SRC TR 89-60

The Design of a Three-Degree-of-Freedom Walking Machine

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ABSTRACT

The walking machine presented in this paper consists of six walking legs arranged in a triangular configuration. Each leg can have two modes of operation: an elliptical mode for walking on a flat plane, and a circular mode for stair climbing. The six legs are mechanically coupled to a single drive motor through the use of chains and sprockets. The coupling is arranged in such a way that three of the six legs, one from each corner of the triangle, are always in phase while the other three are 180 degrees out of phase. When walking, three of the six legs are always on the ground propelling the machine forward, while the other three are in the air in an opposing position rotating forward. Turning is achieved through the use of a two degree-of-freedom mechanism. Through the use of a prismatic joint, the body of the machine can be lifted up-and-down, and through the use of a revolute joint, it can be rotated to any desirable orientation. The result is a simple, three degrees of freedom, walking machine which is capable of walking on a flat plane and some limited stair climbing. Because of the simple construction, the control system is also extremely simple and fast locomotion can be achieved for a small sacrifice of flexibility.

INTRODUCTION

The potential usefulness of walking machines for work, maintenance and exploration in difficult environments is well acknowledged. For effective performance of these tasks, walking machines must be either remote controllable or fully autonomous. It must be implemented with computer software using artificial intelligence, along with well-designed mechanical, sensing, and control systems. Depending on the desired functional requirements, a walking machine may have four to eight legs and the active degrees of freedom (DOF) may be as many as eighteen (1). For examples, the Ohio State University Hexapod and Adaptive Suspension Vehicle are both six-legged machines with eighteen DOF (2, 3) while Hirose and Umetani's quadruped walking machine has twelve DOF (4). Some introductory materials on the design of walking machines can be found in (5).

Although reducing of the number of active DOF generally reduces the flexibility of a walking machine, it also produces some desirable features such as simplicity of the control system and the realization of fast locomotion, etc. Based on this concept, a seven-legged, three-DOF walking machine was designed and constructed.

The walking machine presented in this paper was designed to compete in the Third Annual Walking Machine Decathlon. The Annual Walking Machine Decathlon was initiated jointly by the Colorado State University at Fort Collins and the University of Maryland at College Park in 1987. The objectives of the competition are to give undergraduate students an opportunity to gain hands-on design experience of interdisciplinary nature, to promote familiarity with, and the technological advancement of, the components and systems necessary for the development of robots and other intelligent machines. According to the competition rules, a walking machine is defined as a mobile, terrain adaptive system with eight or less articulated legs which can perform defined tasks in static or dynamic environments. The tasks range in difficulty from a straightline sprint to stair climbing, and from tethered control to autonomous motion.

Following these rules, a group of students from the Departments of Mechanical and Electrical Engineering at the University of Maryland were charged to come up with a sound conceptual design and, then, to perform design analysis, design detailing, parts ordering, machining, assembling, and testing of the walking machine.

ROBOT CONFIGURATION

The walking machine can be divided into three parts: mainframe, legs, and control system. Walking is accomplished through the movement of six legs while turning is accomplished through the use of a central leg.

The six walking legs are arranged in a triangular configuration as shown in Figure 1. Each leg is a one degree-of-freedom, adjustable mechanism and it has two modes of operation: an elliptical mode for walking on a plane, and a circular mode for stair climbing. The legs at each corner of the triangle are keyed together, via a common drive shaft, to be 180 degrees out of phase with respect to each other. Through the use of chains and sprockets, the three drive shafts are then coupled to the drive shaft of a motor. The couplings are arranged in such a way that three of the six legs, one from each corner of the triangle, are always in phase while the other three are 180 degrees out of phase. Thus, when three of the six legs are on the ground propelling the walking machine forward, the other three are in the air rotating toward their ready positions. The triangular configuration of the legs creates a tripod effect which ensures an adequate region of stability for the robot.

A central leg, called the "Bigfoot" as shown in Fig. 2, is used to turn the walking machine. The mechanism uses two concentric shafts which are allowed to rotate with respect to each other, and to move vertically as a unit with respect to the mainframe. A DC motor is used to lift the machine up-and-down and another to rotate the machine. Overall the walking machine has three active degrees of freedom.

