1991-1992 WALKING ROBOT DESIGN

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Abstract

The Universiy of Maryland Walking Machine team designed and constructed a robot. This robot was completed in two phases with supervision and suggestions from three professors and one graduate teaching asistant. Bob was designed during the Fall Semester 1991, then machined, assembled, and debugged in the Spring Semester 1992. The project required a total of 4,300 student hours and cost under $8,000. Mechanically, Bob was an exercise in optimization. The robot was designed to test several diverse aspects of robotic potential, including speed, agility, and stability, with simplicity and reliability holding equal importance. For speed and smooth walking motion, the footpath contained a long horizontal component; a vertical aspect was included to allow clearance of obstacles. These challenges were met with a leg design that utilized a unique multi-link mechanism which traveled a modified tear-drop footpath. The electrical requirements included motor, encoder, and voice control circuitry selection, manual controller manufacture, and creation of sensors for guidance. Further, there was also a need for selection of the computer, completion of a preliminary program, and testing of the robot.

Introduction

The University of Maryland Walking Machine team designed, manufactured, assembled and analyzed a walking robot, "Bob Terpinator," as a prototype walking machine. Funding was mostly provided by a grant from USRA. Significant donations were also made by various other companies. Bob was designed to provide a means for land-based explorations without the limitations of "wheeled" transport vehicles. The long-term goal of the project was the production of a semi-autonomous walking machine able to navigate a broad range of terrain. The short-term goal was participation in the SAE Sixth Annual Robotic Walking Machine Decathlon which was designed to test many aspects of a walking machine's abilities. This provided the team with more specific design parameters to work from as well as a good test forum for Bob's capabilities.

For this competition, a walking machine was defined by its motion. It had to be "supported discontinuously and propelled by articulated mechanisms (legs)," and each leg was required to move with respect to the body and other legs. The competition evaluates the viability of robot entries through ten events, hence the title "Decathlon." The events can be grouped in two categories and were chosen to test a diverse set of robotic abilities.

Manually Controlled
- Dash — walking ability and speed
- U-Turn — dimensions and confined space movement
- Slalom — maneuverability
- Hockey — precision of controls and ability to manipulate objects
- Obstacles — agility over low obstacles
- Stairs — agility over steep obstacles

Autonomous
- Dash — tracking and "wheel alignment"
- Slalom — accuracy under programmed control
- Sensors — navigation using static external references
- Guidance — response to dynamic, non-tethered control

In addition to these events, judges considered esthetics, structural integrity, safety, start-up procedure, and overall design.

The Walking Robot course was two semesters long with responsibilities divided to allow student participation in either one or both semesters. The seventeen students in the Fall Semester 1991 decided on a general design and then split into six groups (legs, body, controls, sensors, motors, and programming) to continue the evolution of specific aspects of the robot. Groups worked independently, and the entire class met for progress reports once a week. Many designs were considered and ruled out during this phase, and most calculations were completed. Groups from the first semester submitted final design recommendations, complete with assembly instructions, at the end of the term. Several students continued through Winter break, and thirteen students resumed organized work at the beginning of the Spring Semester 1992.

These students revised and completed earlier designs, manufactured parts, assembled Bob, evaluated performance, and solved problems. To accomplish this, the students divided into four groups with specific responsibilities. The Leg group handled leg design and drivetrain interface. The Body group's tasks included the chassis, drivetrain, bigfoot, and hockeystick assembly. The Electronics group interfaced the mechanical components with the programs and the user. This included motor, encoder, and voice control circuitry selection, manual controller manufacture, and creation of sensors for the ninth event. The Programming group selected the computer, completed the preliminary program and devised ways to test it before the robot was completed. Once the robot was assembled, the entire team collaborated to solve the various problems that occurred.

Evolution of Design

In designing the walking machine, "Bob Terpinator," the primary consideration was defining the leg mechanism. Once the method for propulsion had been determined, all other aspects of the robot were designed with leg parameters in mind. At the first meeting, the students decided the best approach was to evaluate successful University of Maryland entries from past competitions. After watching videos and discussing the positive and negative aspects of various machines, the group determined the following goals:

i) the robot will participate in all ten events
ii) the robot will not require significant reconfiguration for any event
iii) the robot will utilize an independent turning mechanism
iv) the robot will have a footpath that can be generated by a single motor

The first two goals expressed the spirit of the competition. In exploring new terrain or cleaning up hazardous waste, a machine would have to complete tasks similar to the events. Under such circumstances, complex reconfiguration would not be an option. The third and fourth goals define a general direction for a simple, practical design. It seemed that the most common mistake made in past years was to overestimate a program's ability to handle complex mechanical relationships. Simplicity was the watchword for the semester.

To participate in all events without reconfiguration, a versatile leg-path would be needed. For the events which tested walking motion and speed, the path required a long horizontal region to provide rapid forward motion. Events involving obstacles suggested a path with a substantial vertical component to allow clearance. Students considered many options and finally decided that a modified four-bar mechanism could be designed to meet these criteria. The final design produced a modified tear-drop walking path, similar to that of Maryland's 1991 entry. By adding a pantograph for amplification, a stride with an eleven-inch base and a maximum height of seven inches was achieved. After analyzing the torque curve for this path, the students decided to include springs to equalize torque. Designs for all other components revolved around these decisions. The following sections detail the student's progress throughout the design phase.

