SRC TR 88-63

Walking Robot: A Multidisciplinary Design Project for Undergraduate Students

by

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Abstract

The advances in computer technology have made many forms of industrial automation possible. Machines that help to enable this automation are usually controlled by computers through software. The design of such machines will involve engineering professionals working together as an interdisciplinary team. For engineering students to gain some experience on this design practice, a project course in which the students designed and built a walking robot was offered at the College Park campus of the University of Maryland. A walking robot competition with a comprehensive rules package provided the design objective for the project. The competition rules, the organization of the project, and the actual account of the project in a particular year are presented in the paper.

1. Introduction

The advances in computer technology and the reduction in the costs of computers have made significant impacts on many facets of modern life. Among them are those on modern factories with the use of computer controlled machines such as industrial robot manipulators, machine tools, coordinate measuring machines, and automated guided vehicles. These machines have one thing in common, namely, their actuators are controlled by computers. It is reasonable to anticipate that we will see many more of computer controlled machines as time goes on. Many of these machines will be designed and built by future engineering and computer professionals who are today's students. A project in which students from different disciplines are to work together to design and build one such machine should provide a good educational training to them. What is to be presented in this paper is the experience the authors had in offering such a project. Papers on design projects exist in the literature [1-3], but none of them reports on such an interdisciplinary activity.

The project was to design and build a walking robot that achieves mobility with the use of leg-like mechanisms rather than wheels. Legged robots are not in practical use today, but there have been active research on them since 1960 [4]. They can be simple like walking toys, or very sophisticated like the walking robot at Ohio State University [5]. The range of complexity allows students to set a practical goal that can be achieved within a fixed duration of time. Computer control is required when sufficient sophistication is specified. The walking robot competition, originated at Colorado State University in 1987, provided the design specifications.

In the Springs of 1987 and 1988, students from the University of Maryland at College Park, participated in the first and the second annual walking machine decathlon. The first competition with 3 entries was held at Colorado State University at Fort Collins, while the second one with 7 entries was held at their home campus. The objectives of the competition were to encourage undergraduate interdisciplinary cooperation, to promote familiarity with technological advancement of robots, and to foster creativity.

In the competition rules package [6], a walking robot was defined as *a mobile terrain adaptive system with several (eight or less) articulated mechanisms (arms and/or legs) to facilitate the mobility.* There were ten levels of performance for the walking robot to participate in, and thus the name *decathlon.* The levels were arranged so that they were progressively more difficult to achieve. Each entry that could finish a lower-level performance could participate in the next higher-level of competition.

In 1988, the second year of competition, students from both mechanical and electrical engineering departments participated in the project. This made the project a truly interdisciplinary activity. The design goal chosen was one that computer control was required. This paper summarizes our experience in the second year.

There are several unique features associated with this project. First, the competition dictates that the project be a design-and-build activity rather than simply a paper design. With the actual fabrication and assembly of a robot, students learn about practical design considerations, *which are so vital but yet so difficult to deal with adequately as part of a theoretical lecture course* [1]. Design flaws are most easily uncovered in the process of putting the real things together, and the correction of the design flaws can be very educational. Second, a walking robot, like an industrial robot, is made up of several subsystems, each of which can be a design task carried out by a group of students. For the robot to actually function as desired, all subsystems have to fit together properly, and this requires good coordination throughout the project. The operation resembles the ones for the design and manufacture of many industrial systems. In particular, since different subsystems call for students from different educational background, interdisciplinary coordination is mandatory. Students learn to communicate technically with those from other discipline and they learn about specifying requirements for other subsystems. Additionally, with the competition looming in the students' mind, motivation is strong and creativity is stimulated. It can be intuitively argued that exercising creativity is similar to performing skillful tasks; the more you do it the better you are at it. Finally, since factory automation is generally viewed as the way to be, working on the walking robot induces interests and fosters familiarity with the field of automation. This may have some positive psychological effects that can expedite the move to automation.

2. Summary of Competition Rules

The 1988 Walking Machine Decathlon consisted of a preliminary static judging and ten levels of performance events.

Static Judging: The static judging had a maximum of 1,000 points. Its purpose was to assess the compliance of the design with the rules, its safety and its ability to compete in the performance events. The static judging consisted of general inspection, design evaluation, and technical paper presentation.

The general inspection consisted of six areas of judgement, all of which had to be satisfied. They included: (1) the size of the walking robot not to exceed one meter wide and one meter high, (2) the walking robot had to be judged *safe* from the standpoint of being easily controllable, with no dangerous protruding surfaces, and its feet not to damage the hardwood floor during the performance events, (3) the walking robot not to have more than eight articulated legs and/or arms, (4) the power supply for the walking robot had to be on board and no gasoline engines were permitted, (5) the walking robot had to have a designated front end, and (6) a technical paper with a detailed cost break down, was required to foster information exchange.

The design evaluation included aesthetics, structural integrity, and innovativeness of the design. The walking robot was also required to perform a short *start-up procedure* to demonstrate its ability to compete in the performance events.

The purpose of the technical paper presentation was to promote the exchange of information between participants. The presentation was to be made by a student member of each participating university and had to follow the general guidelines given in the American Society of Mechanical Engineering publication MS-4A.

Performance Events: The performance events consisted of ten levels of performance arranged in order of increasing difficulty. All participants were required to start at level one. After successfully completing the required task at a given level, the participating walking robot had the opportunity to move up into the next level. Each level of competition had a maximum of 1,000 points. The points obtained at each level by a walking robot was calculated by a formula which was based on the time required for the robot to complete a given task.

The first five levels did not require the walking robot to be autonomous. Hence, real-time control by an operator using a tether or radio-control was permitted. A tether could also be used to connect the walking robot to a computer. The only limitation was that power source for the walking robot had to be on-board. Also, once the walking machine was activated to start a particular task, it could not be touched or handled by any member of the team. The last five levels, however, did require that the robot to be autonomous. Therefore, no tether or radio control of the walking robot was allowed.