MAINFRAME

Body

The purpose of the body is to provide a stable base of support for the legs, drive lines, turning mechanism, drive motors, and electrical components. The design must be strong enough to support the weight of the machine itself and an external load of approximately 5 kg under various operating conditions while it must also be light and inexpensive to produce.

For the reason of stability and ease of control, the six walking legs are arranged in a dual-tripod configuration. The weight of the machine is supported by the set of tripod which is in contact with the ground. The dual-tripod also provides a wide region of stability. The center of mass must remain inside this region for the machine to be statically stable. The least stable situation is when a tripod is just about to make contact with the ground or when a tripod is just about to leave the ground. A triangle can be made for each of these extreme cases for each tripod. The common area enclosed by these triangles defines the region of stability as shown in Fig. 3.

The body is constructed by a lower plate and an upper plate separated by two side beams. The two side beams are each made of 64.8 cm long rectangular tube having a cross-section of 10.16 cm by 5.08 cm, and a wall thickness of 0.318 cm. The lower and upper plates are both 0.635 cm thick, 50.8 cm wide, and 40.64 cm long, with some cutouts for the ease of installation. The two side beams are both cantilevered beyond the rear end of the body by 24.1 cm and, a third rectangular tube of the same cross-section is also cantilevered in the center, front-end of the walking machine by the same amount for supporting the legs. These dimensions are selected based on the length of travel of the legs and the space and accessibility needed for the hardware placed on the body.

The material selected for the body is aluminum 6061-T6 which is light, stiff, and inexpensive. Once the material and dimensions of the body were selected, engineering analyses were performed to determine the critical stresses and deflections of the beams and plates. It was found that for an estimated mass of 45.45 kg, there is a safety factor of greater than five for the worst case bending and torsion of the body.