Legs

The Leg group began designing Bob in the Fall of 1991. The final leg design was based on reliability and simplicity, two invaluable engineering concepts. Since the competition tested rather diverse robotic abilities, an additional practical constraint was the walking path, the curve that the legs would trace when going through one full revolution. Given these constraints, the leg group defined three objectives for a successful design:

i) design two legs that could run 180 degrees out of phase
ii) ensure separation of functions, including walking, turning, sensing, and manipulating
iii) design mechanism with three degrees of freedom for propulsion, elevation and rotation

With these objectives in mind, the original leg design consisted of a set of "L" shaped or inverted "T" legs. This satisfied the original constraints and objectives; it was simple, reliable, and followed the desired walking path. It also allowed independent rotation control of each leg, which the group felt was important.

Although this design seemed useful, like all designs it had to be analyzed, reviewed and revised. First, the group considered whether the legs could support the robot during all points of the walking path. They discovered that the peak torque requirements with this design would be too high for the driving motor. At this point, the most important design decisions in the entire design process were made. They separated the legs into two sets of two, and chose to drive these sets independently with separate motors. This provided lateral stability while maintaining reduced support torques. The drawback, however, was the increased complexity. This was addressed by combining parts of the four-bar linkage and the pantograph. This design came after the strengths and weaknesses of many others were considered.

After these important decisions were made, the design had to be finalized, which included design of the four-bar hybrid with an amplifying pantograph, and evaluation of driving torque requirements. A detailed analysis with kinematic and stress calculations for each link ensured proper interface with the robot and no internal motion conflicts.

The walking path was the single largest consideration in determining the final leg configuration. The four-bar linkage provided the desired walking path without requiring any leg alterations during the competition (see Figure 1). However, to create the desired walking path, one that was flat on the bottom for walking and high enough to clear all the obstacles in the competition, the four-bar linkage would need to be enormous. This problem was solved with a pantograph which amplified the motion of the basic four-bar mechanism and made it useful for a robot with Bob's dimensions (Figure 2). However, the number of links for the two systems led to very heavy leg systems and increased complexity. To reduce the weight and complexity, redundant links were removed producing the hybrid four-bar of Figure 3.

When the four-bar linkage and the pantograph were finalized, the torque profile of the walking path and the stresses in the links were calculated. The peak torques in the walking path occurred where the robot made the transition from the flat "walking" section of the path into the "lifting" section. This peak torque provided the information for sizing the motor. One option for reducing the peak torque requirement, discussed later, was the use of springs.