The first five levels of competition started from a simple straight-line sprint (level 1), to a diamond-shaped walking that required the robot to have turning ability (level 2), to a diamond-shaped walking with two controllable walking speeds (level 3), to an obstacle course of randomly located wood beams (level 4), and finally traversing a small staircase (level 5).

The next five levels of competition was essentially a repeat of the first five except that the walking robot had to be autonomous with some artificial intelligence such as audio recognition, vision, and other sensing capabilities. The last few levels were purposely made unattainable with the current technology.

Participant could choose to compete up to the level that was most compatible to their resources and experience. A plaque of recognition was awarded to the top three overall winning teams.

3. Description of the Project

In this section, we summarize the main project activities including concept generation, design and analysis, fabrication and assembly, and testing of the walking robot. The overall project was accomplished within two semesters. In the first semester, a group of twelve students concentrated their efforts on designing the robot. In the follow-up semester, a group of twenty-two students focused their attention on finalizing the design, fabricating and/or ordering various parts, assembling, and testing of the robot. The students who participated in the project were a mixture of senior mechanical and electrical engineering majors, some taking the project for credit while others volunteering their time. Students were encouraged to do work outside their majors, regardless of their level of experience.

3.1. First-Semester Project

The first-semester project was charged with a paper-design of the walking robot. The design was planned to achieve walking at two different speeds, turning, negotiating randomly placed obstacles, and traversing a small staircase. During the initial two weeks of the first semester, students spent their time researching the literature on the topic of walking robots. The following few weeks were spent on selecting the type of leg to be used, an important component of the robot. Due to the type of leg selected, it was realized that the turning of the robot was best to be accomplished by rotating the body about a central leg. It was also decided that the robot would be a hexapod, grouped in two tripods. The tripod configuration were selected mainly for stability and simplicity reasons. The students were then divided into three groups, namely, the leg group, the body group, and the control group.

3.1.1. The Leg Group

The first design concept considered by the leg group was the pantograph leg, Figure 1(a). In this type of leg, two actuators would provide independent control of the vertical and horizontal motion of the leg. This idea, although relatively simple to implement, was not adopted mainly due to the large size of the leg needed for climbing the stairs. Several other leg concepts were also considered including a *cartesian* leg, a leg with three degrees of freedom, a leg that responded similarly to an automobile suspension, etc.

The leg group finally settled upon the cartesian leg concept, Figure 1(b). This concept involved an on-board gear reduction cable-driven mechanism for vertical motion and an off-board cable-drive, mechanism for horizontal motion. A major advantage of this concept, in addition to its simplicity, was that it could provide the lift necessary to clear the stairs without drastically increasing the size of the leg.

It was decided that for simple walking, the body of the robot would be lifted about 0.025 meter off the ground, walking on alternating tripods. To turn, the robot would lower itself to rest on a centerally located foot called *the bigfoot.* The legs would then raise up off the ground, and the robot rotates about the bigfoot to a desired orientation. After which the legs might be lowered again to raise up the robot.

The materials used for the leg design included aluminum for the gear housing, leg, pulley, and support brackets. All shafts, including the idler pulley shaft, the worm/spur gear shaft and the worm gear/pulley shaft were made of steel.

The leg design for the robot was divided into two areas, the vertical drive and the horizontal drive. The requirements considered for the design of the vertical drive is given in Table 1.

Table 1

Vertical Drive Design Requirements for Each Leg

$$\begin{aligned} \text{Weight to be lifted} &= 14 \quad kg \\ \text{Acceleration} &= 0.1g \\ \text{Velocity} &= 0.025 \quad m/sec^2 \\ \text{Leg height} &= 0.5 \quad m \end{aligned}$$

The vertical drive basically consists of a U-shaped tubular leg which has a cable, driven by a pully, attached to each end of the leg. To begin design of the vertical drive, a preliminary prototype was built to demonstrate the concept of the cable drive. The prototype showed that it was inefficient to drive the pulley by a motor directly, so a two-stage gear reduction was used. To save energy, a worm gear is also used to provide a self-locking feature so that the vertical motor can be turned off whenever the robot is standing still. The pulley is placed inside a gear housing while sitting partly inside the leg. The pulley is driven by a DC motor mounted on the top of the gear housing. As the pulley turns one way or the other, the leg is moved up or down by the cable which is connected to both ends of the leg, as shown in Figure 2.

The horizontal drive have to accomodate the vertical design and to provide enough power for the forward or backward motion of the robot. The requirements considered for the design of the horizontal drive is given in Table 2.

Table 2

Horizontal Drive Design Requirements for Each Leg

Weight to be lifted = 14 kg
Acceleration = $0.05g$
Velocity = 0.05 m/sec^2
Travelling distance = 0.15 m

The leg assembly rests on two horizontal shafts, namely the slide rods, which give each leg freedom of a horizontal travelling distance of about 0.15 meter. The horizontal motion of the leg is controlled by a cable which is driven by a stepper motor. The stepper motor is used for accurate horizontal positioning. The cable is attached to each side of the gear housing for pulling the leg back and forth along the sliding rods. The cable forms a triangle with the drive pulley and the two side idlers in the corners as shown in Figure 3.

3.1.2. The Body Group

The body of the walking robot has several functions. It provides the support for and connection between the legs, power source, and control circuitry. It also contains the mechanism to turn the robot. The body was designed to be light, strong, stable, inexpensive, and meet the requirements of the leg and control groups.

