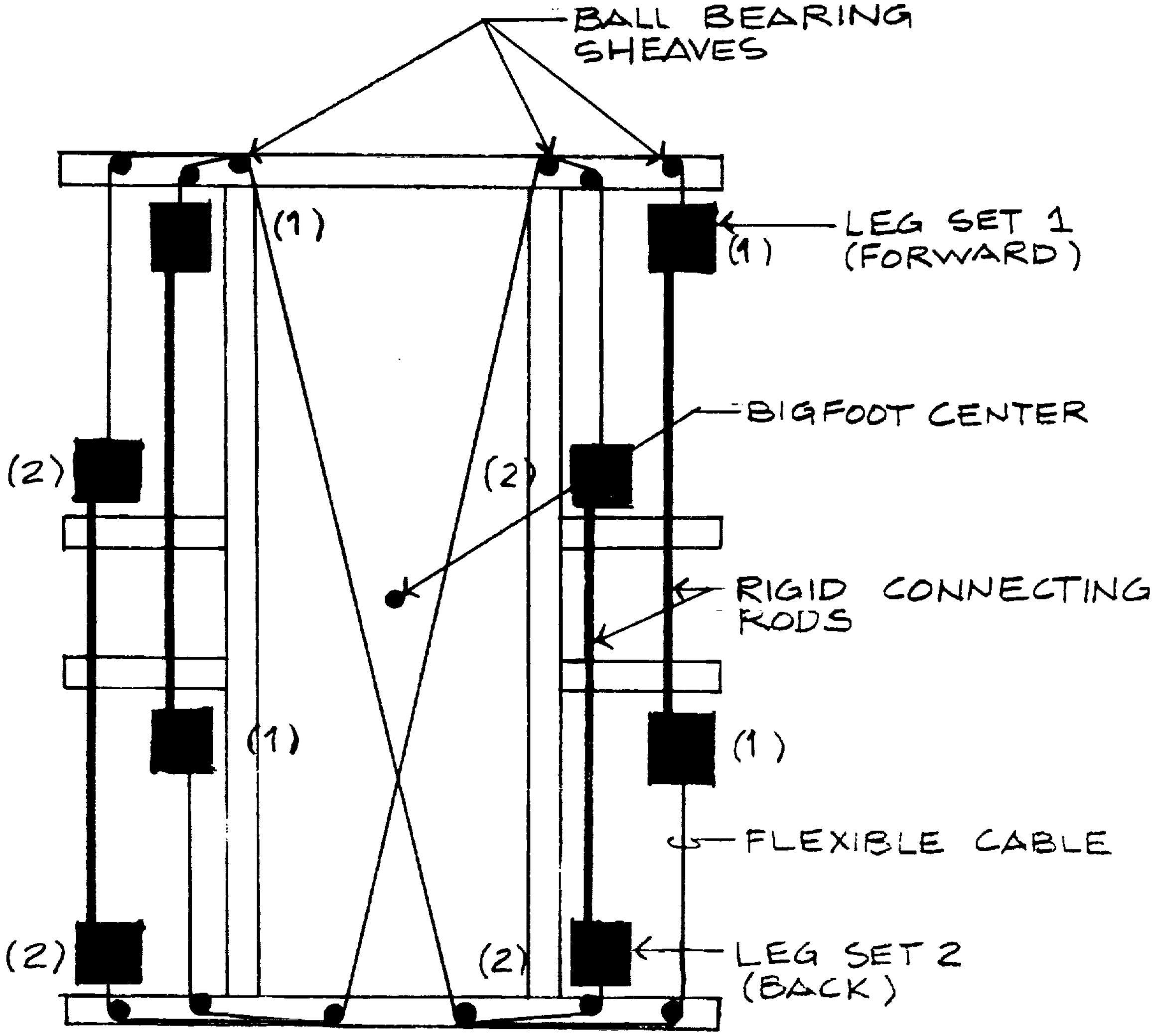


FIG. 7 - CABLE ROUTING

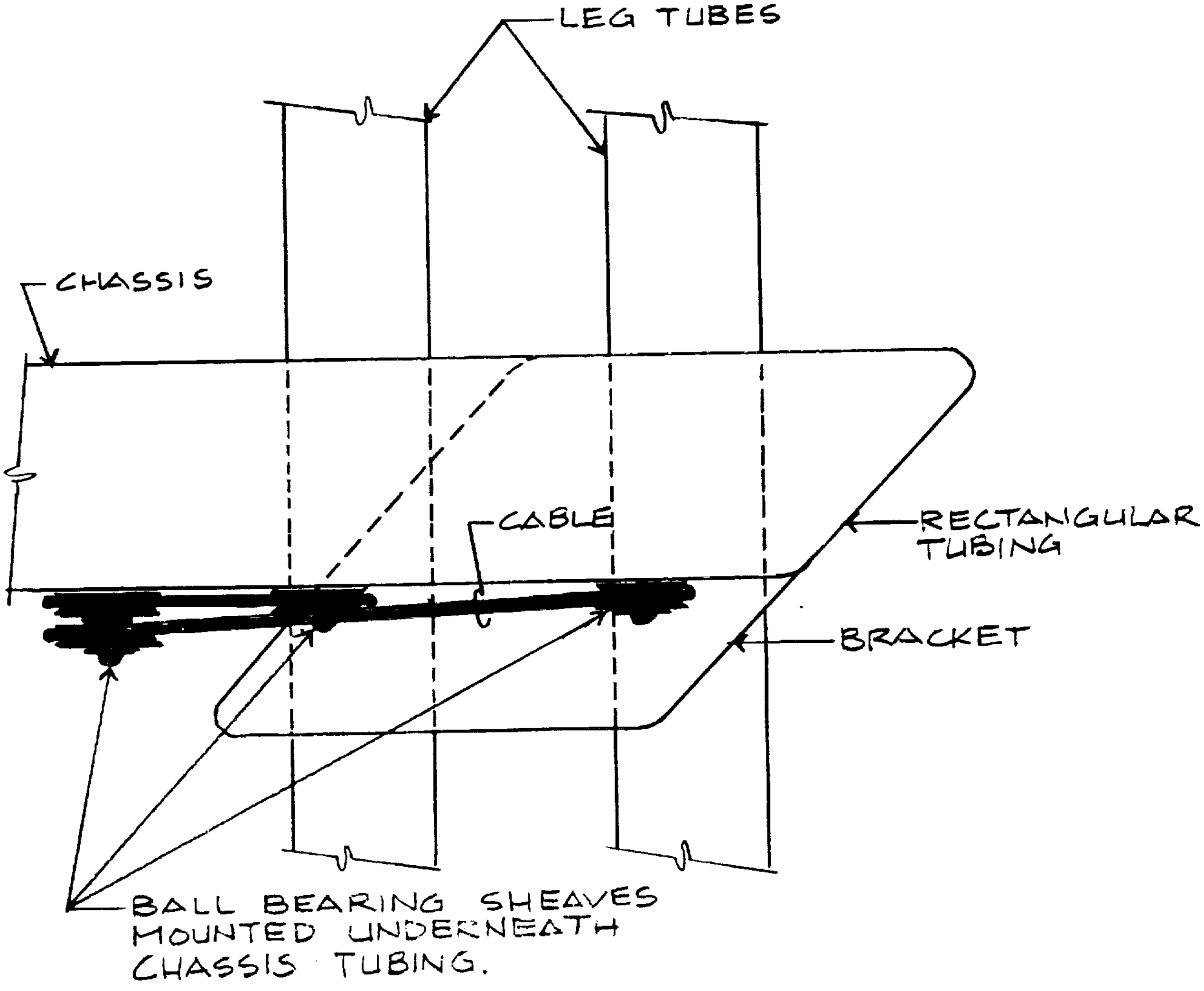


FIG. 8 - BALL BEARING SHEAVE MOUNTING (FRONT VIEW)

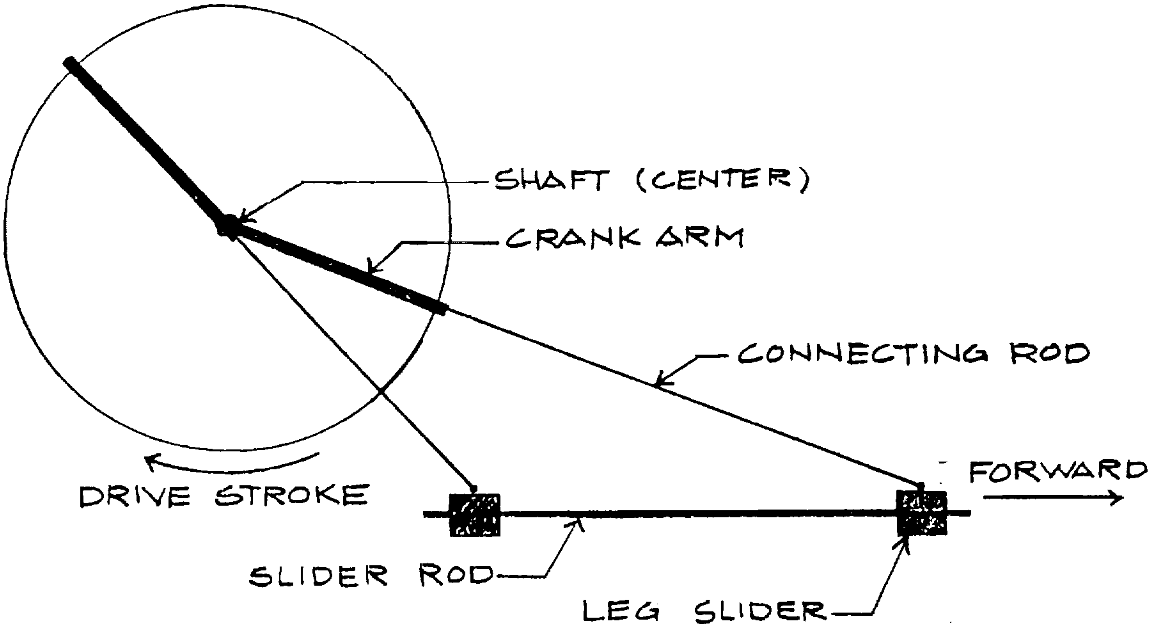


FIG. 9 A - CRANK-SLIDER

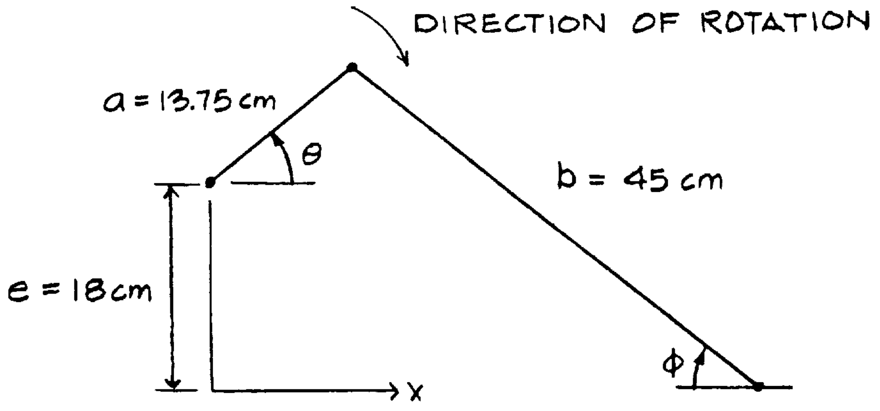


FIG. 9 B - CRANK-SLIDER

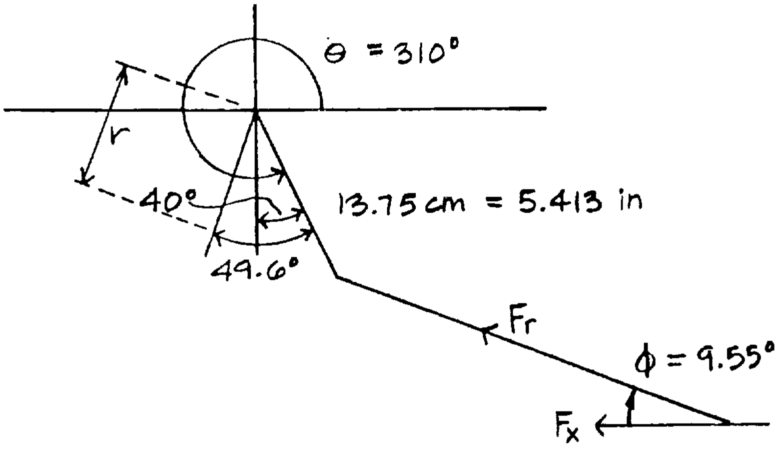


FIG. 9 C - CRANK- SLIDER

APPENDIX B. - CALCULATIONS

$$X = a\cos\theta + b\cos\phi \text{ , WHERE } \underline{a = 13.75\text{ cm}} \rightarrow (eq.1)$$
$$\underline{b = 45\text{ cm}}$$

$$\dot{X} = -\dot{\theta}a(\sin\theta + \cos\theta\tan\phi) \longrightarrow (eq.2)$$

$$\ddot{X} = -\dot{\theta}a(\dot{\theta}\cos\theta + \dot{\phi}\sec^2\phi\cos\theta - \dot{\theta}\tan\phi\sin\theta) \rightarrow (eq.3)$$

$$\phi = \sin^{-1}((a\sin\theta + e)/b) \longrightarrow (eq.4)$$

$$\dot{\phi} = (a\dot{\theta}/b)(\cos\theta/\cos\phi) \longrightarrow (eq.5)$$

$$\underline{\theta = 310^\circ} \text{ , } \underline{\phi = 9.55^\circ} \text{ , } \underline{\ddot{X} = 122.59\ {}^{cm}/_{sec^2}} \rightarrow (eq.6)$$
$$= \underline{4.0219\ {}^{ft}/_{sec^2}}$$

$$F = ma/g_c = (100)(4.0219)/32.2 = \underline{12.49\text{ lbf}} \longrightarrow (eq.7)$$

$$F = 12.49/\cos(9.55) = \underline{12.67\text{ lbf}} \longrightarrow (eq.8)$$

$$\underline{r = 3.512}$$
$$T = F \times r = 12.67 \times 3.512 = \underline{44.48\text{ in-lbf}} \rightarrow (eq.9)$$

$$T(new) = T(F.S.) = 44.48(3) = \underline{133.45\text{ in-lbf}}\ (eq.10)$$

$$POWER = (RPM) \times T/63025 = (30)(133.45)/63025$$
$$= \boxed{.064\text{ hp}} \longrightarrow (eq.11)$$

CALCULATIONS (CONT.)