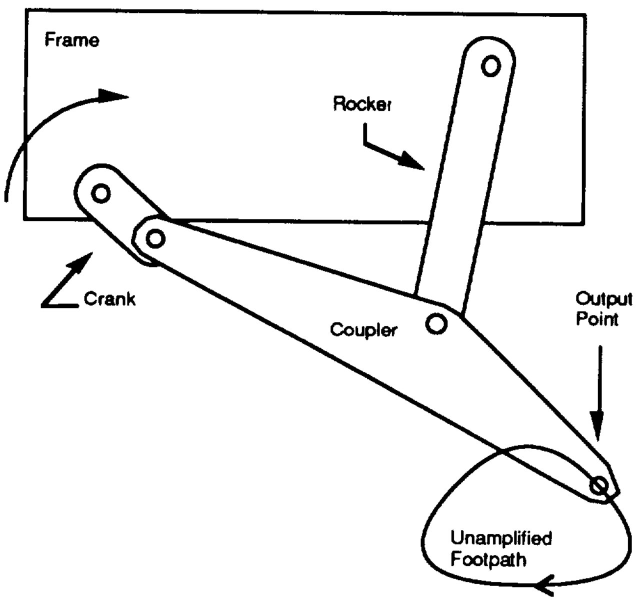

Fig. 1 Leg

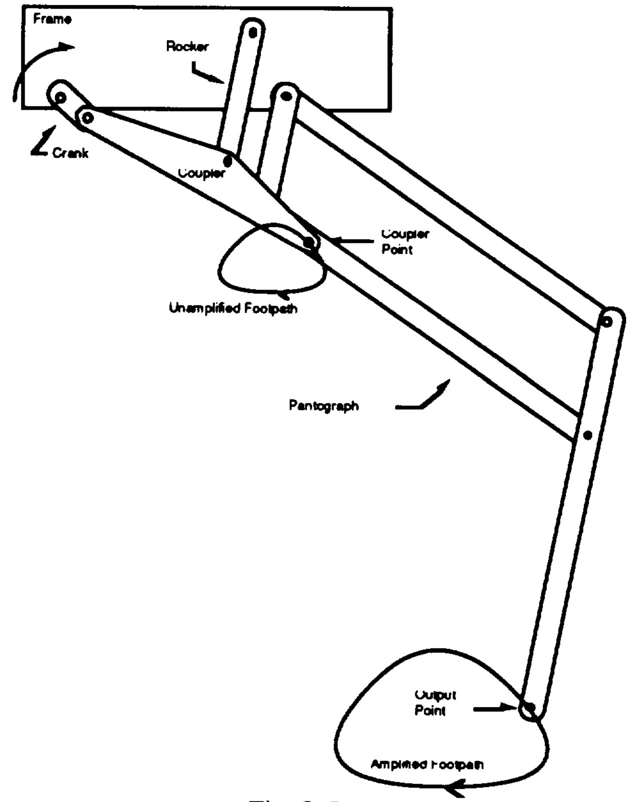

Fig. 2 Leg

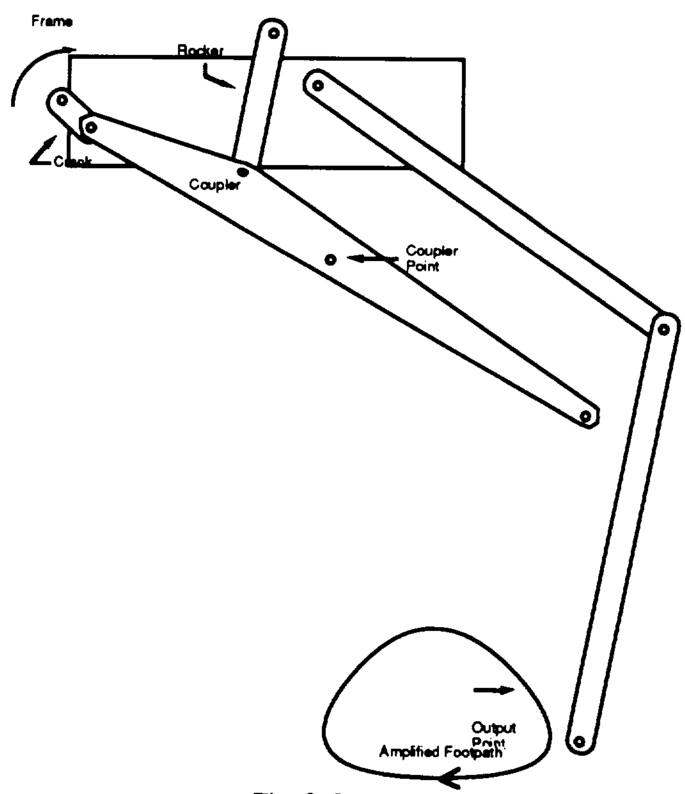

Fig. 3 Leg

Next, the shear and bending stresses in the parts were determined using the following equations:

s=Mc/I
t=VQ/(It)

where s is the normal stress due to bending and t is the shear stress.

After the stress analysis was performed, the group determined that the links with the lowest factors of safety were 2 and 5 (see Figure 2). This prompted investigation of possible buckling in the links due to the length/width ratio of the members. Buckling in the members was checked using the following equation:

Cc = [2(p)E/sy](1/2) = 75

where E is the modulus of elasticity, which happens to be ten million psi for 6061-T6 Aluminum, sy is the yield stress of the Aluminum, and Cc is the so-called "critical slenderness ratio."

In links 2 and 5 the slenderness ratio was found using the following equation:

C=KL/t

where K depends on the mode of buckling, L is the length of the link, and t is the thickness of the link.

Values of 108 and 144 were calculated for links 2 and 5, respectively. This implied that the links did, in fact, yield elastically. Since this was the case, the critical buckling stress was found using the following equation:

sc=p2E/C2.

This revealed factors of safety in buckling of 4.4 for link 2 and 1.6 for link 5. At this point, the detailed analysis was complete, and although the factor of safety for link 5 was relatively low, the design was final.

Body

The Body group was responsible for integrating the control circuitry, batteries, motors, legs, and accessories into a coherent design that would function under all the conditions of the competition. As such, the design depended heavily upon the specific parameters of the leg mechanisms and control hardware. It became a matter of balancing simplicity, performance, weight, esthetics, and cost.

The frame and bodypan design and construction were challenging problems. The torque generated by the footpath meant strength was essential; however, weight was an important consideration. The group decided to use an external frame of two 32" side members, connected together by two 21" crossmembers at their ends. Each of the frame components was constructed from 2" x 2" x 1/8" tubular 6061-T6 aluminum beams. Plates of 1/4" aluminum were attached to the top and bottom of the frame. A 2" x 5/8" x 20" prismatic delrin shaft was sandwiched between the plates for added stability. This created an effective, lightweight I-beam. In order to control the outside leg set, one of the motors had to be at a higher level than the other. Each motor was attached to the I-beam, one on the top, the other on the bottom (see Figure 4).

Torsion of the motors was another problem. Two solutions were used for strengthening against the torsional effects at the motors. One was to use the motor itself as a lever arm, and then clamp it at a point away from the gear train. Another solution was to stiffen the I-beam with offset compression/tension bolts. These were simply constructed with 1/2" aluminum tubing and 1/4" bolts.