The initial design of the body was only a side consideration of the leg design. During the initial leg design phase, the body was simply an undefined structure which provided support at the appropriate points. It was decided, for stability and simplicity reasons, that the robot would be a hexapod. Next, the leg placement configurations had to be selected. Figure 4(a) and 4(b) show two leg placement configurations which were considered. In one of them the legs were configured in two rows of three, while in the other the legs were evenly spaced on a hexagon. Again for ease of construction and assembly, it was decided to place the legs in two rows of three.

Turning of the robot had to be accomplished by the body, since the legs had only two degrees of freedom. Again, at the beginning, two basic concepts were considered. One was for a body with two frames that could rotate relative to each other. The two-moving-frame design would allow the robot to turn as it walked. This concept, however, would permit only small turns (around 30 degrees maximum) of the robot in a single step. The other was *the bigfoot* concept, where the robot would sit down on a centrally located foot and then turn on it. The early concept for the bigfoot required it to extend and retract, thus required an extra motor and additional control. A simpler concept evolved in which the bigfoot was a fixed distance below the bottom of the frame and the robot could sit down on the bigfoot and then turn (the sit-and-spin manuver). Therefore, the bigfoot idea was selected for its simplicity and ease of implementation.

The remaining decision was what to put between the two side beams. Numerous ideas and sketches were considered. The final choice came down to two basic designs, the ladder-and the X-frame, Figure 5. Subsequent analysis and calculations on the two frames showed the X-frame to be a stronger design. At this point, the length and width of the body were also decided upon to be 0.75 meter, hence making a squared robot.

Once the basic design and dimensions were finalized, material and beam type had to be selected. In addition, for the worst possible condition, a stress and stability analysis had to be performed. For the material, aluminum was selected because it was light weight, stiff, strong, and reasonably inexpensive. For the beam type, a reasonable compromise between strength and weight seemed to be the C-section, which was reasonably strong for bending and torsion, though not as strong as a square tubing. Once the sizes of the beams were selected, a stress and defelection analysis was performed to insure that for the worst possible conditions the desired specifications were met. Finally, to have a stable robot, it was imperative that the robot remained upright at all times during walking. A static stabiltiy triangle was used, Figure 6, to ensure that the center of gravity for the robot remained inside the triangle for the worst position of the robot. This position could occur whenever the down-tripod was in its full-forward position and the up-tripod was in its full-backward position or vice-versa.

Finally, the turning mechanism (the bigfoot, the turning drive, the bearing between the bigfoot and the frame), the location of the control circuitry, batteries, and the details of the leg mounting were finalized. For the turning mechansim, the bigfoot had to be connected to a solid and stable base on which the robot could rotate. The final design for the bigfoot has four spokes, 0.28 meter each, at right angles which form a cross pattern. The feasibility of this design has been demonstrated by ordinary office chairs which has a crossed-base and an excellent stability. For the turning drive, a simple gear-pinion planetary selected in which there is a gear on the bearing housing while the frame supports the motor and the pinion orbits the gear.

3.1.3. The Control Group

Once the mechanical design reached a certain stage, it was clear that there would be a vertical and a horizontal motor on each of the six legs and one motor to control the body for turning. It was decided that the robot would walk on two tripods, each consisting of the front and the rear legs on one side and the middle leg on the opposite side. Thus three legs would move in unison, one tripod on the ground, propelling the robot forward, while the other set moved into the position ready to descend.

The goal set for the control group was to provide a control system which was cost-effective and easy to build while flexible to change. It was felt that this goal was achievable if the control system was software intensive. Hence, an available IBM-XT-286 personal computer was selected to communicate with the robot. The computer was equipped with an input/output expansion card to output control signals to the robot or feedback signals from the robot.

At the beginning, for several weeks the control group was asked to investigate the electronics hardware setup needed for the task. Several schemes were considered including an infrared or radio frequency link between the computer and the robot on-board controller. This and other ideas were rejected due to various difficulties projected in their implementation. By the eighth week, it became apparent that all the previous exploration of various hardware setups was premature and that an overview of how the robot was to be controlled, that dealt neither with hardware nor software, was necessary. This overview was greatly simplified by adopting a numbering scheme for the legs and a lettering scheme for the tripods. This is what leg configuration means and as is shown in Figure 7, the legs are divided into two sets. The first set is made up of legs 1, 3, and 5, and is labeled tripod A. The second set is consisted of legs 2, 4, and 6, and is labeled tripod B.

A control hierarchy was also established to divide the robot commands into four levels of control, namely, low-, medium-, high-, and highest-level. A group of low-level control commands makes up a medium-level control. A group of medium-level control commands makes up a high-level command. The high-level commands are assembled to create the highest-level control.

A low-level command is also referred to as an instruction. An instruction involves the finest level of control. It conveys, for example, which motor to be turned on, direction of rotation (clockwise or counterclockwise), duration of rotation, and speed. A group of low-level commands forms a medium-level command. For example, *tripod A move forward or tripod B move backward,* are typical of medium-level commands. The medium-level commands are also called control arrays because they are formed by a set (or a sequence) of instructions. In a similar manner, a high-level command consists of a set of control arrays. A high-level command may be used to build a motion such as *forward and backward* motion of the robot. Using a set of high-level commands (which forms the highest-level command) the robot should be able to perform complex tasks automatically. For example, a highest-level command may involve a *180 degrees turn* followed by a *walk forward for several steps* and a *return back to the original position* of the robot.

3.2. Second-Semester Project

The second-semester project was charged with finalizing the first-semester design, fabricating/ordering the necessary components, assembling and testing of the robot, and competing in the second annual walking machine decathlon. Students involved in the project were divided into five groups, namely, the vertical drive group, the horizontal drive group, the body group, the control hardware group, and the control software group.