$M = S_{yield}\, I / c$, $S_{yield} = 35{,}000$ psi (6061) $\rightarrow$ (eq. 12)

$M = (35000)(.008789) / .375 = \underline{820 \text{ in-lbf}}$

WHERE $I = .008789 \text{ in}^4$ FOR 1/4 x 3/4" SECTION

$c = h/2 = .75/2 = .375 \text{ in}$

$\underline{\ddot{X} = 122.59 \text{ cm/sec}^2} = \underline{4.022 \text{ ft/sec}^2}$

$F = 4.02(100)/32.2 = \underline{12.49 \text{ lbf}} \longrightarrow$ (eq. 13)

$\underline{\phi = 17.84^\circ}$

$F = 12.49 / \cos(17.84) = \underline{13.12 \text{ lbf}}$

$F(\text{new}) = F\,(\text{F.S.}) = 13.12\,(3) = \underline{39.36 \text{ lbf}} \longrightarrow$ (eq. 14)

$P_{cr} = (A \cdot C\,(\pi)^2 \cdot E) / (l/k)$, $\underline{A = .0491 \text{ in}^2}$, $\underline{C = 1} \rightarrow$ (eq. 15)

FOR 1/4" ROD, ROUNDED ENDS

$E = 10 \times 10^6$ psi , $\underline{(l/k) = 283.2}$

SLENDERNESS RATIO

$P_{cr} = (.0491)(1)(3.14)(10 \times 10^6) / (283.2) = \underline{60.422 \text{ lbf}}$

Appendix C
Prototerp IV
Driveline Group Parts List

Company: McMaster-Carr Supply Co.
Address: P.O. Box 440 New Brunswick, N.J. 08903-0440

Qty.	Description	Part #	Cost each	Cost
4	Mini Cable Turnbuckles	3435T12	$7.82	$31.28
16	U-Bolt Wire Rope Clamps	8913T11	$10.87	$173.92
16	Steel Sheaves w/ Bearing	3434T22	$3.98	$63.68
50	7*19 Coated Cable , .63", Stainless	8930T32	$1.09	$54.50
		Subtotal		**$323.38**

Company: Bison Gear Co.
Address: 2424 Wisconsin Ave. Donners Grove, Ill 60517

Qty.	Description	Part#	Cost each	Cost
1	Gearmotor	Model 100	$0.00	$0.00
		Subtotal		**$0.00**

Company: U. of Md. Physics Shop
Address: College Pk., Md. 20740

Qty.	Description	Part#	Cost each	Cost
	Misc. Stock Materials			$50.00
		Subtotal		**$50.00**

Prototerp IV
Driveline Group Parts List

Company: American Bearing
10 Taft Ct. Rockville, Md. 20850

Qty.	Description	Part#	Cost each	Cost
4	Rod End Bearings	Sphereco TR6	$9.41	$37.64
3	Spur Gears	H2472	$19.63	$58.89
8	Bearings	7508DLG TN	$12.98	$103.84
4	Sprockets	35B22-1/2	$12.68	$50.72
2	Sprockets	35BS11-1/2	$6.60	$13.20
1	#35 Chain, 1 10 ft length	35 RIV	$36.20	$36.20
		Subtotal		**$300.49**
		Total Cost		**$673.87**

APPENDIX D

ENME 408

PROTOTERP IV WALKING ROBOT

DRIVELINE TEAM

TIMELINE PROPOSAL

Phase	Approximate due date
I. Machine connecting rod Machine crank arm Connect crank arm to connecting rod Experiment with machine shop processes	Feb. 2 (1 week)
II. Make gearbox housing, attach bearings Attach gears to shafts, shafts to housing	Feb. 16 (2 weeks)
III. Attach gearbox to chassis	Feb. 23 (1 week)
IV. Connect connecting rod assembly to crank shaft and legs Help perform testing of legs	Mar. 9 (2 weeks)
V. Mount pulleys to chassis	Mar. 16 (1 week)
VI. Attach cables	Mar. 22

Notes:

Several phases depend on other groups. The following should be checked or noted:

1. Will the chassis group be ready by Feb. 23 to have the gearbox attached?
2. Will the first leg be complete by Mar. 9?
3. The cables are to be attached to the legs as they are finished.

G. Young
1/23/90

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama
35812

NASA

APPENDIX E - TRIBOLUBE 15

ly to Attn of: EH02 (88-0500) April 29, 1988

TO: [redacted]

FROM: EH02/Mr. F. Key

SUBJECT: Thermal Vacuum Stability Test of Tribolube 17C Lubricant

The Tribolube 17C lubricant submitted by Howard Gibson of EH14 has been tested for TVS/VCM by the procedures outlined in SP-R-0022A.

Test conditions were as follows:

Material:	Tribolube 17C
Pressure:	5×10^{-8} torr
Sample Thickness:	Not determined - See Test Report
Temperature:	125°C
TML:	.18
VCM:	.00
Test Number:	WSTF #87-21710

The above material did meet the acceptance criteria outlined in SP-R-0022A.

C.F. Key
Assistant Director
Materials & Processes Laboratory

cc:
EH01/Mr. Schwinghamer
BAMSI/K. Baker
EH02/Mr. S.E. Davis

TRIBOLUBE™-15

TRIBOLUBE™-15 is a wide temperature range grease for use in extreme environments. It is especially suited for use in systems where nonreactivity with harsh chemicals, strong acids and oxidizers, fuels, solvents, etc. is mandatory, and in vacuum systems where pressures may be as low as 10^{-12} Torr. The grease is suitable for lubricating ball, plain spherical, roller and needle large and small diameter size bearings. It is also suitable for use in electrical contacts, gears, splines, valves, screw actuators and in systems employing elastomeric and plastic seals, gaskets and O-rings. Although TRIBOLUBE™-15 is very inert, newly exposed rubbing surfaces of aluminum and magnesium may react with the grease under certain extreme conditions. TRIBOLUBE™-15 meets the qualification requirements of Military Specification MIL-G-27617D, Type 4.

PERFORMANCE TEST	TEST METHOD	CONDITION	TYPICAL VALUES
Temperature Range			– 100°F to 450°F
NLGI No.			2
Unworked Penetration	ASTM D-1403	77°F	287
Worked Penetration	ASTM D-1403	60 Strokes	275
Evaporation	ASTM D-2595	30 hrs @ 400°F	0.08%
Oil Separation	FED-STD-791 Method 321	30 hrs @ 400°F	11.35%
Low Temperature Torque	ASTM D-1478	@ – 65°F,	
		Starting	910 g-cm
		Running	390 g-cm
		@ – 100°F,	
		Starting	3185 g-cm
		Running	975 g-cm
Four-Ball Wear Test	ASTM D-2266	1200 rpm, 52100 steel 40 kg, 167°F, 2 Hrs	0.90 mm
		1200 rpm, 52100 steel 40 kg, 400°F, 2 Hrs	1.33 mm
Load Wear Index	ASTM D-2596		152.25
Last Non-Seizure		Load/Wear Scar	40 kg/0.40 mm
Last Seizure		Load/Wear Scar	800 kg/1.52 mm
Weld Point		Load	1,000 kg +
Copper Corrosion	ASTM D-130	24 hrs @ 212°F	1 b
Vapor Pressure	Knudsen	68°F	10^{-12} Torr
High Temperature Performance	ASTM D-3336	10,000 rpm, 5 lbs, 400°F	1800 hrs +
		10,000 rpm, 5 lbs, 450°F	500 hrs +
LOX Impact Sensitivity	ASTM D-2512	20 Impacts from 43.3 inches	No Reactions
Film Stability and Corrosion	FED-STD-791 Method 5414	168 hrs @ 212°F	No Corrosion
Dropping Point	ASTM D-2265		438°F
Vacuum Thermal Stability	NASA SP-R-0022A	24 hrs @ 6×10^{-6} Torr	
Weight Loss			0.07%
Volatile Condensables			0.00%
Water Vapor Recovery			0.01%

TRIBOLUBE™-14A

TRIBOLUBE™-14A is especially useful in low pressure vacuum systems and other systems where nonreactivity with chemicals, strong acids and oxidizers, fuels, solvents, etc. is mandatory. The grease is suitable for use over a very wide operating temperature range of −140°F to 450°F in applications including ball, roller, needle and plain spherical large and small diameter size bearings, electrical contacts, gears, splines, valves, screw actuators and in systems employing elastomeric and plastic seals, gaskets and O-rings. Although TRIBOLUBE™-14A is very inert, newly exposed rubbing surfaces of aluminum and magnesium may react with the grease under certain extreme conditions.

PERFORMANCE TEST	TEST METHOD	CONDITION	TYPICAL VALUES
Temperature Range			−140°F to 450°F
NLGI No.			1
Unworked Penetration	ASTM D-1403	77°F	320
Worked Penetration	ASTM D-1403	60 Strokes	333
Evaporation	ASTM D-972	22 hrs @ 300°F	3.74%
		22 hrs @ 325°F	4.92%
		22 hrs @ 350°F	6.39%
		22 hrs @ 400°F	11.10%
		22 hrs @ 450°F	17.52%
Low Temperature Torque	ASTM D-1478	@ −65°F,	
		Starting	293 g-cm
		Running	65 g-cm
		@ −100°F,	
		Starting	358 g-cm
		Running	98 g-cm
		@ −125°F	
		Starting	1528 g-cm
		Running	878 g-cm
		@ −140°F,	
		Starting	5850 g-cm
		Running	2015 g-cm
		@ −150°F,	
		Starting	Frozen
Copper Strip Corrosion	FED-STD-791 Method 5309	24 hrs at 212°F	1 b
			lt. bwn stn
			No discoloration in sample
Liquid Oxygen Impact Sensitivity Test	ASTM D-2512	20 Impacts from 43.3 inches	No Reactions
Load Wear Index	ASTM D-2596		170.29
Last Non-seizure		Load/Wear	80 kg/0.527 mm
Last Seizure		Load/Wear	600 kg/1.711 mm
Weld Point		Load	800 kg
Steel-on-Steel Wear	ASTM D-2266	1200 rpm, 167°F, 52100 steel, 40 kg,	
		2 Hrs	0.69 mm

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Thomas A. Mutch, Raymond E. Arvidson, James W. Head.III, Kenneth L. Jones, R. Stephen Saunders, *The Geology of Mars.* 1975, Princeton University Press

Shigley, Joseph Edward & Mischke, Charles R., *Mechanical Engineering Design /5th Edition.* Equations on Column Buckling, pp. 120-125.

Acknowledgements

We would like to thank John Burke of Bison Gear Co. for his contribution of the main drive motor.

We would also like to express thanks to our advisors, Dr. Azarm, Dr. Tsai, and Mark Uebel for their contributions, which are too numerous to begin to list here.

APPENDIX C:

LEGS

WALKING ROBOT ENME 408

Leg Group - Final Report

Bob Olson
Mani Oliva
Jim Bielec
David Hartsig
Bob Rose

May 7, 1990

Introduction

The events in this year's walking robot competition required the leg assembly to be capable of variable stride, climbing /descending stairs, turning, and autonomous activities. The Prototerp IV's leg assembly was designed and constructed to be lightweight, strong, and achieve uniform motion to minimize the loss of momentum. Due to the requirements of the competition, several specifications had to be met. First, a vertical displacement of 16 inches was required so that the robot could easily climb and descend the stairs. Second, a 3 inch per second vertical displacement with a 10 inch horizontal displacement was necessary so that the robot could obtain a maximum walking velocity and still manage to walk between the reflective stripes positioned on the floor surface. A slower rate of vertical displacement would result in a leg not clearing the ground during a stride. Finally, the leg assembly had to satisfy conditions so that material failures were minimized without over designing the robot to the point where performance was sacrificed. Each leg had to be designed to withstand potential loads of 50 pounds, as well as bending and shear stresses resulting from the vertical and horizontal acceleration/deceleration of the robot.

The University of Maryland has experimented with other leg assembly designs in previous years. A "grasshopper" type leg proved to be very successful for walking in stride but had difficulties in climbing the stairs. These legs forced the robot chassis to tilt backwards when climbing the stairs. As a result, the center of mass of the entire robot assembly was shifted and the robot would fall backwards. In addition, the walking characteristics of these legs produce nonuniform motion and result in large losses of momentum. Another leg assembly used by the University was a telescoping leg similar to this year's design. These legs experienced slow strides and did not have adequate vertical displacement to climb the stairs.

A telescoping leg assembly with a motor for each leg was chosen this year as a result of the school's prior experience in this competition. This design allows the legs to obtain greater vertical displacement for climbing the stairs. In addition to the leg assembly, an eight legged robot was chosen so that the robot will always have 4 legs on the ground. In addition to the stability that having 4 legs on the ground while climbing the stairs produces, the robot experiences a smoother and more stable stride at all times. The choice of this year's legs also allow the robot to be adapted to uneven terrain since each leg can be controlled to be at a different displacement.

Prototerp IV's leg assembly has been designed around the premise that the machine will always be resting on four of its eight legs while walking. This approach to the walking problem provides excellent stability during all phases of maneuvering. During a typical walk maneuver, the first set of the machine's four legs are supporting all of the weight while the second set of four legs is transitioning to the next position. Once this position is reached , the second set of legs support the machine while the first set then moves to the next position. Since all eight legs are coupled together and are horizontally translated by one motor, the horizontal motion of the machine is continuous. The transitioning set of legs remain above the supporting set of legs due to the vertical telescoping design of the legs. This vertical telescoping motion is adjusted by a single motor that is attached to the top of each leg. The vertical and horizontal drive mechanisms achieve the lift and translate motion that enable the machine to walk. The following description contains the basic sequence that constitutes a step. The typical walk cycle has the machine initially supported by one set of legs. The other set is moving horizontally at a level of about three inches above the floor. When the machine reaches its desired horizontal position, the transitioning legs are lowered and the supporting legs are then raised and begin to transition to the next desired horizontal position.