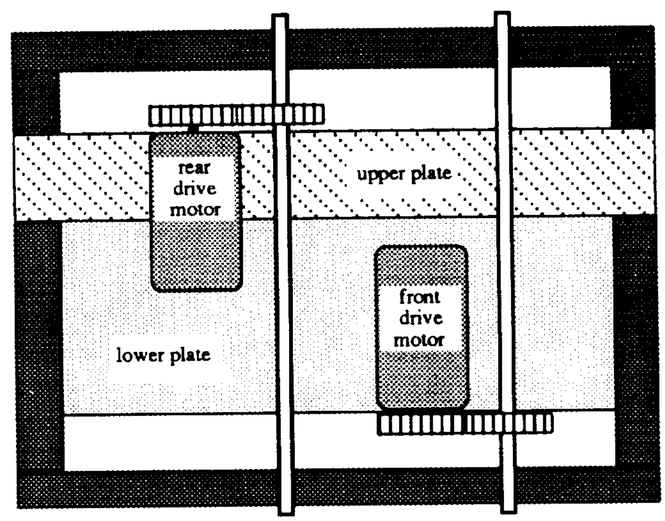

Fig. 4 Body

The transfer of power from the motors was accomplished through 1045 carbon steel rods. The 3/4" face width gears were keyed and held axially with set screws. The ratio of the gears from the motor to the shaft is 2 to 1. The end resulting torque is transferred to the four-bar mechanism through an aluminum link that is keyed and set with a screw. The encoders for the legs were set with a gear ratio of 1 to 1 with respect to the main drive motors.

The central turning mechanism, "bigfoot," was simple in design. There were two main components for the structure of bigfoot. The main structure is a PVC pipe held in compression with a 5/8" all-thread rod. The threaded rod is centered in two thrust bearings. The foot components rotate about the shaft, motor, and body of the walking machine. When the body is supported by the bigfoot, the machine rotates. The second component of bigfoot was the foot: consisting of the foot shafts and the hockeystick. This integrated design reduced the total number of degrees of freedom required to control the machine.

Since the robot only turns when bigfoot is stationary with respect to the ground, attaching the hockeystick to bigfoot allowed the operator to turn the robot without concern for the motion of the puck. By positioning the hockeystick so that the puck remains at the center of bigfoot's turning radius, the robot can settle onto bigfoot, turn and stand, without moving the puck. The user can reposition the hockeystick behind the puck by turning bigfoot, also without moving the puck. The robot then moves forward and drags the puck with it. The hockeystick was designed with linear bearings and delrin rods to compensate for the vertical "bob" of the robot's forward motion. The rods move up and down freely as the robot navigates the course. The blade of the stick was made from transparent acrylic for visibility.

Electronic components were housed in a 30 x 12 x 7-inch box made from 1/16-inch aluminum and attached to the bottom of the lower plate. Rechargeable batteries are held in place with velcro. The computer components needed extra protection from jarring, so a container with cushioning was designed to the specific dimensions of the computer boards. This was bolted to the bottom of the components box. An external disk drive was also mounted directly to the side of the box. Extra room was provided for wiring, amps, and the power supply.

Controls

All of Bob's motions are provided by three motors: one for each of two leg sets (walking) and one for bigfoot (turning). To control the motors, a closed-loop servo motor system consisting of a PID controller card, a motor drive amplifier with a power source, and three incremental encoders was needed. A closed-loop system (with encoders to report on motor position and velocity) has the advantage over an open-loop system (stepper motors) in that it can compensate for gear slippage and manual positioning of the legs. The controller card is a three-axis controller with an internal processor that is used to compute complex positioning and velocity profiles. It controls each of the three motors independently and simultaneously by sending analog signals to the amplifiers. The motors run at speeds proportional to the amplifier voltages and generate torques that are proportional to the currents. The encoders, which are attached to each motor shaft, convert the rotation of the motor into two square wave signals that are 90 degrees out of phase (quadrature output). These signals are then fed back to the controller card to calculate the direction and speed of the motor. Decisions for each component of the system were made by evaluating efficiency, cost and reliability.

The first task of the fall semester Controller group was selection of the motors. They had to meet the following requirements which were specified by the Leg and Body groups:

Leg motor requirements (at load):	
Maximum Continuous Torque	200 lb-in
Intermittent Peak Torque	400 lb-in
Speed	30-50 RPM
Direction	Reversible
Bigfoot motor requirements (at load):	
Maximum Continuous Torque	40 oz-in
Speed	1-10 RPM
Direction	Reversible

The controller must interface with the computer, amplifiers, and encoders. Model 5638 from Technology 80, Inc. is a closed-loop servo controller that uses an LM628 Precision Motor Controller IC from National Semiconductors. It was chosen because of its accuracy, reliability, and adaptability. Conveniently, the controller card is designed to plug directly into one of the expansion slots of an XT Compatible computer and sends commands via the I/O lines. Each axis on the controller card connects to the amplifiers through a 40-pin connector and uses a 34-pin connector to interface with the incremental encoders.

The mechanical position of the robot is controlled using indexed quadrature encoders for each leg. Model 755A by Encoder Products Company was chosen because of its size, high precision, low cost, and rugged structure. The quadrature encoder generates two square signals that are 90 degrees out of phase as well as an index that occurs once per revolution. The controller card decodes the signals to interpret the direction and speed.

An amplifier that closely matches leg set requirements is Model 6410-2 from Technology 80, Inc. It was chosen because it can be run from a single supply in the forward and backward directions. The amplifier for the bigfoot motor had to be able to handle 1-2 Amps of current. A Power Amplifier by National Semiconductors, the LM12, was chosen.