3.2.1. The Vertical Drive Group

The first task of the group was to check the integrity of the vertical drive design suggested by the leg group of the first-semester. It was then decided to fabricate and/or order the parts needed to build a sample leg to see whether it would realy work. During the assembling and testing of the sample vertical drive mechanism several problems were discovered that had to be corrected. The main problems included (1) the existence of more friction than anticipated, hence a larger motor and a stronger cable for the vertical drive were needed, (2) the slippage of the cable on the pulley, hence gasket adhesive were used to prevent the slippage, (3) several unanticipated difficulties during assembling such as incorrect alignments, lack of sufficient precision on some of the dimensions, etc. These and other problems were finally corrected. The group then mass produced the vertical drive mechanism for the six legs.

3.2.2. The Horizontal Drive Group

The first task was to check the horizontal drive designed in the first-semester. For the sample leg, the necessary parts were ordered and/or fabricated. Again, during the assembling and/or testing several problems were discovered, namely, (1) the existence of more friction than anticipated, hence a more powerful motor and a stronger cable were needed, (2) with the powerful motor selected, the gear reduction for the horizontal drive was no longer necessary, hence pulleys were designed for direct drive between the motor and the horizontal motion of the legs. The group then mass produced the horizontal drive mechanism for the six legs.

3.2.3. The Body Group

The construction of the body-frame closely followed the design suggested by the first-semester body group. It consisted of two longitudinal side rails to support three leg-assemblies per side-rail, with the ends of the side rails connected to an X-shaped structure. The center of the X was cut out to form a cavity in which the bigfoot assembly were placed. The bigfoot assembly were composed of two perpendicular crossed square tubing, a shaft, bearing housing, gear housing, and the motor. The body also consisted of a deck for the control circuit board and a platform on the top of it which could hold a five pound weight. This platform was required by the competition's rules [6].

3.2.4. The Control Hardware Group

The control hardware is basically composed of (1) the main control board (the motherboard), (2) the motor driver board, and (3) the power supply. The motherboard receives and sends data from the computer including feedback data, data corresponding to the direction of movement of the motors, and speed control data. The output from the motherboard and the 13 *enable* lines, are sent to the motor driver board. This board comprises the drivers for the seven DC motors which are used for (six) vertical and (one) rotational motion of the robot. It also contains the drivers for the six stepper motors which are used for horizontal motion of the robot. Finally, the power supply for the robot was determined based on the operating conditions of each motor under the maximum estimated load. It was estimated that 7 amperes of current will be needed under maximum current draw conditions. Six 6-volt batteries were then selected and configured to provide the needed power for 45 minutes of continuous operation. For safety considerations, it was decided to separate and properly fuse the power supplies for the motherboard, body motor, and vertical and horizontal motors.

3.2.5. The Control Software Group

Originally, it was intended that the controls to be extremely software intensive. This was found to be not entirely practical nor optimum from the performance point of view. Therfore a control scheme was selected that took advantage of of both software and hardware.

The goals set for the software group were as follows:

1) make the controls as user-friendly as possible,
2) make the controls as flexible as possible allowing for easy changes,
3) make the software compatible with the previous semester design.

Of primary concern was making the the controls as *user-friendly* as possible. This was achieved by the use of an extensive menu system. There are three basic levels of control to this menu system. The highest-level is the Main Menu which has three modes for complex movements (mode 1), simple movements (mode 2), and system configuration (mode 3).

Mode 1 includes choices such as walking, turning, and climbing. In a similar manner, mode 2 includes choices such as single leg movement, tripodal movement, quadruped movement, etc., and finally mode 3 which may be used to change the output addresses, if necessary.

The maximum flexibility in the software was accomplished by using data files instead of coding directly into the program. This allows one to ignore the logic of the program and only be concerned with the file syntax. For example, if one were to develop a new movement, only a small section of the data file would have to be changed instead of searching through the entire code and make the changes.

4. Project Organization

As it was mentioned before, each semester the project was organized into several groups of four to five students each. These groups were then organized into two distinct yet interconnected teams, namely, the mechanical and the control teams. The mechanical team was responsible for the vertical drive, the horizontal drive, and the body. The control team was responsible for the control hardware, and the control software.

A group leader for each group and an overall student project leader were elected by the student body. Each group leader was responsible for the coordination of the work within his own group and for the communication with the other groups and the student project leader. The student project leader, using faculty advisors as his consultants, had the responsibility and authority to coordinate the work amongst the five groups and to monitor the progress of the project as a whole. In addition, all of the students had the opportunity to discuss with the faculty advisors regarding any related technical problems. Figure 8 shows the organization chart of the project.

The whole class met once a week at the presence of the faculty advisors. Under the coordination of the student project leader, a representative from each group made a weekly progress report to the whole class in order to stimulate discussions between the students and the faculty advisors. The representative was rotated from one to the other so that all of the students had a few chances to make the presentation. A project schedule was also developed at the beginning of the semester and the progress of the project was monitored very closely according to the schedule as if it were a real project in the industry.

5. Accomplishment and Benefits to Students

The Second Annual Walking Robot Decathlon was held at the University of Maryland at College Park in April of 1988. The University of Maryland Walking Robot, as shown in Figure 9, entered the competition, passed the static judging, and successfully completed the first three levels of the performance events. The robot was intended for competing up to the fifth level. At level 4, however, it took too long for the robot to complete the event and accordingly was disqualified for entering into the fifth level. As a result, we finished with a second-place overall ranking.

The benefits to the students from participating in such a design-and-build project are numerous. The following are a few examples:

1) Hands-on practical design experience which is not usually present in a formal course,
2) project management experience,
3) team-work experience in a multi-disciplinary project,
4) training in creativity during the initial conceptual design phase,
5) awareness of current technology that are available for the design of an intelligent robot,

6) realization and appreciation of some specific problems associated with the development of a modern technology.

The student found that the transition from the *paper-design* to a working system was not always a smooth one. One student admitted that he learned more in this project than any other courses. *We had to make several unanticipated changes to the original design,* said a mechanical engineering student. *It looks easy on paper, but when you look at the real thing you run into problems,* said the other.