Vertical translations of the legs are made possible by a telescoping design that incorporates the lower, keyed part of the leg to be driven either into or out of the upper, slotted part of the leg. A motor fixed to the top of the leg rotates a ball screw through a worm/worm gear gear box. The ball screw supported by bearings drives a ball nut vertically along the screw. This ball nut is fixed to the lower portion of the leg, the inner tubing, which is keyed to fit into the slotted upper portion of the leg. The key, a delrin strip fixed to the lower part of the leg, and slot, the linear bearing of the upper leg, allow for the ball nut to remain fixed with respect to the ball screw, thus driving the lower part of the leg in a telescoping fashion.

Figure 1, showing the exploded diagram of the entire assembly, illustrates the mechanisms that are involved in the above process. At the top, the motor operating at 12 V drives the worm. An aluminum couple joins the motor shaft to the worm shaft. The other end of the worm shaft is supported by a bearing that is mounted on the inside of the aluminum gear box. The gear box is screwed to the top of the bearing housing. The worm drives the worm gear that is fixed to the ball screw which is supported by two bearings that are contained in the aluminum bearing housing. This bearing housing is screwed inside the top of the outer tubing. The smaller inner tubing of the lower leg holds a linear bearing which forms a slot in which the delrin key of the lower leg slides. This key/slot of the upper and lower parts of the leg prevents rotation with respect to the upper and lower parts of the leg as the ball screw rotates. This allows the ball screw attached to the lower leg to move vertically as the ball screw rotates. The ball screw is attached to the lower part of the leg via an aluminum couple. And finally at the bottom of the lower leg is the foot which holds the various sensors.

Design

Unchanged designs

At the beginning of the semester, we started working on the robot from the designs arrived at during the previous semester (fall '89) in ENME 488. These designs contained details to construct all of the components for the legs. The design process continued with the implementation of the prototype, where designs had to be changed for various reasons. Details were seen when the parts were being made that were sometimes overlooked in the preliminary design phase. Also, the previous class designed with little or no knowledge of machining and manufacturing. Our group soon learned its capabilities and limitations in manufacturing which led to many design changes.

Even though it was necessary to redesign many components, a few parts remained unchanged from the specifications arrived at last semester. This section will briefly present these components with the details centering around the manufacturing and implementation of these parts. For a more detailed explanation of the design and engineering aspects, please refer to the final design report of ENME 488.

Ball Screw:

The ball screws were received as raw stock and cut to lengths of 24 inches. Because the ball screws were donated some machining was required to the ends of the screws. This allowed us to custom machine the ends to fit the bearings we chose for our application, but required difficult machining. The main problem in machining the screws was the hardness of the steel. We learned that the screws were heat treated to a Rockwell hardness of approximately 60 to 65. Several options became apparent after asking a few professional machinists their opinion of the best way to turn down the ends of the screws. These options were to anneal the ends of the ball screws, to grind the ends, or to machine using a carbide tip bit. The decision was made to anneal the screws by heating the end with an acetylene torch until red hot and then placing them in sand to cool slowly. This is what the manufacturer recommends in the ball screw catalog, and it proved to soften the steel sufficiently to machine. The ends were then turned down to a diameter of 3/8" and then were filed and sanded to precisely fit the bearings. This filing and sanding was necessary because the lathe cut a slight taper along the length of the end.

Tubes and Linear Bearings:

The aluminum tubing used for the inner and outer columns of the legs serve as the vertical support structure of the leg and house the ball screw. These tubes were sized to standard tube dimensions that were strong enough to support the weight of the machine and would fit around the outside and inside of the linear bearing for the outer and inner columns, respectively. The linear bearing proved to fit tightly inside the outer column and required only one small set screw placed through the tube into the groove around the circumference of the bearing. The set screw also tightens the bearing around the inner tube. Care should be taken to prevent over-tightening which would result in binding.

Ball Nut / Inner Column Adapter:

The purpose of this adapter is to connect the ball nut to the inner column since their dimensions are not compatible. One end of the adapter has an inner diameter to match the diameter of the threads on the ball nut. Three set screws placed through the adapter against the threads proved to give sufficient strength and stability since the only stresses seen by these screws is due to the weight of the inner column. The other end of the adapter has an outer diameter which matches the inner diameter of the inner column. Three screws were also used, and were placed through the tube and threaded into the adapter.

Motor:

The motor chosen last semester was the Pittman 9412 19v, with a rated torque of 2.55 oz-in with a built-in Hewlett-Packard 256-Line zipper encoder. We were not certain at the start of manufacturing if this torque would be enough to supply the 1.77lb-in torque required of the ball screw after gear reduction. The first goal of our group was to test this motor to see if the power was adequate before placing an order for the motor/encoder packages. A primitive test apparatus was constructed using the same ball screw and gearing design for use in the leg. The test proved successful and the motors were ordered. Later tests using real leg assemblies were also successful, although slow performance at 12 volts forced us to increase the voltage to 18v. This gave enough power and speed for the vertical motion of the machine.

Redesigns

When the manufacturing of parts started, many problems arose due to machining limitations and design flaws. It soon became apparent that the design from last semester, which was thought to be sound, was in fact far from that. From our experiences, we learned that a design is definitely not finished until a prototype has been completed.

During the building of the legs for Prototerp IV, a process of redesigning occurred. These redesigns were a result of the problems stated above and of insights gained as machining skills improved. This redesign-while-manufacturing process was applied to all of the leg components discussed in this section. Details here also center around the manufacturing and implementation of the components. For a more detailed explanation of the engineering aspects, one should consult the final design report submitted for ENME 488.

Motor Mount / Shaft Couple / Bearing Support:

The purpose of this component is to support the motor and worm, which in turn, transfers power to the ball screw assemblies. One of the main problems was the difference in shaft size between the motor and the worm. It was necessary to step up from the motor shaft size of 5/32" to the worm shaft size of 1/4". For this, a coupling was made from 1/2" round aluminum stock which was drilled to the precise size of the shafts and tapped for set screws. The shafts for the worms were made from 1/4" round stainless steel stock, cut to size, and flat-spotted to accept the set screw. Another problem that surfaced was that the worm had a tendency to push out of mesh with the worm gear if not supported at the other end. For this a 1/4" bore flanged bearing was chosen, and held in place by an E-ring on the shaft. To support both the motor and the bearing, a 2x3 inch section of aluminum box channel was found to be the proper size. This whole assembly (shown in Figure 2) was then bolted to the top of the ball screw assembly while making sure the worm and worm gear were aligned.

Ball Screw Mount / Bearing Housing:

The purpose of this assembly was to support one end of the ball screw, which is being rotated via a worm gear. The first major redesign of this assembly became apparent when the test assembly for the motor was made. The bearings chosen proved to be too sloppy so a precision sealed bearing with the same 3/8" bore was selected. Another major redesign was in the housing which supported these bearings; design originally called for a large assembly which "sandwiched" the two bearings between two large aluminum disks which were then, in turn, bolted to the top of the outer leg column. This design was more complex than necessary, and would also be very difficult to manufacture. The redesigned bearing housing consists of a smaller, 2" round aluminum stock which would then be sandwiched by the bearings and held in place by an E-ring placed in a groove on the ball screw. This whole assembly could then be placed inside of the outer leg column as shown in Figure 3.

Inner Column Key:

To facilitate the vertical motion of the leg, it was necessary to keep the ball nut/inner leg column from rotating. Originally designed to do this was a hollow, aluminum key running the length of the inner column which rode in a complex roller guide bolted to the bottom of the outer leg column. This design was too complex for the simple task which it performed. Since the torque necessary to drive the ball screw is relatively small (about 2 in-lbs), we were able to use a solid delrin key which could be guided directly by the opening in the linear bearing at the bottom of the leg. The delrin key proved to be easy to manufacture and provided a relatively smooth, low-friction operation.

In the original design, the wires from the sensors at the bottom of the leg would run inside the hollow key to the top of the leg. Instead of doing this, we simply glued a length of ribbon cable to the front face of the key. From there, the cable was routed out the top of the leg, making sure to leave enough slack on the inside of the tube for full extension of the leg.

Slider Housing:

The purpose of the slider housings is to connect the telescoping legs to the body and facilitate horizontal motion. It is a simple structure which clamps around the base of the outer leg column and slides horizontally on 1/2" hardened steel rods. To reduce friction, linear ball bushings are mounted in the housings and held in place with snap rings. Two housings per leg are used and are spaced approximately four inches apart on the outer leg with the bearings on opposing sides. The original design called for the housings to be made from a single, solid slab of aluminum, 1 1/2" thick with a 2 1/4" hole drilled through it to mount the leg column. It was soon learned that this hole would be extremely difficult to machine, and required tools that were unavailable to us. An alternate design was quickly developed which consisted of two halves radiused to match the diameter of the tubing. These two halves were then bolted together, clamping around the leg tube as shown in Figure 5. The manufacture of these components was both time consuming and labor intensive.

Foot and Sensors:

The purpose of the foot is to provide a structure to mount contact switches and and infrared detectors at the bottom of the legs. The foot also supplies a contact pad between the inner leg column and the terrain. Original designs called for a complex aluminum block with pads glued to the bottom. For a simpler design, a trip to the local hardware store yielded rubber caps which fit over the ends of the leg tubes. Holes were drilled in the bottom of these caps where the contact switches could be mounted. This gave a flexible mount which eliminated any problems of bottoming out and damaging the switches. The original switches were also replaced with ones having a greater over-throw to help prevent bottoming out. The infrared sensors were mounted to a piece of delrin that was then bolted to the inside of the leg tube. A hole was drilled in the bottom of the pad to provide a window for the detector to look through.

Recommended Design Improvements

Based on all of the improvements made to the initial design which eventually culminated into the present robot, it was decided that designs could be altered to produce a better final product. Some of these design improvements include changes in component selection, product manufacturing and assembly, and the overall design. The suggestions for improvement that will be made are based on experience gained through the development and assembly process. These ideas accumulated as we assembled the legs and discovered better ways to accomplish certain tasks or discovered that a better choice in a particular component would result in better performance. All of the modifications that we came up with were in response to the question: "If we could do it all over again, what would we do differently?" By answering this questions and implementing the resulting modifications into a new and all encompassing design, a superior design and final product will result.

The most crucial items that would be changed are aimed at resulting in the enhanced performance of the present robot. These items are the reduction of weight throughout the leg components, a non back-driving worm/worm gear combination, and a more frictionless slotted key. The improvement of each of these items would vastly improve the performance of the robot.

By first reducing the weight of each leg, which comprises about half the weight of the entire robot, we immediately improve the effective performance of the robot. The load on the leg motors would be decreased giving them a greater margin of safety and a more effective power to weight ratio. The implementation of this task is both easy and inexpensive. For starters, materials with smaller dimensions could be used. Smaller leg tubes or tubes with smaller thicknesses could be used for the legs. Another way to reduce the weight would be to reduce the size of the present components resulting in lighter components. Additional mass could be trimmed off of the existing components by cutting off extra or non-crucial material mass. For instance, the legs could be perforated by drilling holes in them to eliminate mass and reduce weight. These holes could be made with a drill at specified locations, not at locations that would critically compromise the overall strength of the leg. The slider housings could also be trimmed down in a similar manner. Mass around the corners could be eliminated, for instance. A closer look at the strength calculations would give the information necessary in determining exactly how much mass could be taken off and in what areas of the individual leg components. All of these ideas are easy to implement and are very cost effective when the added performance of the robot is taken into consideration.

The gear back-driving problem could be solved by implementing a non back-driving worm/worm gear combination which would eliminate the need to send power to the motor when the legs are to remain in a stationary position. Currently the weight of the robot is enough to back-drive the gears and lower the robot. To eliminate this, the computer sends current to the motors which applies enough torque to prevent the legs from moving vertically. In order to get a better worm/worm gear combination, a greater search for parts needs to take place. Once it was discovered that a back-driving problem occurred, we were unable to select a combination that would have the same gear ratios and that would be of the same dimensions in the remaining time left prior to the deadline. Another option would be to purchase a small torque converter, a self contained unit that would transfer the torque coming off the motor shaft to the ball screw. This unit could be purchased with the required gear ratio and the non back-driving gears. These units would be very easy to install on the present upper housings of the legs and would require none of the tedious gear aligning that was required when using the separate gears. The use of the self contained torque converters would also eliminate the need to build the gear housings. The elimination of the tedious aligning procedures and the construction of the gear housings would save a great deal of time in the production process. The containment of the torque converters would be an added favorable feature especially if the robot were to operate in environments that would be corrosive to the gears. The only major disadvantage of these units are their cost which is generally five time the cost of the separate gears.

The next change to be incorporated would be the delrin key slot arrangement of the lower leg. Currently the delrin key rubs against the inside edge of the steel linear bearing in which it rides when the leg is translated vertically. This rubbing causes the metal to dig into the delrin key and shaves off pieces of the delrin creating debris that could foul the ball screw/ball nut mechanism which may become a problem after extended use. To prevent this contact, the linear bearing could be outfitted with a plastic covering that would serve as a contact point on the bearing. This plastic cover could be mounted on the linear bearing prior to assembly. The major objective of the plastic covering would be to cover the sharp edges of the metal linear bearing and to create a plastic on plastic interface for the key to ride.

The three listed changes would be very easy to implement and at costs well worth the benefits they provide. Future designs and prototypes should take these suggestions into consideration to insure the greatest attainable performance.

Conclusions

As a group, we each feel that we learned a great deal about the total design process. Designs that looked good on paper did not always look so great once we got to the machine shop. Despite all of the limitations that faced us during the design and construction of the legs, we accomplished our task according to our original schedule. Although we discovered several improvements that could be made in the future, the legs that were built this semester met all of the functional requirements and performed well.