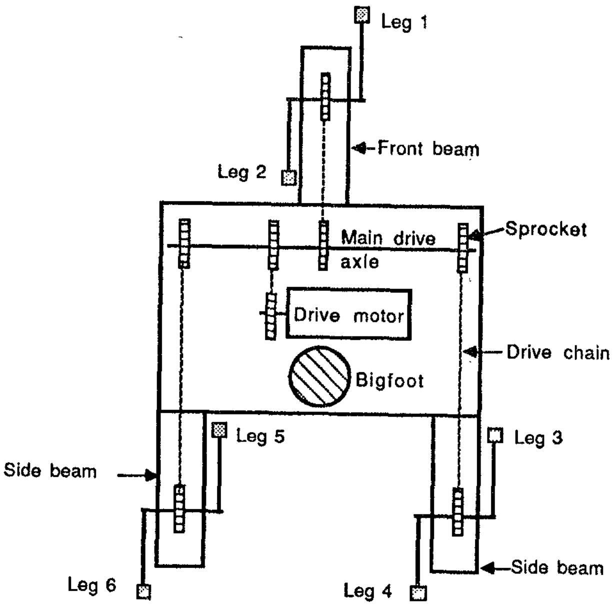

Fig. 1 Walking Machine configuration - Top view

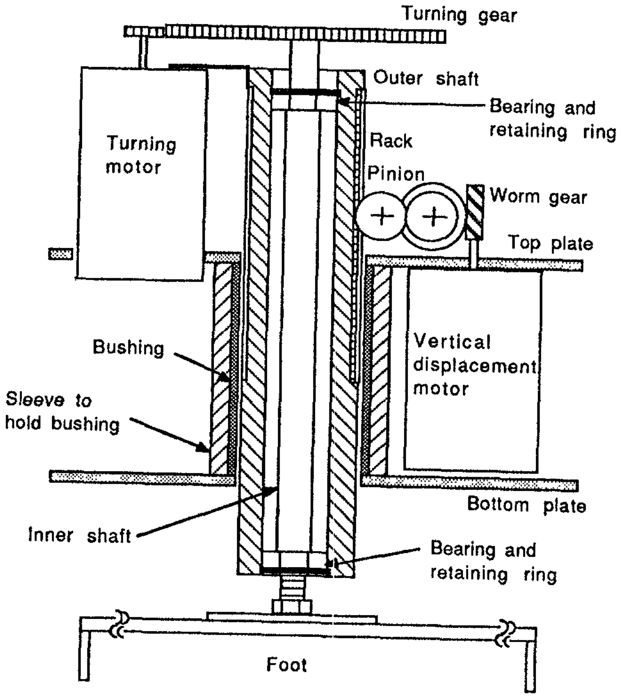

Fig. 2 The bigfoot

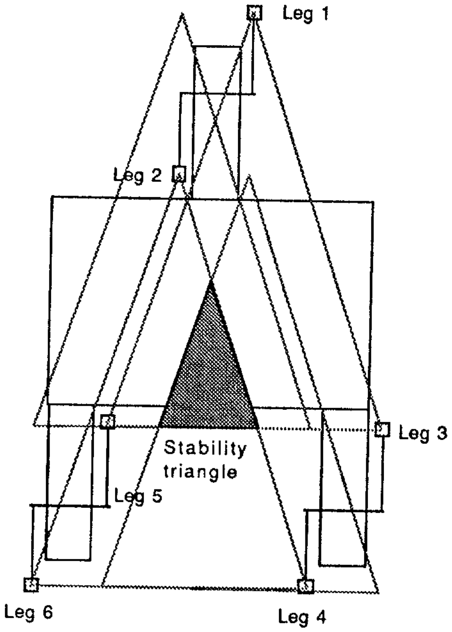

Fig.3 Stability triangle defined by the extreme positions of the legs.

Turning Mechanism

"Bigfoot" is the name given to the steering mechanism of the walking machine. It is a two degrees of freedom, prismatic and revolute jointed mechanism. To make a turn, the walking machine must first come to a stop, a vertical displacement motor lifts the legs off the ground, and then, a turning motor rotates the machine to a desired orientation. When the desired orientation is achieved, the turning motor is shut down, Bigfoot is retracted, and the machine begins its new course of forward motion.

The bigfoot is located near the geometric center of the stability triangle. It is also important to locate the center of gravity of the entire walking machine as close to the geometric center of the stability triangle as possible. This has been accomplished by installing the drive motor as close to the bigfoot as possible and by using batteries as counter balance weights.

The components of the bigfoot are shown in Figure 2. The outer sleeve, the vertical displacement motor, and the up-and-down gearbox assembly are fixed to the mainframe. The outer sleeve holds a bronze bushing through which the outer shaft slides up and down. The outer shaft is the backbone of the bigfoot assembly. Vertical motion of the outer shaft is controlled by a vertical displacement motor through the use of a rack-and-pinion assembly. The rack is attached to the side of the outer shaft. The pitch diameter of the pinion is 2.54 cm. Further, the pinion is coupled to a self-locking worm gear assembly with a 50:1 gear reduction. The inner shaft is connected to the outer shaft by a pair of angular contact ball bearings. Turning is controlled by a turning motor which is attached to the outer shaft by a steel plate. A 12:1 gear reduction unit transfers torque of the turning motor to the inner shaft of the bigfoot assembly. Finally, the lower end of the inner shaft is attached to a circular plate which is used as the foot to support the walking machine.

For a desired maximum up-and-down speed of 2.54 cm/s, the top speed of the vertical displacement motor is 100 rad/s or 955 rpm. Assuming a 50% efficiency for the worm gear assembly, the required torque for the motor is 0.226 N-m for a 45.45 kg walking machine.

Finally, for a desired turning speed of 1.05 rad/s, the speed of the turning motor is 12.6 rad/s, or 120 rpm. And, assuming the moment of inertia about the center line of the bigfoot is 2.13 kg-mm and the maximum desired acceleration is 0.698 rad/s/s, the required torque for the motor is 0.124 N-m.

LEG MECHANISM

When walking on a flat plane, it is desirable to limit the vertical motion of the body. Vertical motion causes undesirable vibrations as well as excessive energy consumption associated with the up-and-down motion of the body. However, when climbing, the foot needs large vertical lift to ascend and descend a flight of steps. Thus, in order for the machine to have walking and stair climbing capability, it is necessary for the legs to have two modes of operation. In the first mode, the foot follows an elliptical path, while in the second mode, it follows a large circular path. The elliptical motion, with its major axis parallel to the ground, provides maximum horizontal movement of the walking machine while minimizing the up-and-down motion of the body. While climbing, a different set of problems must be addressed. The main concern is to have enough vertical lift of the toe to allow for the climbing of the machine over various obstacles such as stairs and blocks of wood while at the same time keeping the machine stable on an inclined plane. The large circular motion of the foot makes limited stair climbing and obstacle crossing possible.