The project bridged the theoretical aspects of robotics with real-world design. The purpose was to challenge the students and to give them practical experience. The students learned to work together and consider design factors normally outside their field of study.

6. Grading Method

Because of the nature of the project, no examinations were given to the students. Instead, we developed the following scheme for the assessment of students.

The grades were determined mainly by the following three factors:

1) Student's weekly reports; the weekly written and oral reports, and discussions made by each student were carefully evaluated and used as the first factor for the final grade.

2) Student peer evaluation; since all the student spent a lot of time working on the project on their own and as a group, we asked all the students to evaluate each other within their own group. This is then used as the second factor in determining their grades.

3) Contents of the notebook and a short meeting with each student to see how much effort each student put in the project and also how much each student understood and learned from the project.

7. Concluding Remarks

The most tangible result from this project was the walking robot. However, the most important result was the experience each student obtained by participating in the project. When solving problems in a textbook, students are often given ideal situations, e.g., gears line up properly or resistors have values as printed on their case. The project demonstrated that problems and situations are far from ideal in the real world and that inefficiencies might come from many unanticipated sources.

Students also learned that the design process is far more than just defining a problem, finding the best solution, and moving on. It was necessary for each student to express his/her thoughts clearly to convince other students of the feasibility of his/her ideas. In addition, like professional engineers on the job, students learned that in order to complete the project on time, they had to have a systematic and practical approach to the project. In short, they had to plan the project and plan it well.

8. Acknowledgement

This paper is based in part on a series of weekly and final project reports prepared by the students during the academic year of 1987-88. Financial aid for building the walking robot was provided by the Department of Mechanical Engineering, Dean's Office of the College of Engineering, and the Systems Research Center of the University of Maryland.

Our special thanks go to Dr. William Fourney, Chairman of the Department of Mechanical Engineering, for his constant support and encouragement during the course of the project.

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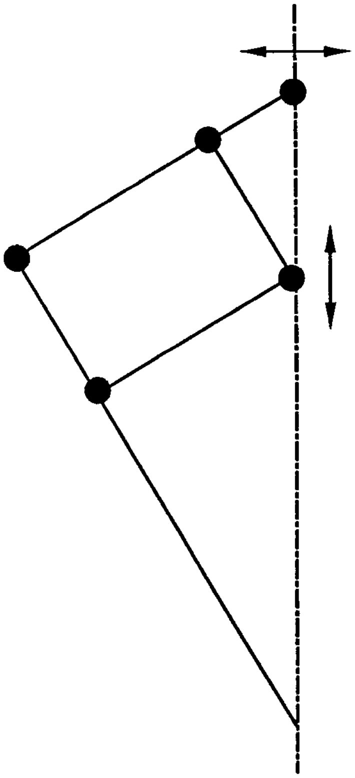