There are three methods for providing user control. The first is the computer interface. The method developed minimizes the number of commands and takes advantage of the 5 input pins of the parallel port of the XT 8088 computer. Commands are input to the computer through a 16-button keypad. The 16 keys are encoded into four bits by using a 74LS138 priority encoder; the fifth bit is used as an enable bit to check that a new key was pressed. The CPU constantly polls the parallel port looking for a key press, then starts the appropriate command.

A backup method to control the motors was implemented. As a safety precaution, a manual control was designed to override the computer if complications or failures arose. A switch on the main control box activates six relays that in turn bypass the CPU and place the op-amps into manual mode. In this mode, a joystick is used to control each leg, and a resistor network is used to control bigfoot. Each of these components produce ±10V outputs, which mimic the signals provided by the controller card.

To facilitate event ten, the robot responds to six commands given by voice. The design uses a VCP200 voice recognition chip from Voice Control Products, Inc. It receives a quasi-digital signal as an audio input from an LM324 op-amp and decodes the signal into digital logic levels which are then fed into another 74LS138 priority encoder like the one used by the keypad.

There was only one more item for the controls group to handle. Event nine called for sensors to read the external environment. Up to five beacons could be placed outside the contest area. The sensors could be either active (producing the signal which they then detect) or passive (simply reading signals produced by external sources). Passive sensors were chosen because they are sightly easier to build than active ones. It was decided that they would respond to light sources because light detectors were readily available and light sources are cheap.

The sensor design went through several stages. It called for two light detectors attached to arms which swept back and forth. As the arms swept through their motions, the detectors would produce logic level signals when light was seen. By measuring the angles of the arms at the points where light was detected and using geometry, the distance and angle to the light could be calculated. A three-bar mechanism would be used to produce the sweeping motion of the arms. Unfortunately, arms which sweep back and forth do not have a direct angular relationship with their drive motor. In order to measure the angle to the light source, an encoder would be mounted on the drive motor and a microprocessor would be used to keep track of the motor's angular velocity and the time to reach the measured angle. Alternatively, an encoder could be used at the pivot point of one of the arms.

The second method is preferred for its simplicity; however, since motors with built-in encoders were available from a previous year's walking robot, the first method was suggested. Unfortunately this method led to a complicated interface card and extra programming.

An alternative method, which uses a turntable with a light detector offset from the center (a top view of the new sensors is shown in Figure 5), was developed. The turning sensor has a direct relationship with its drive motor. As the sensor turns, the motor's encoder is used to clock a binary counter. When a light source is detected, a logic level signal is produced which latches the count into buffers. The CPU can then poll the buffers and read the angle to the light. Again geometry is used to calculate distance and angle to the light; however, this time the calculations and results are sightly more straight forward. One problem with this method is getting power to -- and receiving signals from -- the detectors on a rotating turntable. A commutator could have been used (a circular trace with spring contacts), but commutators are very noisy and might have introduced errors in the signals. Instead, an onboard power supply and relay LEDs were used.

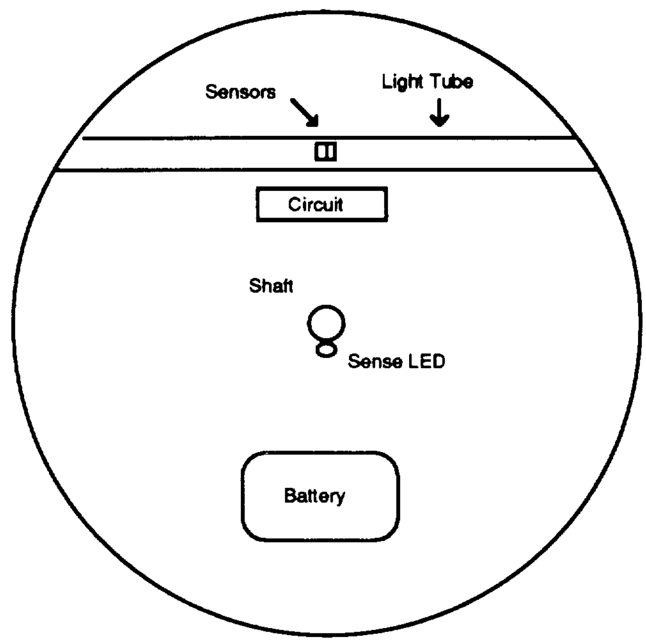

Fig. 5 Controls

Programming

During the Fall semester, the class determined that Bob needed a computer for controlling the unique footpath. The essential components for Bob's brain were selected, ordered, and received. An uncomplicated motherboard, a disk drive, a disk drive controller card, and a video monitor card with a parallel port were necessary for efficient operation of the robot. For developmental purposes, a keyboard and monitor were borrowed from the University's facilities. The group used an IBM XT motherboard (8088 microprocessor), a 3.5", 1.44M high density floppy drive, a disk drive controller card, and a monochrome video driver card with printer port. These items were ordered and received at the end of the fall term 1991.

Manufacture and Assembly

The Spring semester 1992 was devoted to finalizing designs, machining and ordering components, assembling the robot, and solving problems. Through most of the semester, students worked in four groups and reported progress at weekly meetings. Three weeks before competition, Bob was largely assembled, and students worked more closely together to evaluate Bob's performance and to solve problems.