Leg Assembly

The leg assembly consists of three major links made of 6061 T-6 aluminum as shown in Fig. 4. The first link is keyed to the drive shaft while the third link makes contact with the ground. Each of the first and second links carries three gears which are used to constrain the motion of the third link and to transfer torque from the drive shaft to the third link.

The leg has two modes of operation and, therefore, must accommodate these two modes mechanically. Rather than completely remove the entire leg assembly and replace it with a different assembly, the leg was designed to be physically altered to accommodate movement in either the elliptical or circular mode. This change from elliptical to circular was accomplished by removing a fork pin and adding a set screw to the leg thus modifying the leg configuration.

As shown in Fig. 4, the first gear is permanently fixed to the mainframe of the walking machine thus forcing the leg assembly to revolve around the first gear as the drive shaft rotates. The second and fourth gears are simply two idle gears used for changing the direction of rotation. The sixth gear is keyed to the third link via a common shaft. In the elliptical mode, the third gear is keyed to the second link via a common shaft, while the fourth gear is pinned to the first link. In the circular mode, the third gear is keyed to the fourth gear, while the first link is pinned to the second link. It is this adjustment which makes the two modes of operation possible. The gear ratio between the first and the third is 2:1, and between the fourth and sixth is 1:2. A rubber stopper was fixed to the bottom of the third link so that the legs can have good traction.

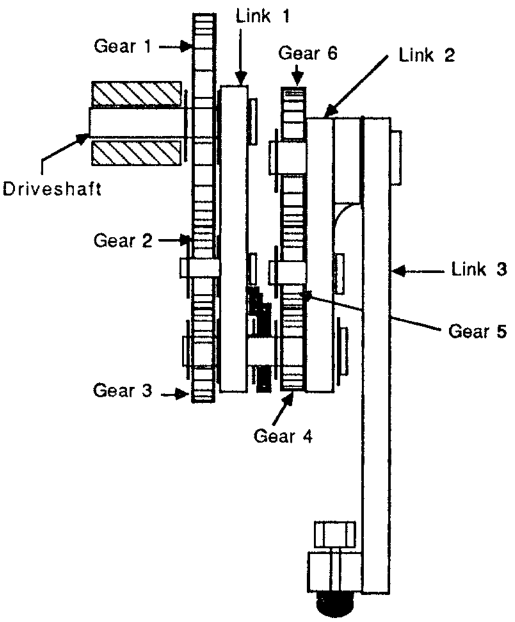

Fig. 4 Leg mechanism

Elliptical Mode

The third gear is keyed to the second link, via a common shaft, and the fourth gear is pinned to the first link for the elliptical mode.

Applying the theory of fundamental circuits (6), it can be shown that when the first link is driven at a constant angular velocity with respect to the mainframe, the second link, due to the 2:1 gear ratio, will also be rotating at a constant angular velocity. The angular displacement of the second link, when measured with respect to the first link, is twice as large as that of the first link but opposite in direction. However, the angular displacement of the second link, when measured with respect to the horizontal reference line, is always equal to that of the first link and opposite in direction as shown in Fig. 5. Consequently, making the second link slightly shorter than the first causes the outer tip of the second link to travel in an elliptical path as the drive shaft rotates.

Similarly, it can also be shown that the angular displacement of the third link when measured with respect to the second link, due to the 1:2 gear ratio, is equal to that of the first link and in the same direction. However, the angular displacement of the third link when measured with respect to the horizontal reference line is always equal to zero. Hence, the third link remains perpendicular to the ground at all times when the machine walks forward. This ensures that the toe, located on the bottom of the third link, will follow an elliptical path as the drive shaft rotates.

It can be shown that the displacement equations for the toe are given by:

$$x = (a+b)\cos(q), \tag{1}$$

and

$$y = (a-b)\sin(q) - c, \tag{2}$$

where a, b, and c are the lengths of links 1, 2, and 3, respectively, and q is the angular displacement of link 1 with respect to the mainframe. Equations (1) and (2) are two parametric equations describing the locus of the toe as the first link rotates counterclockwise. It is an ellipse having 2(a+b) as its major axis, and 2(a-b) as the minor axis.