Figure 1(a). Pantograph Leg

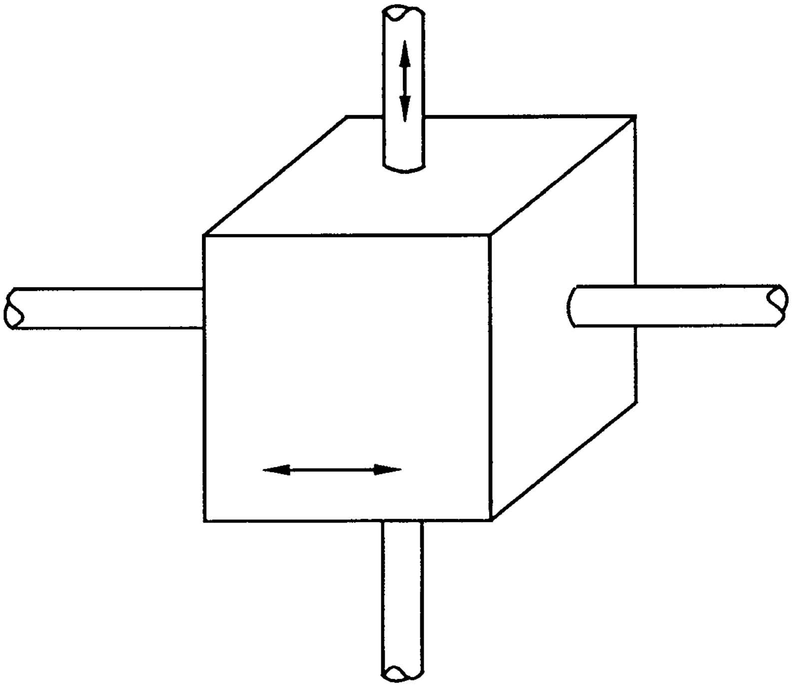


Figure 1(b). Cartesian Leg

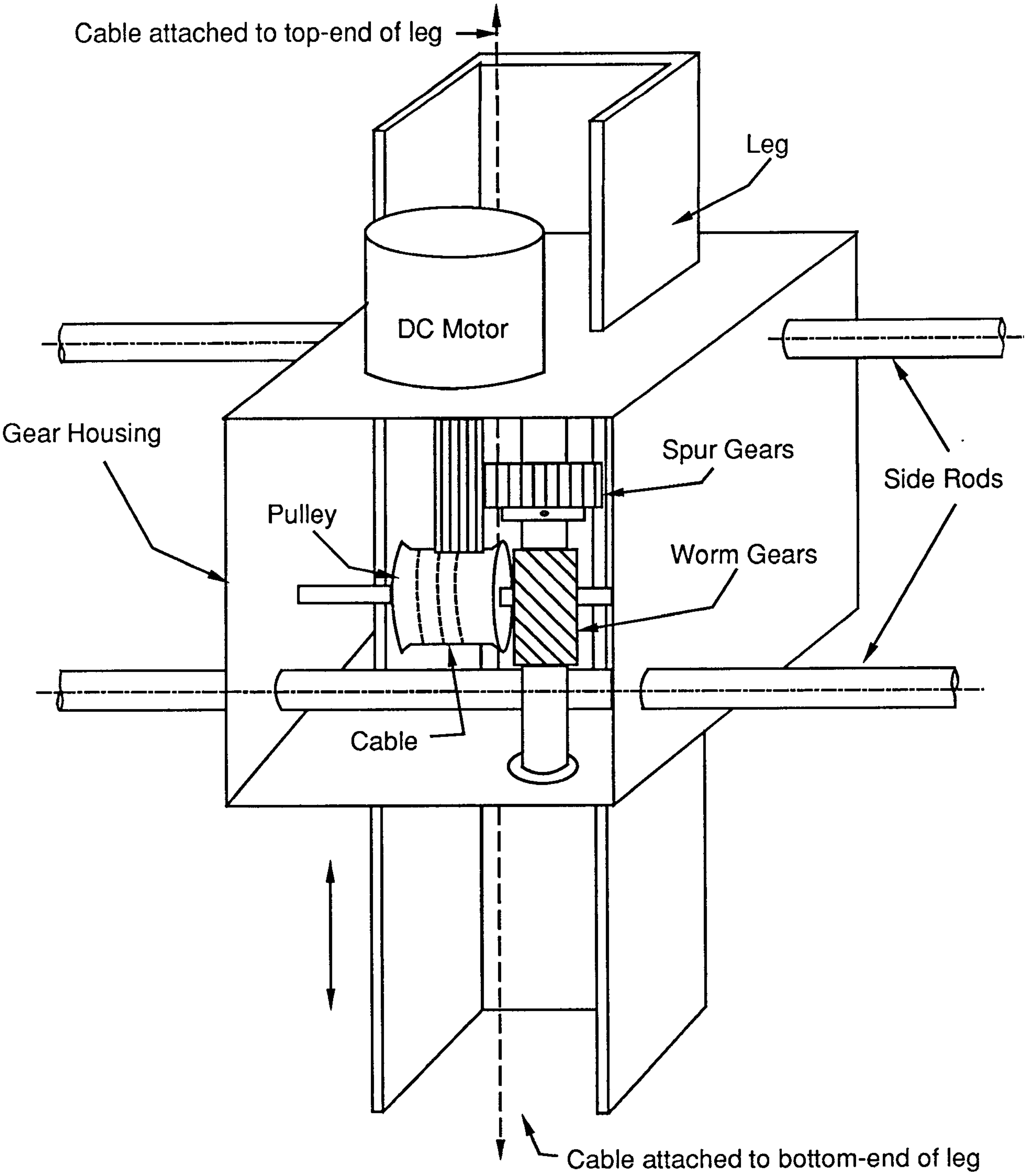


Figure 2. Vertical Drive Assembly

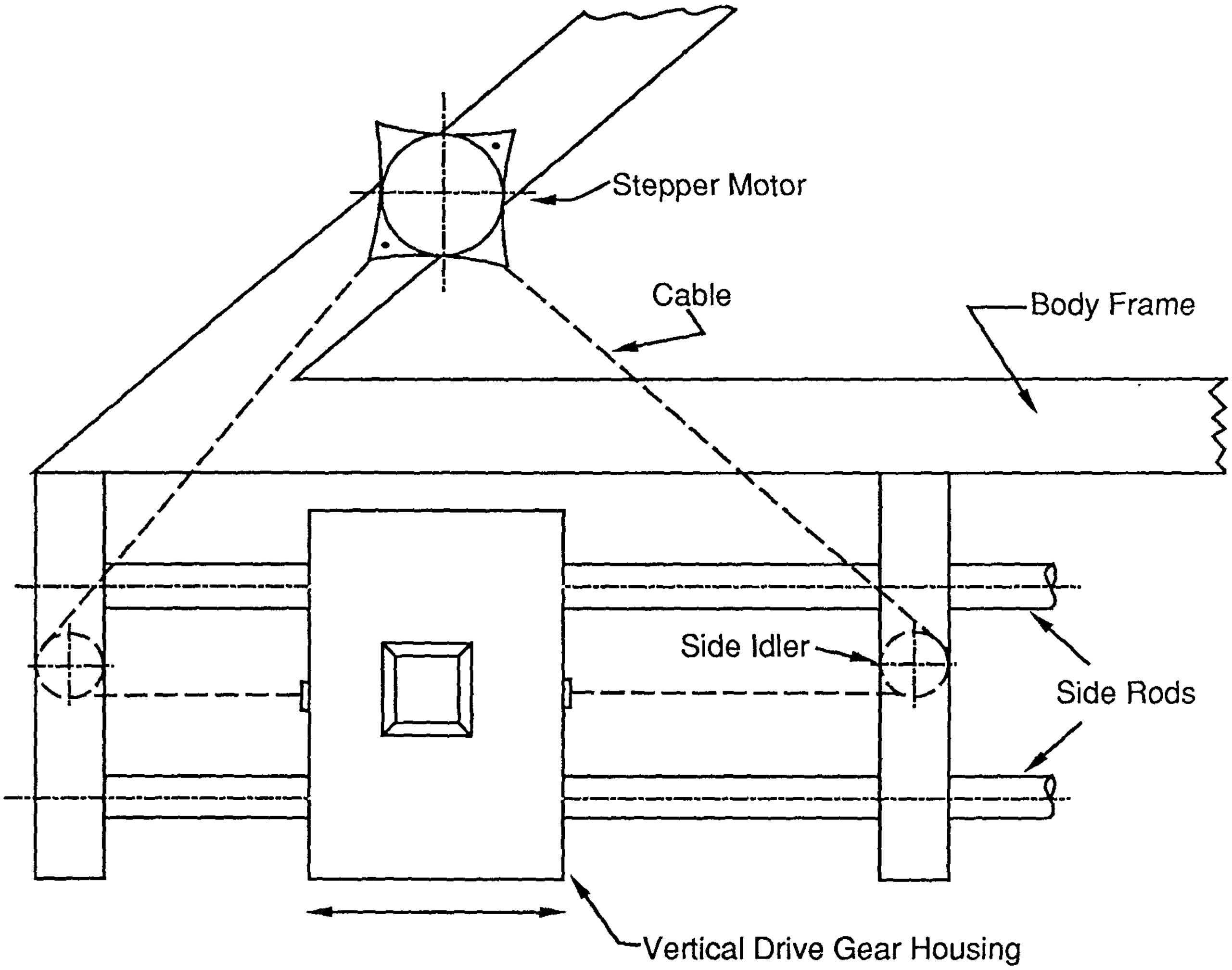
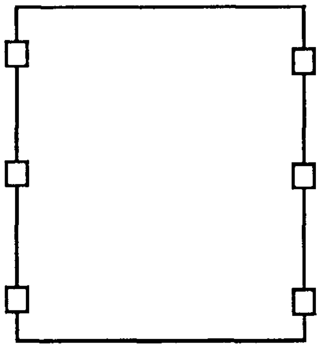
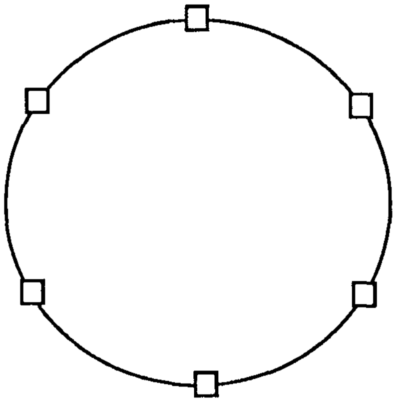