Legs

The leg group had one design which needed further optimization, the "sandwich" joints. As designed, the joints would not adequately transmit the driving torque necessary to power the robot. Optimizing the design required reviewing bearing selection to ensure the bearings could transmit the necessary torque and still provide the lateral support needed to stabilize the robot. Many possibilities were considered, including needle bearings, journal bearings, roller bearings, and ball bearings. The criteria for the final decision were: the bearings' ability to transmit torque under stress, their durability under shock and repeated loading, their size, and their cost. Having designed the links, finding the proper bearing became a much more challenging task than originally assumed. The final constraints listed, size and price, turned out to be the most difficult to deal with. This led the group to a close examination of several types of bearings including the needle and journal type. Needle type bearings were ruled out for several reasons. Needle bearings use the shaft that is rotating as their inner race, or inner rotating surface. The group was concerned about the bearings' ability to function under axial thrust and angular misalignment, particularly in conjunction with each other. Also, needle bearings would be difficult to mount, and replacement might be necessary. The journal bearings seemed to be a good selection due to their mechanical simplicity; however, eventually they were rejected because of their inability to transmit torque effectively under angular misalignment. Ultimately, roller bearings suited our application most closely with their ability to transmit torque under axial misalignment and axial thrust, and the available sizes, but their cost was prohibitive. In this regard we were very fortunate to receive a contribution from the Torrington Company; they donated all the Fafnir bearings that we needed. This contribution allowed the group to move closer to completing the design.

The final concern in the design of the legs was the interface with the robot. The joint that connects two legs to the robot frame was critical. Originally, the proposal was to use artificially aged aluminum as in the rest of the robot. Based on calculations made by the group, aluminum would not withstand the bending stress inherent in the "shoulder plates." The group investigated other materials, including stainless steel and various types of hardened and unhardened carbon steel. Stainless steel did not have the requisite strength. Hardened steel had an overabundance of strength for the bending stresses, but it is difficult to machine. From a manufacturing perspective it was unacceptable. This led the group to the final decision, 1018 steel, which had the strength and manufacturing characteristics that the group desired. This decision completed the design from a manufacturing standpoint.

After finalizing the design, the group began manufacturing the pieces. The first plan was to machine the pieces manually. However, although the leg components seemed simple, time and tolerance requirements made this unfeasible. Since the legs included two sets of connected leg-pairs with a pantograph, the group decided that identical reproduction of parts was critical. If they were out of tolerance, the components of the connected leg-pairs would be subjected to a pre-stress from incompatibility with one another.

Moreover, the bearings required a very close tolerance in their mounting holes to function properly. The group was concerned about students' abilities to adhere consistently to these tolerances; therefore, the decision was made to have most of the leg components machined on a computer numerically controlled (cnc) milling machine. This provided a short machining time, identical reproduction of parts, and the ability to store the programming for modification if necessary. On campus at the University of Maryland there is a cnc machine shop run by one of the professors. The group contracted with this shop to manufacture all of the moving pieces in the leg. We provided the shop with all the necessary raw material and bearings for sizing the holes. They built a prototype leg set to insure proper function. The advantage of cnc machining became clear at this point. If the pieces were not properly designed, the programming could have been altered to suit the group's needs relatively simply; if there were no modifications, the remaining pieces could be made very quickly since the programming was already done.

The "foot" was the one piece of the leg manually machined by the group. It consisted of a one inch by one inch aluminum tube with holes drilled. These were for placement of rubber bumpers ("toes") which the robot rests upon and allowed adjustment for different positions.

After verifying that the mechanism did, in fact, function properly, including all joints and connections, the remaining pieces were ordered from the machine shop. After obtaining all the pieces from the machine shop, assembly began. Pins for the joints were pressed into the center links, and all the bearings were press-fit into the "sandwich" links. When the links were together, washers were included between them to guarantee proper spacing. The feet were then connected to the links, and finally the entire mechanism was attached to Bob's body. During final assembly, shims were added at each joint to reduce the robot's lateral movement as much as possible. These shims were placed between the bearing and stop ring on the connecting pin at each joint.

The connecting pins that ran through the joints were press-fit into the center piece and had grooves machined into them at the ends to hold the retaining ring. These pins were made of precision ground stainless steel–an expensive material, but one that ensured that the pins would interface optimally with the bearings. Any interference could cause growth of the inner race which would affect the bearings' rolling motion and ultimately lead to alignment problems.

The drive shaft, connected to the driving link (link 1), needed to be fastened securely. The group proposed keying the shaft and link and using a set screw. The Leg group worked closely with the Body group, who was in charge of the drive shafts, to make certain that these parts would match. Finally, the toe placement on the foot needed to be optimized. This task was addressed by the leg group by leaving many holes at various spacings to allow for a suitable combination for the competition.

Body

The Body group decided to have students machine most parts. Based on designs from the first semester, materials were ordered, and the parts for the frame and body pan were machined. For ease of assembly, all nuts and bolts were 1/4 inch in diameter. As more weight was added to Bob, it became clear that extra support for the bodypan would be necessary, so an angle bar was added underneath the bottom plate. Aluminum adapter plates were attached to the face of the motors for encoder placement.