It can also be shown that torque, T, required for the drive shaft is given by:

$$T = - F_x(a+b)\sin(q) + F_y(a-b)\cos(q) \tag{3}$$

where F_x and F_y are the x and y components of the ground reaction force at the tip of link 3 and where inertia forces of the links have been neglected.

For the current design, a = 7.94 cm, b = 6.35 cm, and c = 14.6 cm. Hence, for each revolution of the drive shaft, the walking machine advances 28.58 cm while its body hops up-and-down 1.59 cm. Further, for a 45.45 kg walking machine, the required torque to support its own weight is given by:

$$\begin{aligned} T &= 45.45 * 9.8 * ((7.94-6.35)/100)\cos(q) \\ &= 7.08 \cos(q) \text{ N-m} \end{aligned} \tag{4}$$

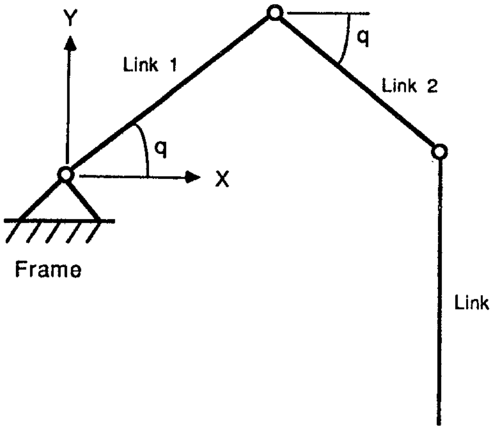

Fig. 5 Elliptical Mode

Circular Mode

In circular mode, the third gear is keyed to the fourth gear while the first link is pinned to the second link. Several mechanical adjustments are made to the leg to allow for this change. In this mode, the first and second links are effectively one long link as shown in Fig 6.

Because of the 2:1 and, then, 1:2 gear ratios in the gear train, the third link will remain perpendicular to the ground at all times as the drive shaft rotates. Again, this ensures that the toe will follow a circular path with a diameter of 2(a+b) as the drive shaft rotates. The displacement equations for the toe are given by:

$$x = (a+b)\cos(q), \tag{5}$$

and

$$y = (a+b)\sin(q) - c, \tag{6}$$

And torque, T, required for the drive shaft is given by:

$$T = (a+b)\,[- F_x\sin(q) + F_y\cos(q)] \tag{7}$$

For the current design, the overall torque required to support its own weight is given by:

$$T = 63.6\cos(q) \ \text{N-m} \tag{8}$$

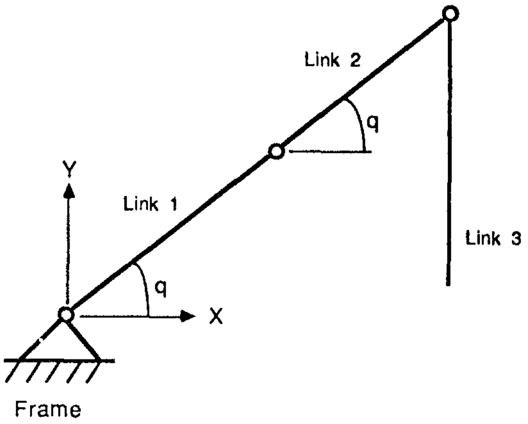

Fig 6. Circular Mode

CONTROL SYSTEM

The control system has been organized into three subsystems: analog hardware, computer hardware and computer software. Computer hardware and software are incorporated in the system so that motions of different parts can be more readily coordinated. They also provide flexibility for accommodating system modification whenever it is needed.

Without proper actuator coordination the machine cannot be successfully maneuvered in different scenarios. An example is that the machine cannot make a turn without stopping its forward motion due to the mechanical design of the machine. The controller with its software must be designed to ensure that the sequence of operations is proper before executing a command. Computer is also necessary when autonomous operations of the walking machine are desired. The control system designs are described in the following.

Analog Hardware

The basic elements of the analog hardware are the motors, the motor drive electronics and the battery. A 12-volts, 10 ampere-hour rechargeable battery is used to supply power to the motors while a dispensable 12-volt, 1.2 ampere-hour transistor batteries is used to power the computer hardware.