Figure 3. Horizontal Drive Assembly

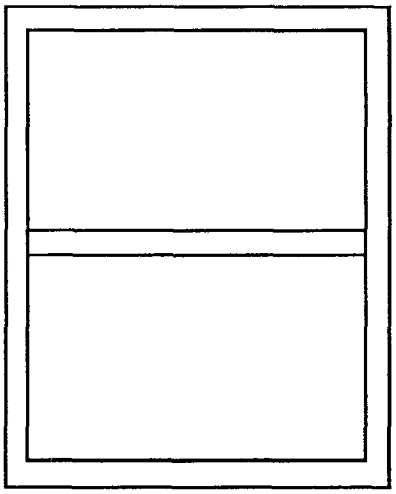


a) Two Rows

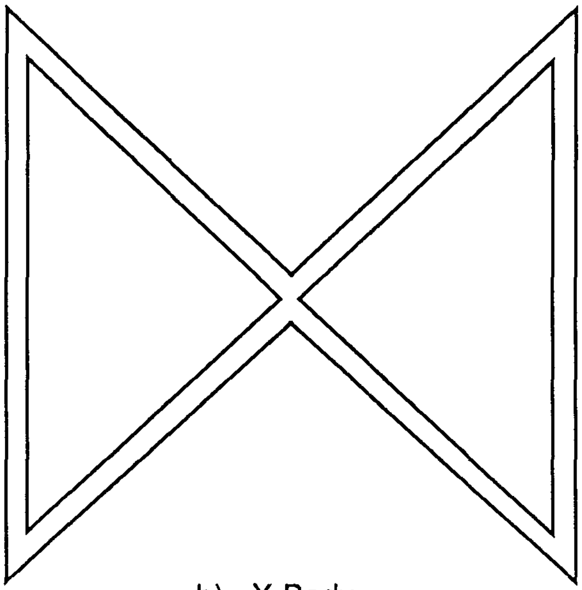


b) Hexagonal

Figure 4. Leg Placement Configuration



a) Ladder Type Body



b) X-Body

Figure 5. Body Design Considerations

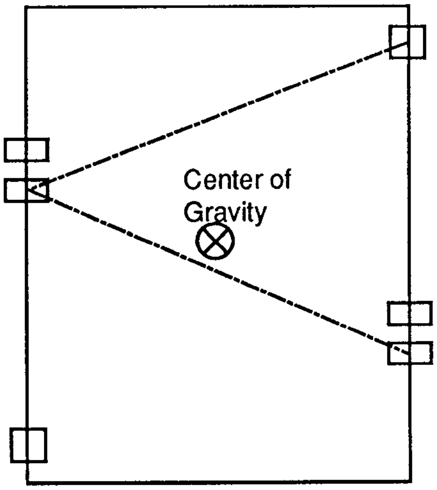
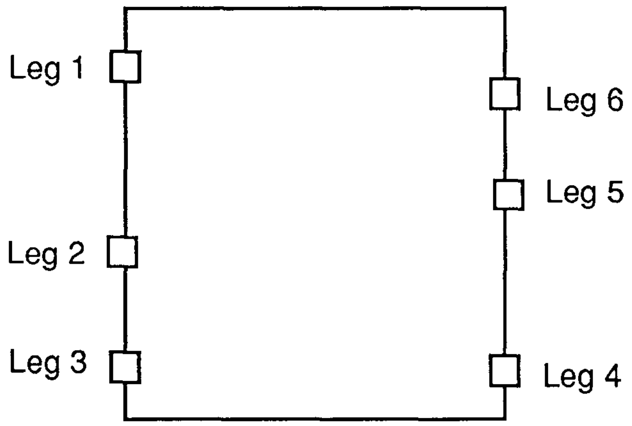