Because of time constraints, the group decided to use the bigfoot apparatus from the 1990 robot. Since the design for this semester had been based on that model of bigfoot, only minor modifications were necessary. It was attached to the lower plate of the body as described in the design. Brackets for the hockeystick were mounted to the feet, and the hockeystick was added. Holes were drilled into the delrin rods and pins were inserted to keep the hockeystick up out of the way during events that did not involve it.

The drivetrain was machined and assembled without deviating from the design. Careful attention was given to dimensions to be sure leg placement would be within specified tolerances.

Controls

As problems arose, it became apparent that a backup power supply might be necessary. Using an LM12 Power Amplifier, a system was built that can supply up to 15 Amps of current. The disadvantage of the design is the requirement of two supplies. Since the robot would run in reverse only for short periods of time, the Negative supply was reduced from -24V to -12V to minimize the weight of the batteries.

An amplifier using ±12V supplies was built using the design from last semester with minor modifications. This amplifier takes ±10V input from the controller and runs it through an LM12 power op-amp. The anticipated current was less than 3 Amps.

The voice controller design from the previous semester enabled the robot to recognize various commands given by voice. Modifications were made on the original design to minimize the sensitivity at the input of the VCP200 chip. From the updated design, resistor values were changed on the LM324 to allow the audio input to the VCP200 to accept only commands of sufficient strength. With these modifications, the robot would respond to six commands accurately in a relatively noisy environment. To ease connection of the voice control circuit to the computer, the output of the VCP200 was fed into an 8 x 3 encoder similar to that used by the Keypad unit. This provided a modular control input design: to switch from manual control to voice control, one simply has to unplug the hand unit and plug in the voice control unit.

During construction of the sensors many different techniques were used. The circular sensor disk was made out of double-sided copper-clad board with the light detection circuit etched directly on it. The technique known as "board scratching" was used instead of photo-plotting. Scratching is an alternative method to silk-screened boards drawn with CAD/CAM software and then etched in an acid bath. The circuit schematic was drawn using a schematic program. A file containing circuit point-to-point connections was produced. This file was then fed into a board layout program which was used to draw the traces and pads to be routed on the copper-clad board. At this point the circuit would normally be silk-screened to the copper board. Instead, the drawing was sent to a third program which controls a milling machine. The machine moved a milling bit over the copper-clad board, etching traces as it went. Scratching the board was more convenient because results were immediate and changes could be made easily. This process produced a very professional looking board which was easy to work with. The second technique used was wire wrapping. The sensors interface circuit was built on a pc proto-board. Instead of soldering wires point-to-point, wire wrap sockets were soldered to the board, wires were wrapped between pins to be connected, and chips were placed. This allowed for easy correction of mistakes.

After the sensor board was populated and debugged, the shaft and driven gear were attached. The sensor motor mount was then machined; the bearings and the motor with drive gear were mounted. Next, this whole assembly was attached to the front of the robot. Even though the light tubes prevented any light from reaching the photo sensors from any direction but the ends, the sensor board was covered to ensure further no extraneous readings would be made. This produced a very clean, wafer-like disk. The disk was mounted in its bearings and a clip was attached to keep it from jostling as Bob walked. Finally, a light-blocking cover was built and mounted to control the sensor field of view.

Programming

During the semester, the programming group faced the tasks of assembling and testing the computer parts ordered last semester and creating software capable of controlling the robot during all the events. The hardware and software development decisions were based on balancing the costs with the needs of the robot design. Most of the hardware decisions and purchases were completed in the Fall term 1991 and have previously been described. Additions to the original hardware design included a portable power supply for the computer, an audio speaker, and an LED power indicator. The software decisions made during the Spring term 1992 consisted of selecting a programming language, interfacing with the controller software, and developing the final version of the robot's software.

Hardware development began this semester with the assembly of the computer components. The following computer components were assembled and tested: an IBM XT motherboard (8088 microprocessor), a 3 1/2" disk drive, a disk drive controller board, a monochrome video card with printer port, and the 5638 Servo Motor Controller board. An LED power indicator was attached to the motherboard to indicate whether the power was activated. A speaker was also attached to the hardware so that music could be played to identify the different routines Bob entered during competition. The music was also added to improve the competitive nature of the robot.

The portable power supply was designed to provide power to the computer during competition. The supply was designed for four different voltage levels, ±5 VDC and ±12 VDC. Two 12-Volt batteries provided the voltage for the power supply. This eliminated the need for any type of rectification and ripple filtration. The power supply consisted of four separate power conditioning units combined on a common PC board. In order to maintain the required voltage levels to within ±5.0%, LM78xx and LM79xx series voltage regulators were used. Over-current protection is provided at the input of each of the four regulators by having a resistor in series with the input and a power transistor in parallel with the resistor. If the voltage across the resistor exceeds a predefined limit, the transistor is turned on, and current is shunted into the input of the voltage regulator. The regulator is then driven into thermal overload, effectively shutting down the entire circuit.

Once the 5638 Controller board was received and installed into the motherboard, post–installation testing was conducted to verify controller function. The test software that was received with the controller was run, and accurate operation was verified. Three small motors were attached to the controller board in order to simulate the three actual motors that would be used on the robot.