Special thanks go to Bob Anders and Mark Uebel for their daily support and patience throughout the semester. We would also like to thank Dr. Azarm and Dr. Tsai for their consultation.

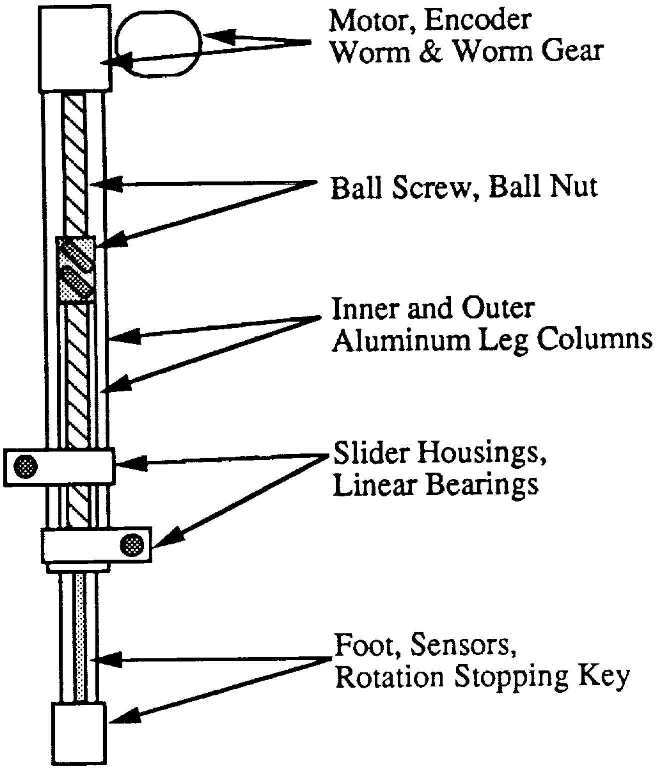

Figure 1. Leg Assembly - Block Diagram

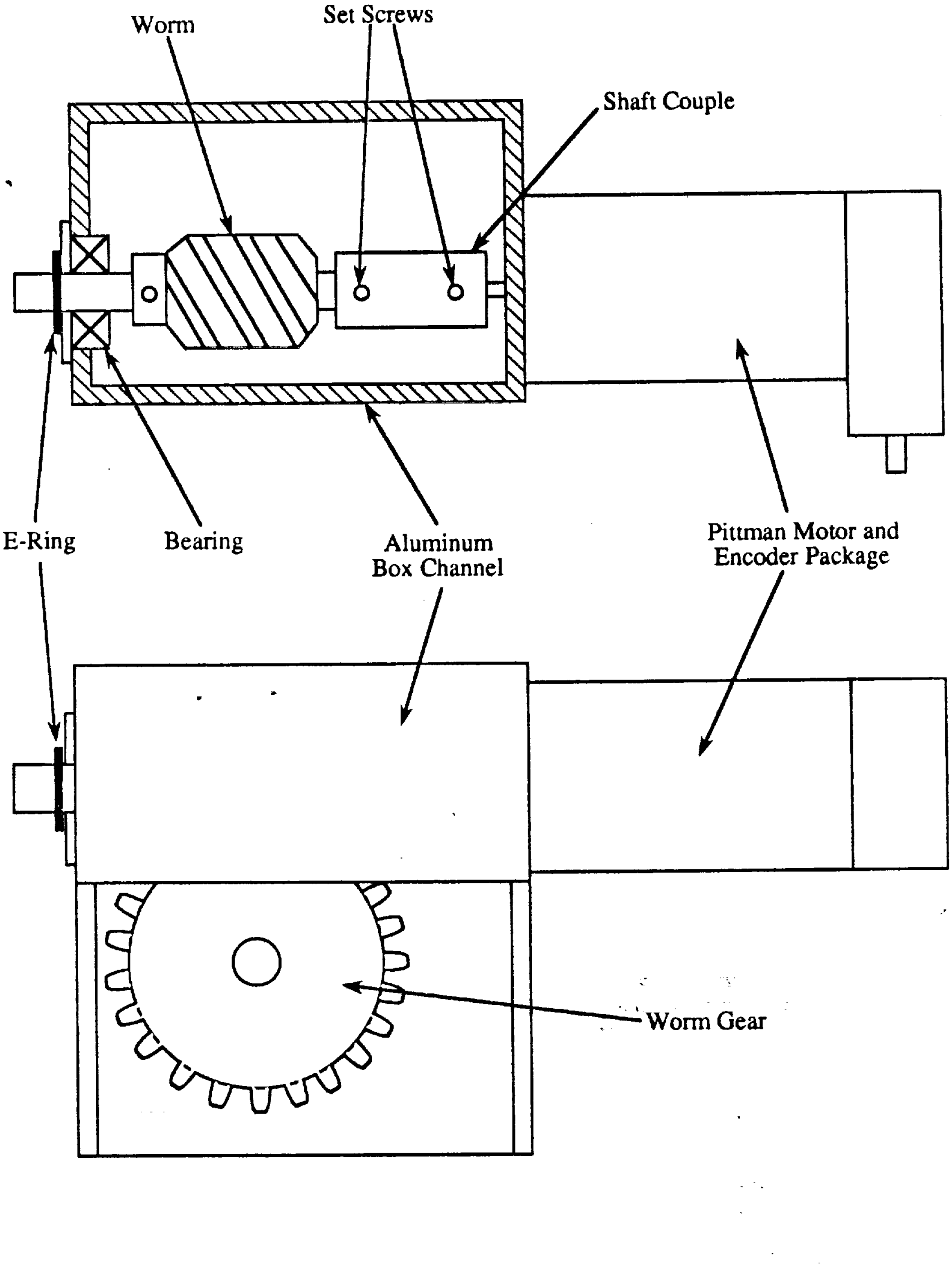

Figure 2. Motor and gear housing

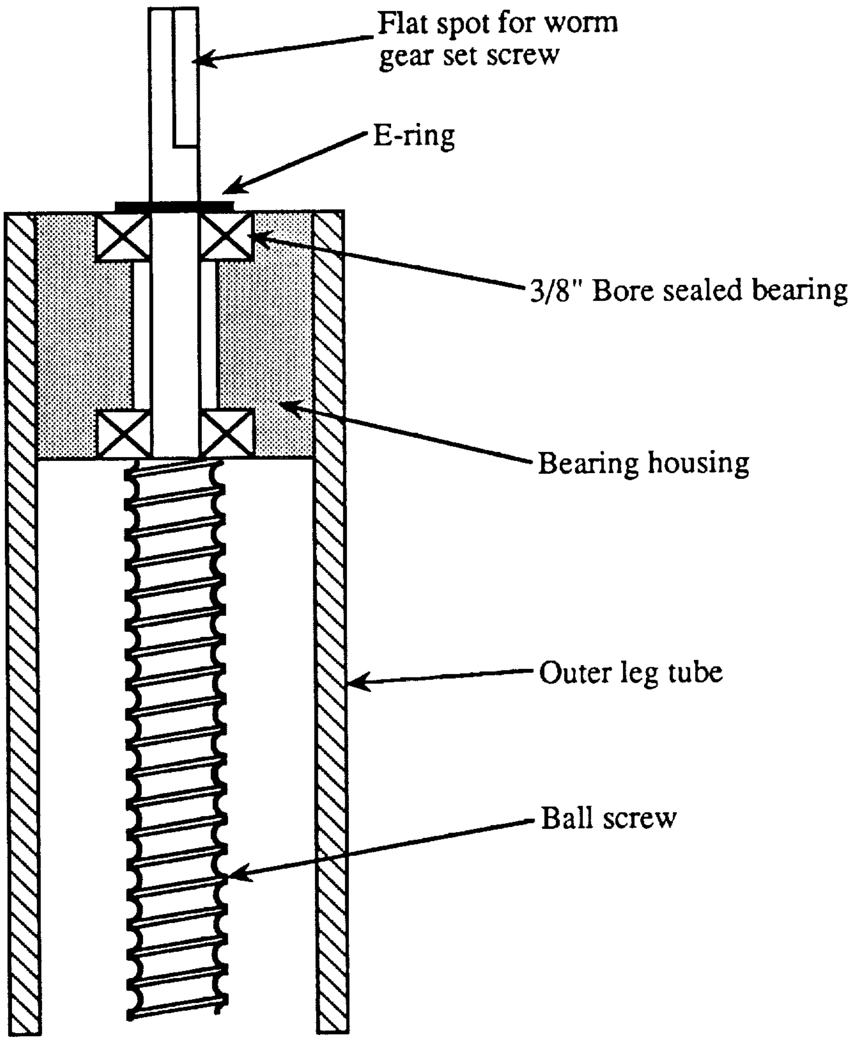

Figure 3. Bearing housing / ballscrew mount (cross sectional view).

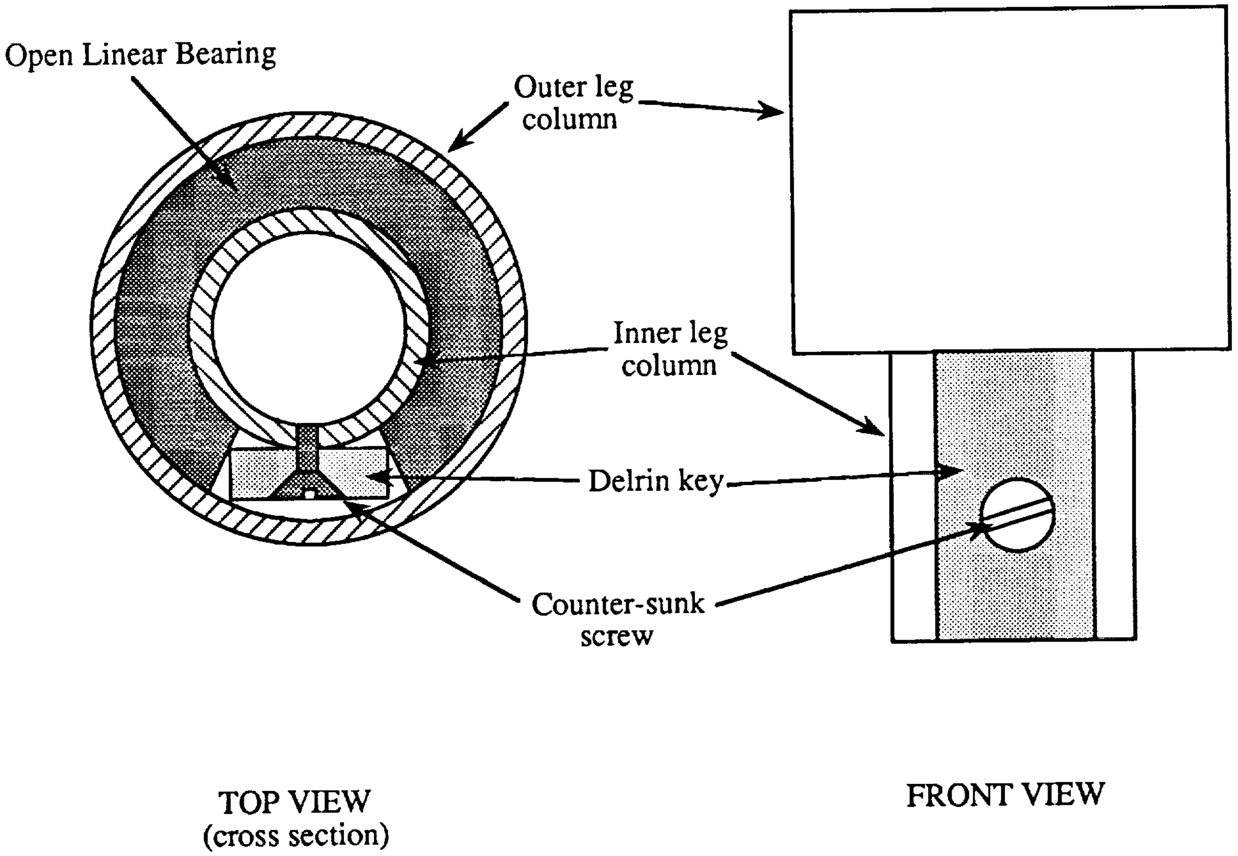

Figure 4. Inner column key

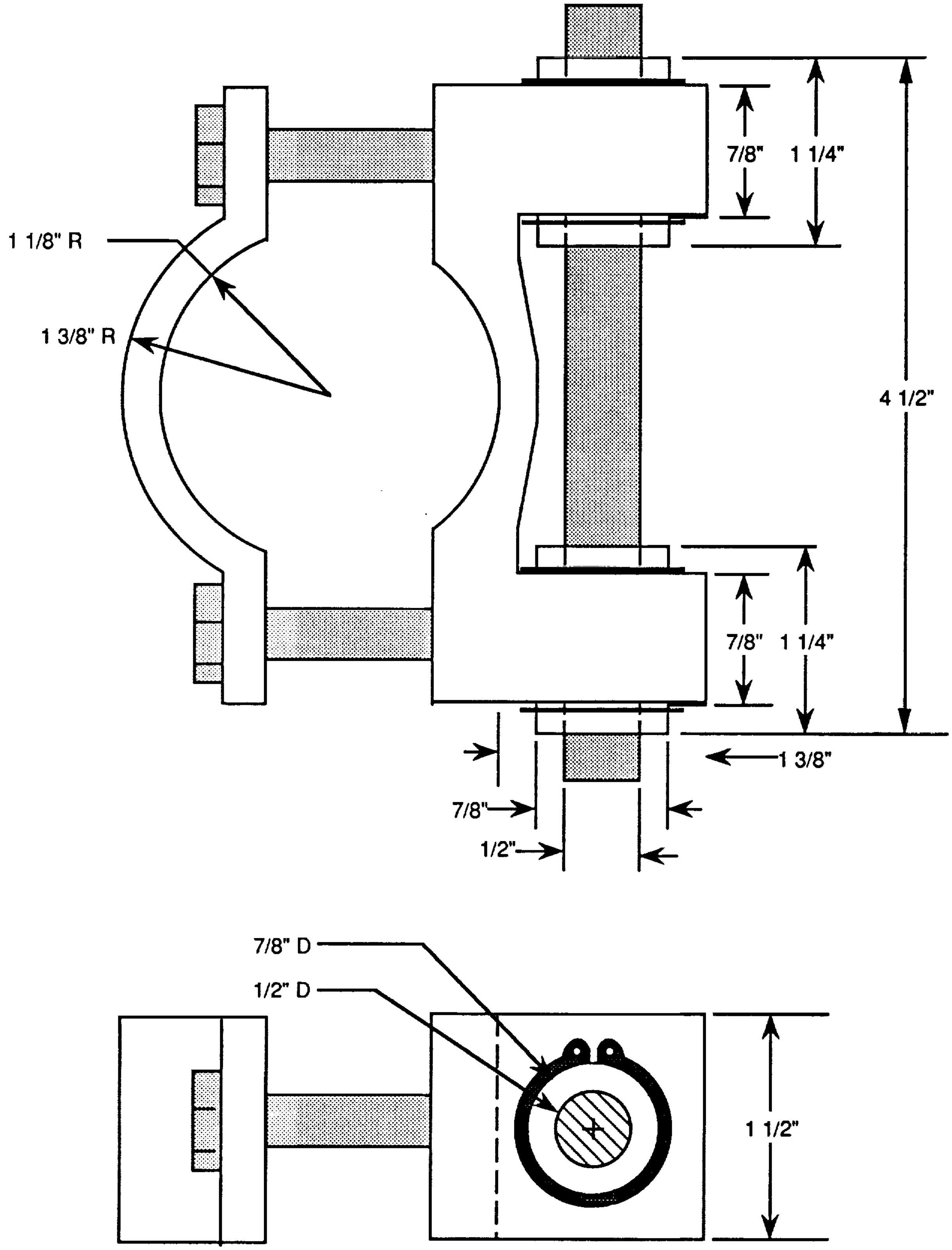

Figure 5. Top bearing housing of the slider assembly.