There are three motors in the machine: one to drive the legs, one to turn the bigfoot and one to raise and lower the bigfoot. The machine is required to move at different speeds and this means that the drive motor for the legs should be controlled to run at different rates. Pulse width modulation (PWM) scheme for driving the motor is chosen to satisfy this requirement because of its efficient use of power. A motor with rated voltage of 12 volts was selected as a result of the choice of 12 volt battery and the PWM speed control scheme. The requirements for the leg motor are that it should be capable of producing 7.08 N-m at 45 rpm for the elliptical mode and 63.6 N-m at 10 rpm for the circular mode. Specifications of the geared motor chosen is shown in Table 1, and it can be seen that the torque requirements are satisfied. As to the motors for the bigfoot, it was decided that identical ones will be used for both turning and lifting, since torque requirements are similar.

Table 1. Motor Specifications

	Leg Motor	Bigfoot Motor
Rated Voltage (V)	12	22
Rated Current (A)	12.6	4.4
Rate Speed (rpm)	50.2	1000
Rated Torque (N-m)	17.1	0.49
Stall Torque (N-m)	93.2	0.98

With the motors chosen, the power requirement for the motor battery was estimated to be 3.5 ampere-hours for a half hour walk. Additionally, the battery should be capable of providing peak current of about 20 amperes. A rechargeable 12-volt battery was chosen based on the requirements and it weighs 5 kg.

The drive circuit for the leg motor involves mainly the on/off operation and the pulse train generation for controlling speed. The former depends on the position of a two position switch and the latter is determined by a potentiometer setting. Power MOSFETs are used to supply electrical current to the motor, and an optical isolator is applied to isolate computer circuitry from motor noise. A single chip motor controller is chosen for the bigfoot motors because of the lower current requirements. This chip can be used to control the direction of each motor and supply the necessary pulse width modulation.

Computer Hardware

Instead of using a commercially available personal computer (PC), the design group decided to custom design and make their own computer. The Intel 8085 processor was chosen as the central processing unit because of students' familiarity with it and the availability of software and hardware development support at the University of Maryland. Two 8255 chips provide the system with 48 I/O lines for interfacing with peripheral devices such as switches and motors. An 8254 chip supplies the pulse width modulation signal for driving the bigfoot motors. There are two sockets for memory: one for RAM and the other for EPROM. An Analog Devices AD7828 chip provides 8 channels of high speed A/D conversion which are used to read the potentiometers indicating the desired motor speeds. There are also an 8250 UART chip and a MAX232 chip to establish an RS-232 port for serial communication needed for downloading software developed on a PC.

Computer Software

The program developed for the walking machine are all in 8085 assembly language. The program was first generated on a PC with the use of CROSS 16, an 8085 cross compiler. This environment provides ease of editing and initial debugging, but whether I/O ports can be accessed properly cannot be determined. The program has to be tried on the actual computer hardware together with its peripheral devices to see if they work properly. This was done by using MON85 run time assembler/debugger on the actual hardware. MON85 provides means for receiving the assembled code from a PC, and for debugging the code. The debugged program was burnt into an EPROM which was then placed in the EPROM socket. Once this is done, the program will be in execution when the power is turned on.

The program is a modular one in which basic procedures to move legs, to rotate the bigfoot clockwise or counterclockwise, and to lift or lower bigfoot form the independent modules. These modules will be repeatedly executed in sequence. During the execution of each of these modules, the settings on the hand controller will be inputted and then proper actions, which are programed into submodules, can be taken accordingly. Each of the actions, once activated, will remain activated until a different action is activated.

SUMMARY

Because of the relatively small number of DOF, the control logic of the walking machine has been substantially simplified and fast locomotion of the walking machine has been achieved. This is accomplished with some sacrifice of flexibility in comparison with conventional walking machines. The innovative design coupled with the students' determination and hard work have led to the development of an impressive walking machine. Nine universities entered the Third Annual Walking Machine Decathlon held at the Texas Tech University in April, 1989. The University of Maryland's machine walked away with an overall Second Place. The students have gained valuable knowledge and experience in the designing and building of a fairly sophisticated electro-mechanical system. Each has experienced the intricacies of translating an idea to a technical drawings to a physical reality and has definitely gained from the experience.

ACKNOWLEDGEMENT

The financial support of the Department of Mechanical Engineering, the Systems Research Center, and the College of Engineering at the University of Maryland for this design project is greatly appreciated. Undergraduate students participating in this project need to be credited for the successful design and building of the machine.

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