Various programming languages were explored for the software development. Several test routines were written in Microsoft C, Assembly, and Microsoft Quick Basic. Microsoft Quick Basic was determined to be the most capable, efficient, and uncomplicated language available. It possessed the necessary capabilities that were required such as:

i) parallel port input/output ability
ii) adequate running speed
iii) compatibility with the available controller board routines

The necessary functions and motions of the robot were evaluated to determine what should be included within the software routines. The following are the functions that were selected for control over the robot from the hand-held control panel:

1) Stop
2) Home Position
3) All Legs Down
4) Bigfoot Right 45 degrees
5) Bigfoot Left 45 degrees
6) Bigfoot Right 10 degrees
7) Bigfoot Left 10 degrees
8) Bigfoot Down
9) Legs Forward 10 degrees
10) Legs Backward 10 degrees
11) Hop Forward
12) Hop Backward
13) Walk Forward–Slow, Med, Fast
14) Walk Backward–Slow, Med, Fast
15) Stairs
16) Autonomous Events – Slalom, Dash, Beacon

The Stop function immediately stops all motors on the robot. The Home function brings the robot into a standard position with one set of legs all the way at the top and one set of legs completely down. The All Legs Down function brings all four legs of the robot into their lower most point so that they are all resting on the ground.

The Bigfoot Right and Left functions turn bigfoot to the right or to the left by the number of degrees indicated. This allows bigfoot to be used for turning the robot and for rotating the hockey stick during the hockey stick event. Bigfoot Down lifts the walking legs of the robot in preparation for turning; this lowers the robot so that is rests on bigfoot.

The Legs Forward and Backward 10 degrees functions move the highest set of legs forward or backward by 10 degrees. This is useful during the obstacle course in order to tap the top of the obstacle. Hop Forward and Hop Backward are used for fine adjustments while setting up for the events. They move the robot a small amount forward or backward.

The Walk Forward and Walk Backward functions are used for any walking that the robot does. Three speeds of walking are available: slow, medium, and fast. The Stairs function is an automated stairs climbing routine to be used during the stairs climbing event. Autonomous Events are run completely without human interference and consist of the Slalom, Dash, and Beacon competitions.

The individual routines for all the above functions were written and debugged first with the small motors and then with the actual robot for fine tuning purposes.

Performance Evaluation

Robot assembly was completed two weeks before the competition. Upon testing, various problems arose in the following: (1) high motor torque requirement, (2) overheating of electronics, (3) programming algorithms, and (4) misjudgment of time.

The high motor torque requirement was attributed to drivetrain friction. The weight of the robot was higher than expected which increased motor deflection, causing the gears to mesh poorly. This problem was diminished by rigidly securing the drive motors to the body.

The high torque requirement demanded more current to drive the motors, thereby overheating the amplifiers. A booster was added to increase the current output from $\pm$ 10 volts to $\pm$14 volts. In addition, a fan was added to cool the components. Even with these changes, the torque produced when the computer and batteries were placed on-board was too much. The power op-amps were overloaded several times.

The leg motion consisted of a propelling phase (bottom of footpath) and a return phase (top of footpath). The return phase was faster than anticipated, while the propelling phase was slower. The result was a stomping walk. Compensation was made by adjusting the algorithm timing.

Most of the students overestimated their abilities and/or underestimated the time needed to complete a task. As a result, the robot was still being worked on through the competition. Needless to say, Bob did not perform in many events. He did, however, do a wonderful stomp/lurch walk for event one (the "dash").

A further result of the rush to make Bob work was the decision not to worry about specialized events. There was no pretesting of the hockeystick nor the sensors. The hockeystick was a flawless design and in all likely scenarios would have performed marvelously. At least the test models worked without a hitch. The sensors did respond to the beacons and it was clear that the angle counting was working. However, an integrated test was never performed, so the accuracy was never tested. Nor could an evaluation be made of their performance during the distinctive walking motion which earned Bob his name.

Conclusion

The class was by no means a loss. Even though the competition did not go as planned, it was still a terrific learning experience for the students. They learned what it was like to work as an integrated team. They found out the group dynamics of a large volume of people that got twenty hours of sleep between them. And most importantly, they learned many new skills and techniques which they will be able to take to prospective employers. Some of the more valuable skills include:

- modern techniques of design and manufacture
- better estimates of abilities and requirements
- better social skills as they apply to the work place
- improved time management and organizational abilities

Even though Bob did not walk, he was not a failure. He utilized a clever walking motion which integrated vertical travel as well as horizontal clearance. This was accomplished using a very unique and innovative mechanism. The footpath was designed to accommodate rather tall obstacles while still providing a long stride. This meant further coverage during each step. Bob had the best hockeystick design at the competition. While his hockeystick was designed to work with his walking motion, other robots had hockey sticks which looked like afterthoughts. They were invariably attached to the front of the machines and would loose contact with the pucks as the machines turned. This meant that the other robots would have to be backed up and repositioned behind the puck again.

While all of the other robots had been designed to compete in most events, Bob was the only one designed to compete in every event. The mechanical and programming designs accomplished this. Even the electrical designs would have sufficed had more leeway been given to errors in torque and current requirements for the motors.

But this is not the end for Bob. In all likelihood, next year's class will use the same leg mechanism. This will give them a definite advantage. The legs were the most time costly aspect of the robot. Having them already designed with only a need for refinement will leave more time for debugging and refining other aspects. This should produce a better robot which has already been put through its paces and give time for operator practice.