APPENDIX D:

CONTROL HARDWARE

University Of Maryland

Walking Robot Design Team '90

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Control Hardware Group

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Abstract

The control system of the University of Maryland Walking Robot is based on a closed loop feedback system, a first of its kind at the University of Maryland. In this configuration information is constantly being exchanged between the Intel 87C196KB microprocessor and the walking robot. The robot has eight legs, each of which are independently controlled both horizontally and vertically through the sensory feedback system.

The encoders on the 8 leg motors, the bigfoot motor and the main drive motor all send to and receive information from the controller. In addition the contact switches, the infrared sensors on the legs, the long range sensor (which is mounted in front of the robot), and the hockey stick provide information about the robots environment. Therefore, at all times the computer is aware of the horizontal and vertical location of each leg, as well as the direction in which the motors are turning. This information allows the computer to determine the absolute position of the robot.

Introduction

The purpose of the Walking Robot Control Hardware group was to design, test, and fabricate the control system for the Walking Robot. The members of the group set about fabricating the computer from a design that was proposed the previous semester. During construction of the computer many obstacles were encountered which inevitably resulted in numerous design changes from the original plans.

The control system of this robot uses an Intel 87C196KB Microcontroller. This is a 16-bit CHMOS high performance controller with time average for a typical applications of 0.5µs - 1.5µs. For our application ports 1 through 4 will be used as primary information flow between the computer and the robot.

The exchange of data is accomplished through the data lines and address lines via ports 3 and 4 of the processor. The memory mapping was divided into four primary groups: address' C00F-FFFF are dedicated to RAM; address' 8000-BFFF are dedicated to the inputs from the motors and leg position sensors, the outputs are from the microprocessor to the motor and leg control; address' 4000-7FFF are dedicated to ROM; finally address' 0-3999 are dedicated to on-chip ROM.

Experimental procedure

Due to the complexity of the control system it was necessary to divide the computer into subsystems. The computer system was divided into the following subsystems: Microprocessor and Main Memory; Input/Output; Pulse Width Modulators (PWM); Motor Control; and Leg Control.

Microprocessor and Main Memory

The Intel 87C196BK microprocessor was chosen as the Central Processing Unit. The 68 pin LCC socket was mounted on a printed circuit board. This was chosen because of the difficulties associated with wire-wrapping in a densely packed environment. In addition, extensive prior experience with soldering dictated this choice as the logical alternative to wire wrapping. Problems associated with this fabrication technique were a result of several design changes encountered during the course of construction. The decision to use the 87C196BK instead of the 80C196BK resulted in the need for extensive reconstruction late in the semester. This resulted in damage to the printed circuit board and existing wiring.

The Intel 87C196BK microprocessor uses four 8-bit ports (busses) to send and receive data. Port 1 was used to control the PWM's and through them the speed and direction of the main motor and the leg motors. Port 2 was used in conjunction with Port 1 for controlling the PWM's. Ports 3 and 4 were used as a data bus between the main memory and the multiple sensors on the robot.

Testing of the microprocessor and main memory was done by using the ICE96 emulator supplied by Intel. The Ports and RAM were tested by writing a bit or a word to the emulator which in turn would write to RAM. The output from the CPU was observed using a "window" or by reading the same address location. If all address locations were functioning properly any 16 bit combination could successfully be written to and read from any address location.

Input/Output

The 20 chips used for the purpose of latching information from the sensors and then sending information to the computer were all wire-wrapped on three perforated boards. The data from the sensors was stored in the buffer chips and then transmitted to the microprocessor when the 8 bit buffers address was enabled. The data was then transferred via ribbon cable on data lines 0 through 15. This information was received at data Port 3 and 4 on the microprocessor.

The Texas Instruments SN74HC244 Octal Buffers are high speed Complementary Metal-Oxide Semiconductors (CMOS). These devices are used to receive and store 8 input bits from the sensors until the microprocessor requests the information stored in the buffer.

Testing of the Input/Output was done by inputting a waveform into the buffer, then enabling the buffer and observing the output. In this way the wiring and operation of the buffer was insured prior to final assembly of the computer.

Pulse Width Modulators

The PWM's were used to individually control the speed and direction of the leg motors, the main drive motor, and the bigfoot motor. This was necessary because of an unforeseen backdriving problem in the telescoping legs which could not be solved mechanically. The PWM's control motor speed by varying the frequency of the pulse train to the motor. As the frequency of the incoming modulated signal increases the speed of the motor increases proportionally. By varying the input signal from 0 to 255 in discrete intervals, the motor speed can be incrementally adjusted from 0 to max. motor speed. The PWM's were tested by sending a control signal to the PWM's via the main memory board from the emulator and by observing the output on a digital oscilloscope.

Motor Control

Motor Control was accomplished using Sprague motor control chips in conjunction with a pulse width modulated signal. Motor Control chips were essential in maintaining accurate speed of the motor during leg motion. This chip was not correct for the application for which it was chosen. The chip was designed to control stepper motors which use a phase difference to control motor direction. Numerous problems were encountered in attempting to facilitate the use of this chip for our application. Finally, a pair of Zener diodes were placed across the motor inputs to prevent a current spike during motor direction switching. This was a workable solution except in the event of a motor stall which led to the destruction of the motor control chip. The rated current of the chip is exceeded at stall, a successful solution for this problem has not been discovered.

Leg Control

The four chips used for each leg controller consisted of two 8-bit buffers and two up/down counters. The incoming pulse train from the sensors on the telescoping legs was inputted to the clock of the counters. This resulted in the counters incrementing whenever a sensory input was received. In this way the absolute position of the leg was continuously updated and monitored. The information from the counters was stored in the 8-bit buffers and was immediately available to the CPU via data bus lines 0 through 15. Testing of the Leg Control was accomplished by inputting a digital pulse train to the clock input of the up/down counter. The output from the buffer was continuously monitored on a digital oscilloscope to insure accuracy of the count (and subsequently the position of the leg). Unfortunately the up/down counters chosen for this application were not CMOS. This lead to a problem when trying to integrate these TTL (transistor-transistor logic) chips into a CMOS environment. TTL output high is 3.5 volts whereas CMOS high input is minimum 3.7 volts; therefore, the counters could not drive the buffers high consistently. The solution to this problem was to add pull-up resistors to every output of the counters to ensure a solid five volt high reading. This solution worked well, but as there are 18 8-bit counters, they required 144 pull-up resistors. The solution was time consuming to implement.

Experimental results

The control system was successfully tested and is fully operational for use with the Walking Robot. To date the motor control circuitry has not been successfully redesigned.

Discussion

Suggested methods for solving the motor control problem are redesigning of the motor control circuit or limiting the travel of the telescoping leg to prevent motor stall. Travel limiting can be accomplished in software by closely monitoring the leg counters and never allowing the legs to reach their extreme positions, either up or down.

If the problems associated with backdriving of the leg motors were reconciled the necessity of the PWM's would be eliminated. This would result in less power consumption, reduce the overall cost and complexity of the design, and reduce the possibility of system failure.

Application of the Robot to the Martian environment

For the robot to successfully operate under the extreme environmental conditions associated with the Martian environment the control hardware would need extensive modification. The extremely low temperature conditions on Mars would necessitate some method of temperature control for the control components. In addition the control computer should be built on a custom made printed circuit board and then sealed to prevent intrusion of the Martian environment. Position sensors for the robot would need to be redesigned to incorporate sensing of the rough Martian landscape. Additional sensors would be necessary to insure the safety of the robot by monitoring the height and depth of the surrounding terrain, the pitch and roll of the robot, and any other potentially hazardous terrain features.

Conclusions

The successful building of a complex microprocessor-based closed feedback system provides the groundwork for future applications of this technology to the Walking Robot Project. The problems which were encountered and solved indicate the feasibility of continuing this level of complexity for the Walking Robot control system.

APPENDIX E:

CONTROL SOFTWARE

SOFTWARE GROUP

May 7, 1990

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C2

Abstract

This paper discusses the software strategies currently employed in the University of Maryland's 1990 walking robot, the Prototerp IV. It concerns itself primarily with problems encountered in the interface between mechanical and electrical hardware and the larger macro routines that have been designed. The discussion then turns to the subject of software modifications to make placement on the surface of Mars a feasible concept. Redesign includes intelligence systems, navigation, performance monitoring and a secondary mode of travel.

Introduction

The purpose of the software for the Prototerp IV is to take the inputs from the tether and environment and transform them into outputs to the motors. There are 29 inputs from the tether. In addition, there are 25 sensors available to indicate the position of the robot and of the position of each of the moving parts on board (i.e. legs).

The software is written in increasing levels of complexity, each building off the lower levels. The lowest levels job is to send the appropriate signals to the motors. The levels above deal with transforming inputs to outputs. These are further subdivided based on complexity and redundancy. For instance, the transformation of the command walk, contains the same transformations as the command move leg up, in addition to others. This redundancy occurs frequently, therefore, many of the routines at the lower levels are used by the upper level routines.

Backdrive

Without the aid of software the robot will crash to the ground. This is because the leg motors backdrive under the load of the robot. Therefore, software has the task of continually sending a stopping voltage to those legs which are in contact with the ground and not supposed to be moving. This check is done at the very lowest level of the software in a routine called legmotors. Sensors are installed on the bottom of each leg which indicate whether that leg is on or off the ground. This information is used in conjunction with the speed and direction the motors should be going to calculate the voltages to send to the motors.

There are six possibilities for each leg. A leg can: go up under load; go down under load; stop under load; go up under no load; go down under no load; or stop under no load. In each case, a different calculation must be done.

Feedback Control

One of the major tasks of the software is to coordinate the horizontal and vertical movements of the legs. This task is split into two parts. The first part is the control of the vertical position. The second part is the path planning.

The vertical control of the legs is required to respond fast enough to keep up with the horizontal movement of the legs, and to be accurate enough so errors will not cause the robot to be off balance. The vertical position of the legs is controlled using proportional feedback.

Encoders are installed on each of the 8 leg motors that intern connect to a "16 bit counter" with a resolution of 2400 counts/inch. One subroutine called legcontrol is dedicated to sending the commands to drive each of the leg motors almost simultaneously at variable speeds. These commands are received by the legmotors routine described above. The speed of each leg is individually calculated by multiplying the difference of the actual vertical position and the desired vertical position by a constant. This constant is determined by trial and error. This is not the final speed, because a check must be done to see if the leg is within an acceptable error. This error window is also established by trial and error. The smaller the error window the slower the response. Another thing to consider is the stability of the legs. As the error window gets smaller the system becomes less stable, until eventually it becomes unstable. Unstable means the legs never get to the desired position, but instead they oscillate around it.

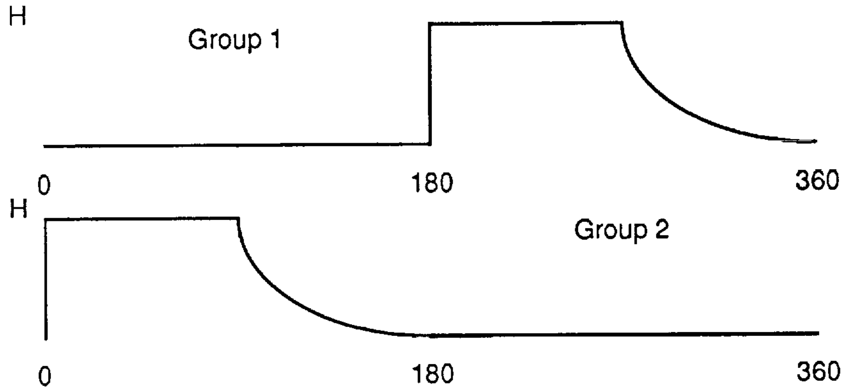
The path the legs will take is planned out by another routine called walk. This routine feeds the desired position to the legcontrol routine. This desired position is calculated based on a predetermined function of the horizontal position of the legs.