Figure 6. Stability Triangle



Tripod A : Legs 1,3, and 5
Tripod B : Legs 2,4, and 6

Figure 7. Leg Configuration

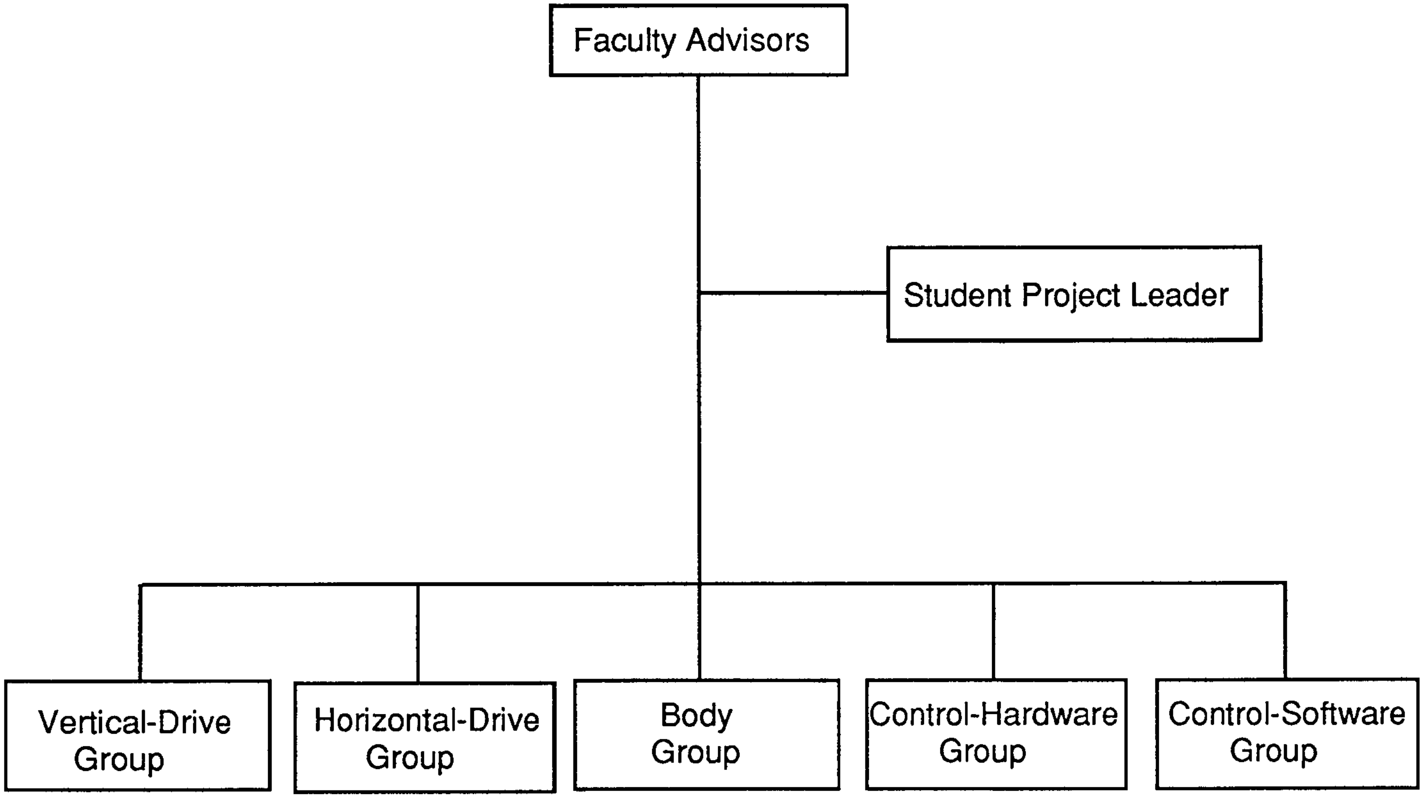


Figure 8. Project Organization Chart

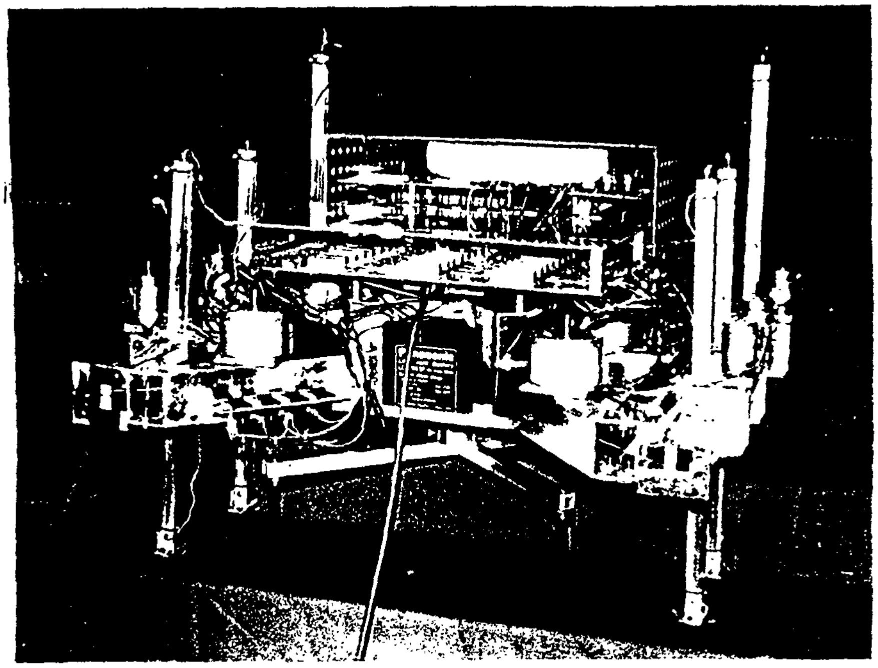


Figure 9 The University of Maryland Walking Robot