Walking

The robot walks through the interchange of two leg groups of four . One group assumes the weight of the robot and, as it moves down the length of the slider rods, propels the chassis of the robot forward. During this stroke, the other group of legs move up the slider rods to position themselves to accept the load for the next cycle. As all of the legs are mechanically linked, their motion is dependent on one central drive motor.

One feature of this mechanical design is the "quick return" of the legs. In every rotation of the crank arms, more than 180 degrees is spent with the legs under load. It is apparent that the velocities of each leg group with respect to the chassis must be momentarily match as the legs change direction. The nice feature of the mechanical design means they are equal when they are moving the chassis of the Prototerp IV forward, and provide for an easier transition from one leg group to the other.

Designed into the existing software is a generic walk routine. Based on the position read from an absolute encoder on the main drive motor, the slider position of each leg can be determined. Each turn of the central motor corresponds to exactly one turn of the crank arms. Using these features and the velocities of each leg group with respect to the chassis, we have designed the following paths for each leg group in space:



Leg Height versus Angular Position of Drive Motor

The decay to the ground level at the end of each stride follows a function of the form $y = H(1 - X/L)^2$. The requirement produces a decay from height H within a length L with no vertical velocity at the point $x = L$. This ensures the smoothest possible transition between leg groups, and if correctly executed, will limit the shearing stresses placed on the legs. Our use of proportional feedback also initiates the greatest possible acceleration in the legs that must lift from the ground to return forward. The expectation is not that they travel a finite distance in an infinitesimal time, but rather that they move as quickly as possible. The actual response of the legs will look similar, but not the same as the graph in the figure.

Walking in an environment with rough terrain requires an obvious redesign to the strategies employed above. Where calculated paths can be made in laboratory environments with finished floors, this process falls short in naturally made environments. A second strategy employs the contact switches designed into every foot. If the legs are allowed to simply travel downward until they contact the ground and are then shut down, the rough terrain does not present a problem. The rough terrain, however, does not ensure that the chassis will be as level as possible. The slight tipping involved when the leg motors are driven to stop under load have been great. Therefore, there is confidence that this problem will be of little significance.

Turning

Autonomous turning with Prototerp IV by a calculated or desired amount is accomplished by initiating maximum acceleration, then decelerating at a maximum speed half way through turning. This will provide the first approximation in turning process. Further turning is likely to be required for pin pointing the robot at the proper angle. This is done by inching to the desired angle with short bursts of voltage, and feeding back the position from the bigfoot encoder. Once the desired angle is reached, a software locking algorithm will keep the robot stable until all legs return back to the ground, especially if the robot is on an incline.

Prototerp IV Modifications for Martian Environment

Intelligence

For applications on Mars, some other control software features should be implemented in the robot's program for on-board automation. But unlike the autonomous events in SAE's annual walking robot competition, this kind of automation must be capable coping with the uncertainties of a real physical world. Therefore, self reliance features such as inspecting, repairing, assembling, etc., are essential for the robot's survival and longevity in an alien environment. Furthermore, the minimization of human interaction with advanced space robots would make exploratory missions on Mars, and other planets, more economically feasible than manned operations.

When Prototerp IV is placed on Mars to roam and explore, it must, in a sense, be able to 'think' in order to make decisions and solve problems, and to perform various unknown tasks autonomously without preprogramming, and without human intervention. Such high-level control would classify Prototerp IV as a type artificial intelligence (AI). The decision making process would be done by manipulating current information with techniques such as advanced on-board sensory processing, world modeling, and task decomposition. Sensory processing involves detection of events, recognition of patterns and objects, and correlation functions of observation versus expectation, also known as expert functions. World modeling includes modeling of objects and structures, maps of areas, and tables of state variables that describe the environment; and task decomposition involves planning, servo control, and actual decision making based on a hierarchical structured control system that examines and evaluates the sensory inputs, world models, and the expert functions in layers of mathematical operations that assign a 'decision value' at each level. After several levels of computation of growing complexity, the robot will make a decision as to what task to perform based on the decision values at each level. The task most likely to be frequented is collecting and analyzing data, the primary directive of any exploratory operation; so decisions as to what data to retain and how to process them are crucial to the success of the mission

Navigation

Navigation of Prototerp IV on the surface of Mars requires a comprehensive visual system, one perhaps introducing Neural Network integration to reduce computation and memory overhead. Moving to and around objects in the path will be determined by size and classified into one of three categories:

a) Objects that can be walked on or over. These pass underneath the chassis of the robot and/or legs. Important in this determination will be how high the legs must be raised in order to clear the obstacle.

b) Objects that must be walked around. The fifteen inches of clearance between the chassis and ground at full extension will not always be enough. To walk around such an obstacle, the visual system must give the robot the opportunity to determine the shortest path around the obstacle.

c) Objects that are impassable. Sudden steep grades or cliffs are of utmost importance. The Prototerp IV will be as helpless as any insect if it falls over onto its back. The visual system must be able to distinguish these hazards, giving the robot the reaction time it needs.

Autonomous Performance Tests

In order to maintain proper functioning throughout its mission on Mars, Prototerp IV would have to continually inspect all electrical and mechanical systems with a well organized, quick, and efficient systems check routine that would detect any mechanical or electrical malfunctions, and glitches within the software itself if information were somehow lost. The best approach for a systems examination would be to break down the testing algorithm into several 'trouble shooting' levels, and to work from outside to inside, so the robot can zoom in on the root of the problem. This allows the robot to report on any system failure.

Every attempt, of course will be taken to ensure the mechanical integrity of Prototerp IV's mechanical hardware. However, wear is inevitable and the performance of the walking machine will have to be monitored. Simple software routines can be written to monitor the moving parts. The 87C196 microprocessor allows for real time experimentation. By sending a standard pulse width modulated signal to a motor, performance becomes a matter of comparing translation in time to known optimal values. While knowledge of a failing bearing will certainly not initiate a repair on an unmanned mission, Prototerp IV will have the wherewithal to compensate and "limp" home to the lander once it senses what is wrong.

Electronic hardware may also be tested by the microprocessor. Simple memory accessing can confirm component integrity. Mechanical switches may also be tested. Assuming that multiple system failure is not likely, the Prototerp IV has the ability to input data from several sources to ferret out inferior data. For example, at full extension, all contact switches will close and the absolute encoders will report a standard data pattern. The robot can confirm switch performance by assuming this stance, and testing each switch in succession.

The robot will also come equipped with electronic backup systems. A simple design of an microprocessor hierarchy can power only one system at a time. Redundancy and conflict can be eliminated by designing a master microprocessor. A processor as simple as an 8085 can be given the ability to power up and down the more powerful 87C196 processors and other memory components thereby allowing for some electronic failure and still have operation.

All robot controls must be both flexible and permanent. Different or unexpected situations will require some ingenuity and off the cuff programming from Earth, and the systems must be designed to handle last minute changes. The 87C196 comes equipped with autonomous programming ability that can be utilized. With the 8085 master processor system, the 87C196's will look to download any of a variety of operating systems. These systems may be placed on magnetic sources while others will be permanently affixed on proper ROM. This allows for continuous redesign of software without the hazard of losing at least the basic functioning abilities

Leg Redesign

Perhaps the most inefficient motion the Prototerp IV will undergo is the transition from walking to turning and back. Navigation of any slalom means an endless number of transitions to make slight modifications to direction, effectively bringing the robot to a halt. While the current central Bigfoot design is effective for large angular turns, its inefficiency grows tremendously for small modifications.

The possible redesign of the slider rod assemblies and attachments to the chassis of the robot may give Prototerp IV exactly what it needs. By giving these rod assemblies small horizontal translation ability, the computer may introduce a radius of curvature to its path, and avoid obstacles that would have partially obstructed its path. Signs of the same design strategies are already seen in the automotive industry, where the back wheels of cars turn slightly. This tightens the turning radius and improves performance. In this design, it means much less transition from legs to Bigfoot. It makes for a faster robot.

The independent nature of the two leg groups would still have to be maintained, but from a controls standpoint, the implementation is simple. Mechanically, this design seems plausible also. One would have to design a system with a potential energy minimum at zero degrees deflection.

Conclusion

It is evident that no set of algoriths developed here on Earth can ever hope to achieve systematic walking on the surface of Mars. Regardless, the methods developed in this preliminary exploration into possible walking starategies, if ever expanded, can form a basis to make operation possible. The surface of Mars is not uniform, nor is continuous from one region to the next. Software control of any robot, therefore, cannot be comprehensive. The robot must be in constant contact with operators on Earth, and, though it will not learn to adapt to the conditions of that dynamic planet, the human beings behind its operation will. It is those engineers that will finally determine how well Prototerp IV will operate on Mars. Those of us in Software like it that way.

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APPENDIX F:

MARTIAN CONSIDERATIONS

DESIGN ALTERATIONS OF PROTOTERP IV FOR MARS EXPLORATION

CHASSIS AND BIGFOOT GROUP

SPRING, 1990

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TIM CONDON

Abstract

There are two major advantages that walking robots have over standard robots, such as those possessing tracks or wheels. Legged locomotion provides a greater versatility to handle any given terrain, and walking machines can theoretically travel in places inaccessible to other machines. One promising application for walking machines is nuclear waste clean-up and removal. Another is in space exploration. Since Mars possesses very uneven and diverse terrain, a natural application would be a walking Mars rover. The feasibility of adapting the University of Maryland's walking robot, Prototerp IV, to a Mars rover is examined. In particular, issues relating to Prototerp's chassis and centrally located turning mechanism, "Bigfoot" are addressed.

Introduction

In the future, machines capable of autonomous operation through the use of artificial intelligence will play a crucial role in space exploration. NASA's Automation and Robotics Technology Development Program has stated that the "goal for intelligent automation is to increase robustness" and create machines that are able to "cope with a greater variety of circumstances through increased sensing"[1]. A major problem in developing versatile walking robots and autonomous vehicles in general, is the limitation imposed by the sensors[2]. As technology develops and improves sensor capabilities, walking robots will become more sophisticated and widely used.

The Prototerp IV design possesses some versatile features including the independent control of each leg's height, and variable stride capabilities. However, Prototerp's Bigfoot assembly which enables the robot to rotate and change direction, limits the possible terrain to flat and level surfaces. Design modifications are proposed to enable the Bigfoot assembly to handle uneven and inclined terrain. The ultimate goal is to enable the robot to change direction in any area that the robot may travel.

Another important change that must be made, is the reduction of the Prototerp's weight. The Prototerp exceeds 440 Kg which is unacceptable for space applications. The main chassis and Bigfoot material, aluminum, must be changed to a material with a higher strength-to-weight ratio. Also, a protective covering must be designed to protect the robot's electrical and mechanical components.

The general philosophy of the proposed design modifications was to increase the capability of adaptation to a Mars environment, without unnecessarily increasing the complexity of the overall system. Some important design criterion have been stated in "Issues and Options for a Mars Rover"[3].They are stated as follows:

1. Minimize delays caused by obstacles in walker's path.
2. Maximize kinds of terrain the rover can handle.
3. Minimize the number of stops needed to request help from Earth.
4. Minimize cost, weight and power.
5. Maximize redundancy and backup modes.

To better understand the needed capabilities of the design, the Martian environment is examined in more detail.

Martian Environment

The Martian environment poses many challenges for an autonomous walking robot. A Mars rover must be able to receive information from its surroundings and make changes accordingly. To prepare Prototerp IV for a Mars mission, every possible situation must be taken into account and the robot must be given the capability to adapt.

Exploration of the possibilities for a Mars rover was motivated by the irregular and varied types of surface conditions present on the planet. Of major concern are the rocky fields which cover nearly half of the planet's surface. Boulders of up to eight meters tall have also been reported[4]. Just as treacherous to a walking machine are the desert-like areas having sand dunes composed of fine particles. Mountains, volcanoes, crusty surfaced craters, and ice-covered poles are also present.

Weather conditions pose additional problems. Maximum steady winds of up to 70 m/s have been predicted to occur on Mar's surface[5]. At these speeds, fine sand particles can be picked up from the surface and create sand and dust storms[6]. When this occurs the robot may be isolated from earth control.

There are also several factors that would help a robots performance. There is no water in the liquid state, therefore there is no rain. The atmosphere is composed of CO_2, N, Ar, and other inert gases, having minor constituents of water vapor, dust, CO, O_2, and O_3. These would not pose problems to a robust rover. Finally, the gravity on mars is only 38% of earth's, which would help reduce the power requirements, and the weight of the robot.

Changes to Bigfoot

The present Bigfoot design has square aluminum tubing mounted to a central bearing which is geared to the Bigfoot drive motor as shown in Figs.1.a. and b. Connected underneath the channel are four contact pegs. When the robot switches from the walking to the turning mode, its main legs telescope up and the robot comes to rest on the contact pegs. The bearing and motor assembly could adapt well with a Mars rover, but the channel and legs comprising the foot must be changed to accommodate inclined and uneven areas.

One suggested solution to the problem was through the use of constrained rods which could hug the particular contour and still maintain a level robot frame (Fig. 2). This design creates many problems. It does not incorporate the possibility of walking on a grade and it has the potential for instability on certain types of terrain. The other concerns are the difficulty in fabrication and the weight of the assembly.

Three other modifications are suggested. The first is to have the foot made up of many flexible joints connecting the contact pegs to the aluminum channel (Figs. 3.a. and b.). The second suggestion is similar to mount circular housing assemblies on to a disc. The contact pegs could then be spring loaded into the housings (Figs. 4.a. and b.). Both designs have limits on the types of terrain they can handle. Finally, the design could incorporate a leg assembly similar to that designed by Stephen Bartholet for Odetics, Inc.[7].

The first generation of the design incorporates a vertical actuator mechanism shown in numbers 32 to 34 in Figure 5. This mechanism allows the leg to fold out to support the robot during turning and retract when the robot is in the walking mode. Several major advantages are apparent. The structure provides the best possible stability of the robot under rough and inclined terrain conditions, and the assembly can be made very compact due to its folding ability. The inventor improved on this first design by incorporating a "dogleg" on member 17 as shown in Figure 6[8]. This allows the legs to fold even more compactly against the robots center. Also shown is a horizontal leg drive, numbers 50-55.

This horizontal actuator system could act as a backup leg drive unit. By making member 22 in Figure 6 spring loaded into member 23 the terrain handling capabilities could be further increased. The drive gear, 41, could be meshed to the present Bigfoot motor through an electric solenoid and this would negate the use of a separate motor for the vertical actuator (40 in Figure 6).

This leg system has been tested and proven to be capable of walking on a 30 degree grade[9]. Due to this and the above mentioned advantages, it is the last design that is recommended. An analysis would still be needed to size the components, determine the number of Bigfoot legs required, etc. A working drawing, including the entire robot assembly, should also be created to ensure that the Bigfoot's legs could operated under the constraints of the main drive legs.

Material selection

An important consideration for space application is weight. Prototerp IV's structure is made almost entirely of aluminum components. Aluminum was chosen for its strength, ease of machinability, cost and availability. As stated previously, its weight requires that we limit its use as much as possible. In areas where we need to use metal, such as the slider rods, bolts, etc., alloys with higher strength-to-weight ratios such as Titanium-Al alloys should be considered[10]. For the support frame and other areas, however, a good choice would be carbon fiber composites.

Carbon fiber composites have a very high strength-to-weight ratio, excellent fatigue strength and are easily formed by machining and molding. As seen in Figure 7, the strength of this material is independent of temperature from 0^{o} C to well above 1500^{o} C ,which exceeds any temperatures which will be encountered on Mars[11]. Due to the geometry of the carbon fiber matrix, crack propagation is retarded so that if the robot were to fall, little damage to the frame would result. These materials cannot be welded together, but can be fastened mechanically with bolts, rivets or epoxy. Care must be taken when fastening the composite. If bolts are used, drilled holes should be used rather than molding the holes into the material because during the molding process, the fibers will deform around the hole and cause a weak joint. It is also recommended that the holes be reinforced with composite fabric at 45 degree angles to the hole and that each bolt or fastener be tightened the same amount because the material will not transfer any load to another fastener. The ideal joining method is a combination of bolting and bonding with adhesives[12].

The Mars environment has dust storms, large temperature fluctuations and other phenomenon that would interfere with the robot's electronic and mechanical components. A method is therefore needed to shield these sensitive parts. One suggestion is the fabrication of a cover which would fit overtop of the robot without interfering with its operation. A cover for the bottom of the robot would also be needed. As with other components, carbon fiber composites would be a good choice for use as a cover material. Methods such as thick film or silicon coating may be considered for increasing the wear resistance of the covering.

Conclusion

Many design changes would have to be made to convert Prototerp IV into a Mars rover. The overall design must start from the beginning to ensure that one ability or feature does not interfere with a necessary capability. For example, seemingly basic problems such as a protective cover and material considerations, may necessitate changing the design of the leg assemblies. This is an extreme case, but with a complex machine such as Prototerp IV, it is impossible to foresee all of the possible problems which may arise.

The suggested modifications stated, are meant as initial guidelines and a more detailed analysis should be performed before deciding on an option. After the materials have been selected, structural computations should also be performed to ensure that the final assembly incorporates the proper factor of safety. With lighter materials and the reduced Martian gravity, great reductions can be made in weight. This in turn would allow motors, gears, sprockets, etc. to be sized accordingly. Prototerp IV's large chassis area leaves ample room for the necessary sensors, cameras, etc., required for a Mars mission.

The Martian environment provides a challenging arena in which to operate an autonomous walking machine. Many difficult problems remain to be solved. However, given the versatility and adaptability of the present design and the knowledge to be gained , these problems are worth resolving.

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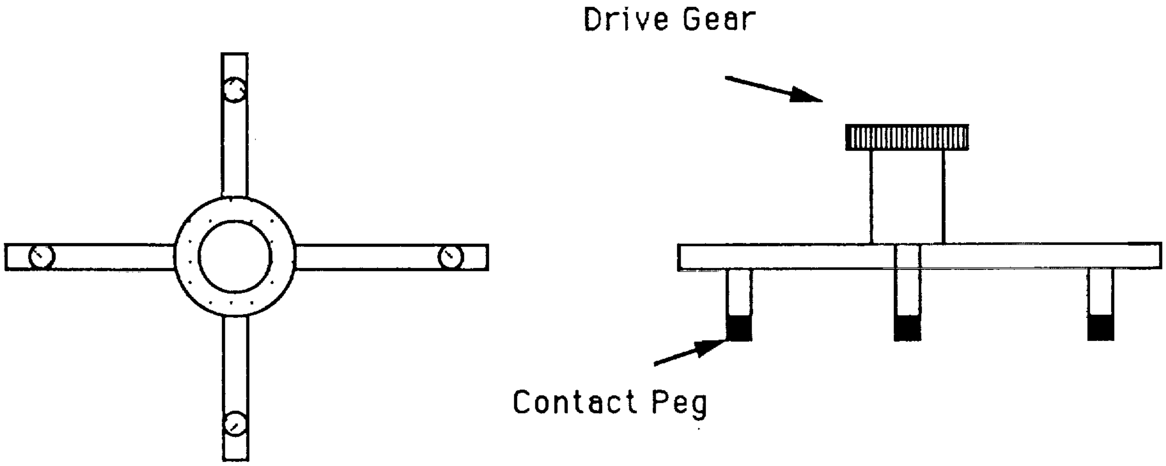


Bigfoot - Present Design

Fig. 1.a. Top View

Fig. 1.b. Side View

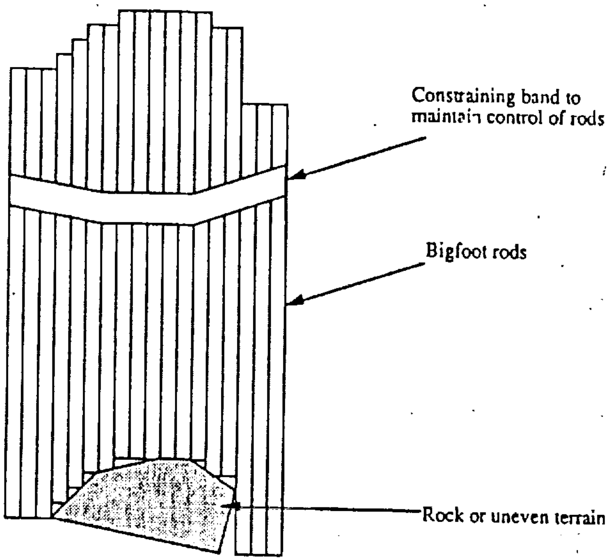
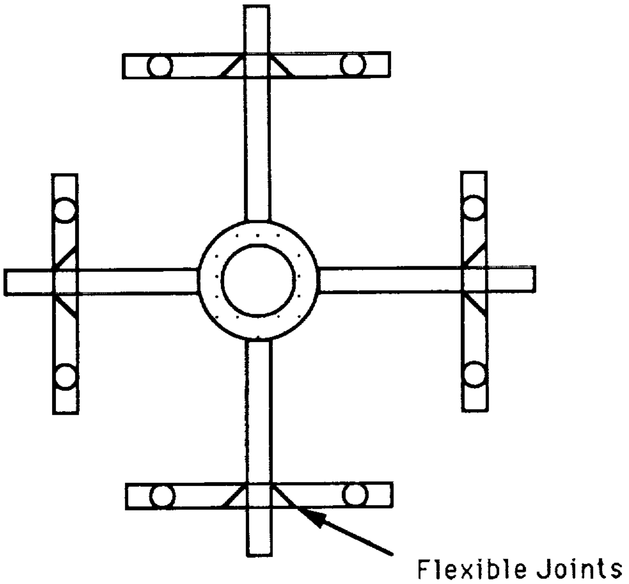
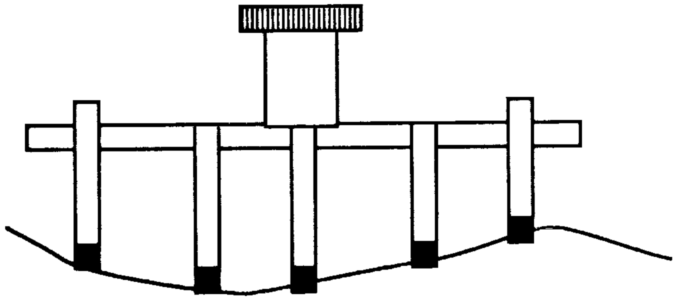


Figure 2. Bigfoot Modification Using Many Rods

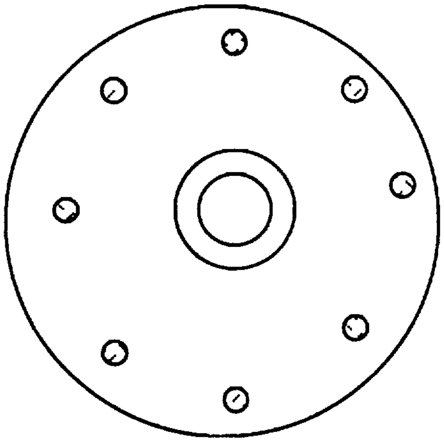


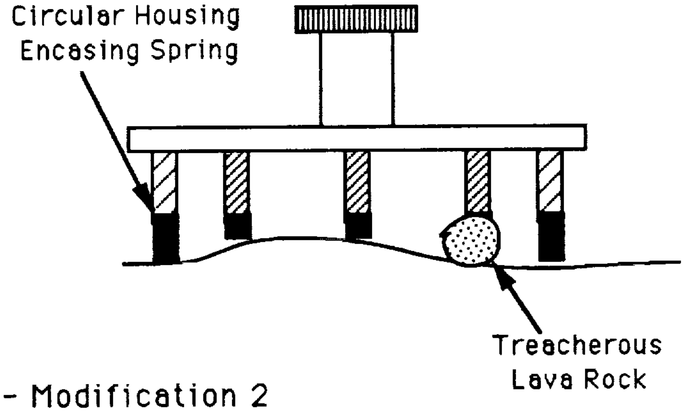


Bigfoot - Modification 1

Fig. 3.a. Top View

Fig. 3.b. Side View





Bigfoot - Modification 2

Fig. 4.a. Top View

Fig. 4.b. Side View

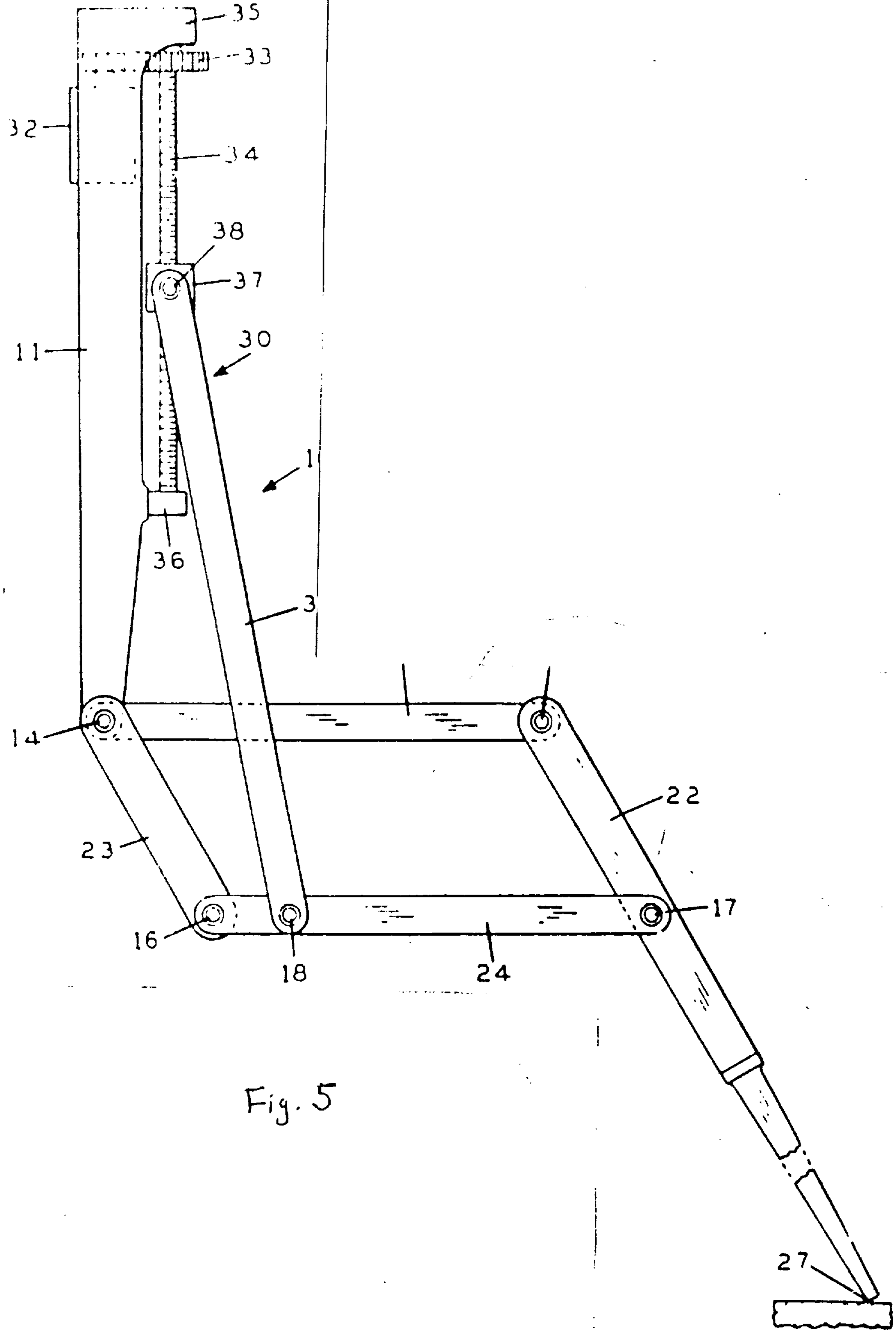


Fig. 5

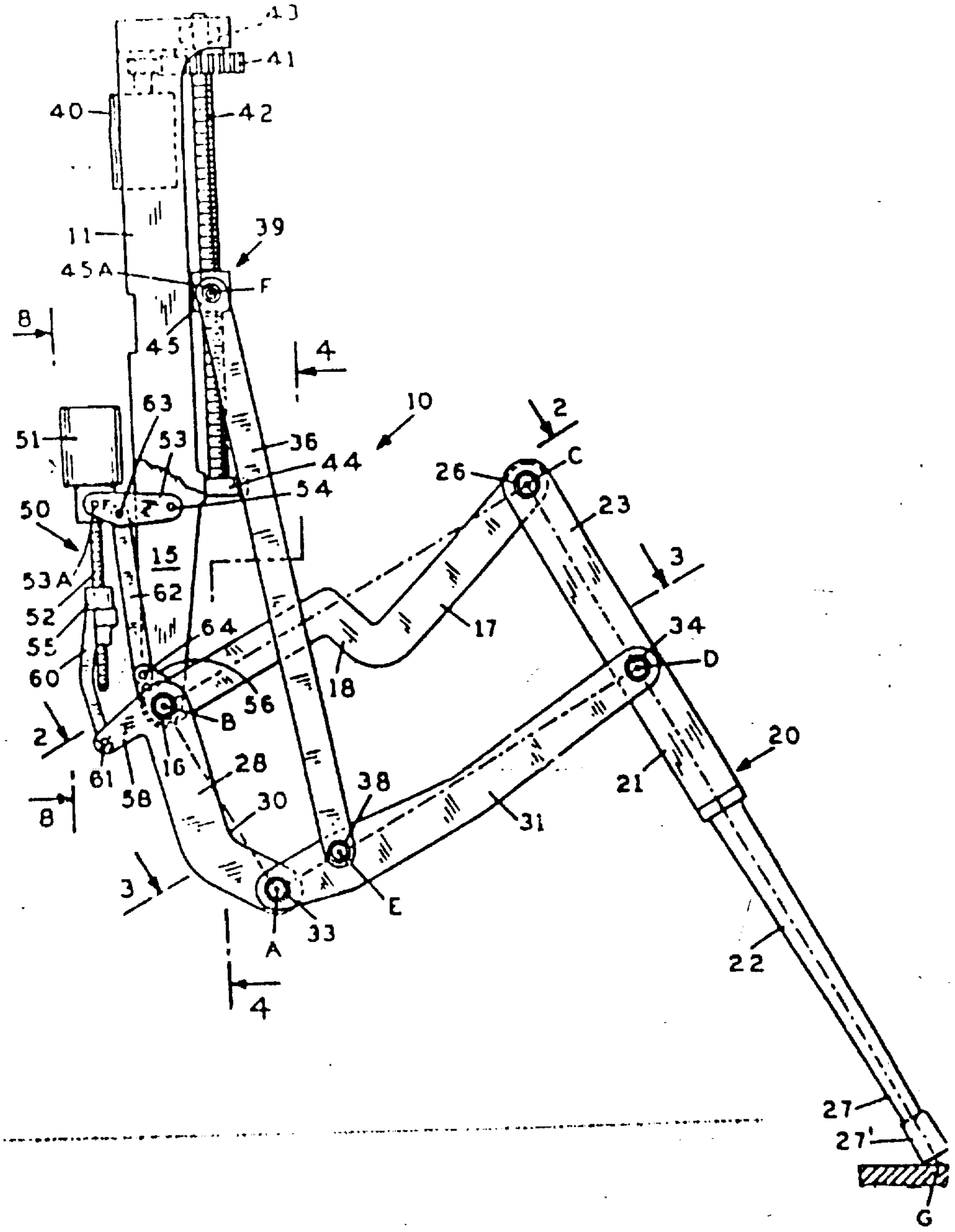

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Fig. 6

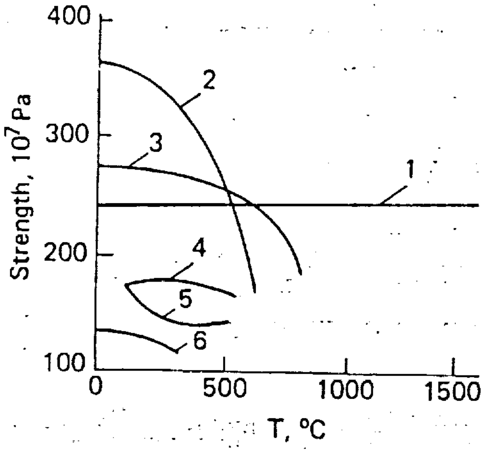

FIG. 7. Temperature dependence of strength of different materials (inert atmosphere): (1) high-modulus CF; (2) glass fibre; (3) boron fibre; (4) steel; (5) titanium; (6) aluminium.

ADAPTATIONS OF PROTOTERP IV WALKING ROBOT
FOR MARS EXPLORATION
(LEG GROUP)

ENME 408 Walking Robot

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Prepared By: Jim Bielec
David Hartsig
Manuel Oliva
Bob Olsen
Bob Rose

INTRODUCTION

The Viking missions of the 1970's gave the world a direct view of Mars from its surface. Since that time a Mars Rover/Sample Return Mission has been called for. One of the unique aspects of this mission is a Mars rover which not only will collect data and samples, as did Viking, but also have the added flexibility of mobility. Design ideas for a rover include simple four wheeled vehicles which are easy to build and control, but cannot traverse many different terrains. Caterpillar like wheeled vehicles are more stable than the four wheeled version, yet can not roll over obstacles of considerable height. According to "Issues and Options for a Mars Rover"[6], the best design for a Mars rover would be a multi-legged walking robot. Such a robot would be able to travel over many terrains and thus be able to explore a large part of the surface of Mars. This paper deals with the adaptation of the PROTOTERP IV for service as a Mars rover.

According to a NASA Jet Propulsion Laboratory briefing, an ideal Mars exploration rover should weigh about 1,700 pounds, travel at least 0.6 miles a day over a three year period, and be able to climb a 60% smooth grade or a 35% loose sand and gravel grade[1]. In addition, an assumption was made by the authors that the rover would encounter sudden drops of no more than 17 inches and travel on terrain similar to Figure 1.[2]

Figure 1. The near field at the Viking 2 landing site. A trough filled with fine-grained sediment runs from the upper left to the lower right. Most of the rocks are deeply pitted, as a result of either a primary vesicularity or etching by the wind. The more massive rock to the upper right is about 1 m across. (Viking lander 2 event no. 21A024)

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Such requirements could be met by the PROTOTERP IV if the legs were slightly modified. The advantage of the PROTOTERP IV compared to a wheeled or tractor design is it's ability to vary leg extension and stride length under different surface conditions. This allows the rover to remain horizontal on varied surfaces and to step up to or over most obstacles. Although a wheeled rover would be faster and simpler to build, it's maneuverability and range would be decreased, due to craters and rocks, and thus defeat the purpose of the rover, which is to travel over many varied surfaces[2].

Some of the modifications needed to adapt the PROTOTERP IV include, larger motors, seals to keep dust out, a new foot pad design and material and lubrication considerations. Each modification is discussed below.

Because the weight of the rover is only 1,700 earth pounds which is about 600 pounds on Mars, each leg will only have to carry 150 pounds with four legs on the ground at all times. The tubes and bearings used in PROTOTERP IV are capable of this load but the worm gear and especially the motor would need to be increased in size. Based on practical experience with PROTOTERP IV, the worm gears would need to be twice as large and the motor four times as powerful.

The Mars atmosphere can be very dusty with dust storms quite common[3]. Dust could be very damaging if it reaches the motors, gears, bearings or screw jack. Sealed bearings should be used because they are self contained and do not require servicing. The motors and worm gears should be completely enclosed, preferably within the outer tubing of the leg. With the motors and gears completely sealed on the top of the outer tube, the only manner in which dust could enter the screw jack is where the inner tube slides in and out of the outer tube. A seal at this point would therefore eliminate any dust from entering.

Because the Martian surface varies from heavily cratered regions to one of sand dunes, the feet must be modified for each leg. Below is a sketch of a possible foot design.

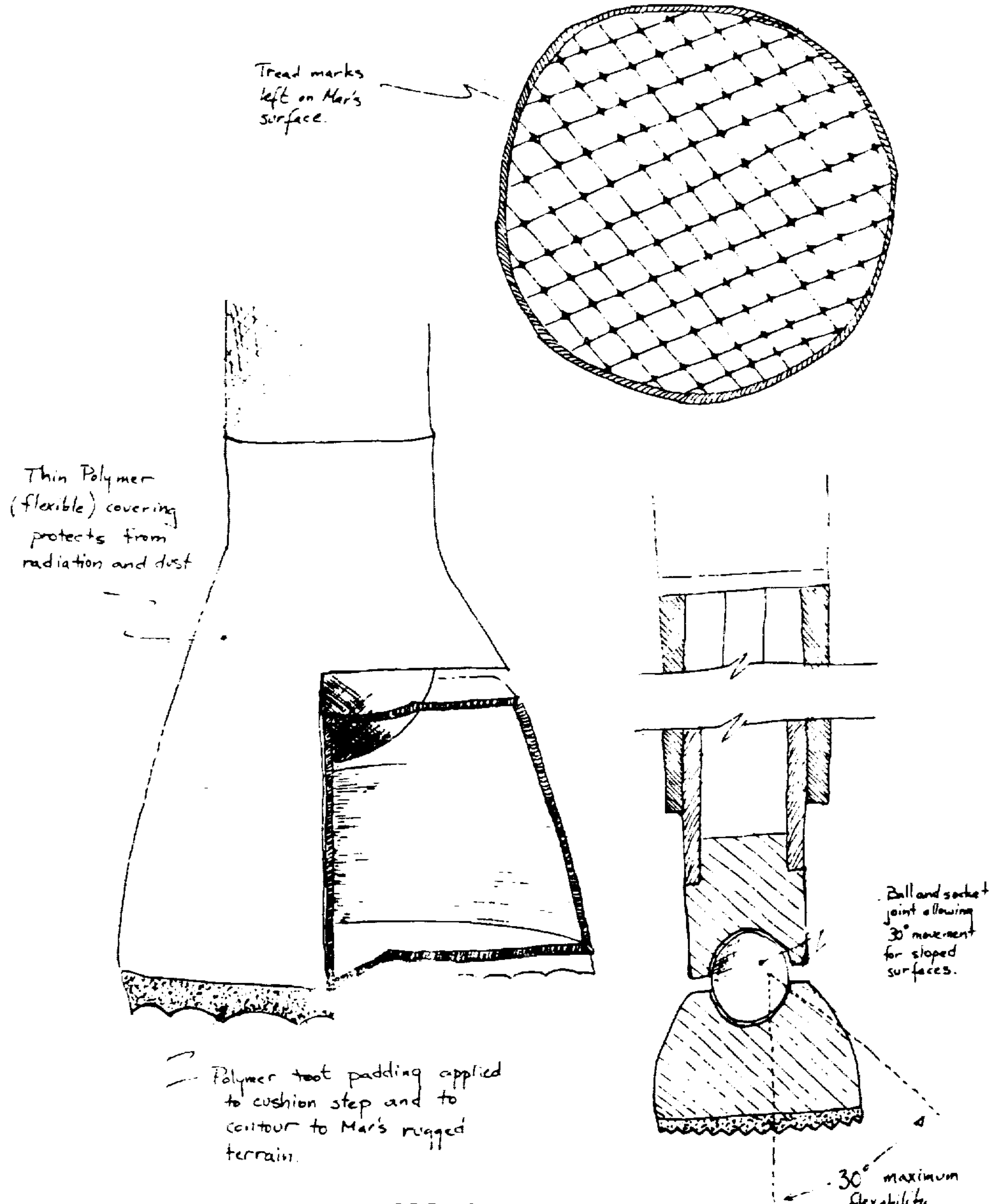

Figure 2. Possible foot design of Martian rover.

The foot design above has a larger surface area than the current design to prevent the legs from sinking into sandy surfaces, yet is small enough not to interfere with the leg motion. The ball joint allows the foot to pivot 30° from the vertical plane to ensure proper footing for stability.

The polymer pad gives traction and allows the bottom surface to contour to the shape of the rough terrain. A rubber cover is used to prevent dust from entering the ball joint and the bottom of the inner tube.

The materials for such a mission need to be strong, light weight and able to withstand sudden temperature changes between -140°C and 68°C[4]. While both aluminum and titanium are light and strong, aluminum can be hard worked, is easy to machine, and resists chemical corrosion better than titanium. Another requirement of the material is its reflectability of the sun to reduce heat gain. This is important because the Mars sun can be strong when there are no dust storms. Aluminum also satisfies this requirement. High carbon steel used in the bearings and screw jack will not rust because of the lack of moisture in the Mars atmosphere. Therefore, the same materials used in PROTOTERP IV could be used in the Mars application.

Lubrication for the gears and screw jack would need to withstand long duty life and large temperature changes. Synthetic lubricants are the best choice since they have a wide service temperature range. This means they maintain good flow characteristics at low temperatures and are stable at high temperatures. It is, however, important that the lubrication and seals are properly matched to ensure compatibility[5].

One major modification which would be required is the addition of an "escape device", in order to prevent the rover from becoming trapped on the hazardous martian surface. For example if the rover were to fall over or get trapped in a deep hole, a mechanical arm could be used to pull the rover out of trouble. This same arm could obviously be used to collect samples from the surface. It is important that the design of the arm take into consideration it's possible use as a ninth leg. Other possible design options would be the use of air bags, stabilizing struts or even winches and grappling hooks[7]. For extreme situations, breakaway mechanisms such as the foot pads could be sacrificed to allow the robot to break free. Although this would hinder the robots ability to maneuver, it would allow the mission to continue.

Because the current design of the PROTOTERP IV offers high maneuverability, it is possible to explore a large extent of the Mars' surface. As seen, modifications would be needed in order to meet the specific environment of Mars. Because the modifications do not affect the basic operation of the rover, any experience gained by PROTOTERP IV could have direct application in understanding how future Mars missions could be successfully planned and performed.

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