# Industrial-Strength Human-Assisted Walking Robots

## *Design and Control of Human-Operated Industrial Machines that Can Successfully Maneuver Heavy Loads in Isolated Areas for an Extended Period of Time*

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Integrating humans into the operation of robots has increased the performance and utility of many types of robots. For example, teleoperated robots eliminate the need for sophisticated terrain-acquisition sensors, terrain-mapping capabilities, and path-planning capabilities. The same approach can be applied to autonomous walking robots in regards to balance and foot placement. Having the operator perform these tasks results in more practical machines with industrial applications.

The problem of transporting moderate loads over rough terrain is common to many real-life tasks, such as construction, emergency rescue in isolated areas, and disaster relief. An examination of the possible devices available to assist people in the above tasks reveals that the options are limited. (By moderate loads, we are referring to loads up to 80 lbs, which is the upper limit of what a human can carry with effort.) One of the possible devices is a wheelbarrow, which requires significant operator effort, especially on inclines, and is limited in the types of terrain it can traverse. The other options available are also in the form of wheeled vehicles, like motorcycles and jeeps, which are too large for many applications. Additionally, these vehicles tend to embed themselves in muddy or plastic soil and have traction difficulties on steep slopes.

As a solution to this problem, this article discusses the design of a machine that can successfully maneuver heavy loads for extended periods of time over unstructured terrain, as found in forests, jungles, and deserts, as well as over structured terrain, such as stairs. Although there are machines that have sophisticated electronic and mechanical hardware that function successfully in rugged environments, increased reliability can be achieved by reducing the number of these sensors. Additionally these types of machines become prohibitively expensive. Our design sought to increase the robustness of the robot and reduce cost by limiting the number of sensors and actuators. The machine had to be self-contained—capable of carrying its own energy supply and controller, if necessary. Moreover, we required that it be easy to "recharge" the ma-


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chine after its own energy supply was exhausted. The final design specification was that this machine be a human-assisted device designed specifically to interact with the human operator. Allowing the machine to be human operated eliminated the need for a fully autonomous robot.

## Steps in the Right Direction

The design specifications for the machine did not call for a specific type of locomotion to be used. The choice lay between the two basic types: legged and wheeled locomotion. The latter included tracked or treaded type vehicles, which are special types of wheeled vehicles that carry and lay down their own road. One difference between the two types of locomotion is the possible types of terrain that they can traverse. According to a U.S. Army report, only 50% of the Earth's land surface is accessible to wheeled or tracked vehicles [1], whereas humans and other animals can access almost all of it using legged locomotion. Another significant difference between the two types of locomotion is how they interact with the soil. In wheeled locomotion, the wheel sinks into the soil and makes a depression that it must then climb out of as it rolls. By contrast, the legged vehicle creates isolated depressions, and any slip forces soil behind the foot, which increases traction. Bekker [2] has conducted extensive research comparing the power requirements for various types of locomotion. His results revealed that legged locomotion, on soft soil, requires less power per unit weight than wheeled or tracked locomotion. On extremely irregular or soft terrain, the advantages of legged locomotion over wheeled can be summarized as

- better fuel economy
- higher speed
- greater mobility
- better ride quality
- less environmental damage
- greater range of possible terrain.

Significant progress has been made in the field of walking robots, especially dynamic bipeds, over the past 30 years. In the laboratory, self-stabilizing bipedal walking robots have been designed [3]–[5] that can walk on level ground as well as up small steps. These machines are limited by the requirement of an external power supply, and the computing source is often external. By having numerous expensive and delicate actuators and sensors, these robots are strictly designed for laboratory use and not for operation outdoors.

The Adaptive Suspension Vehicle (ASV) built at Ohio State University [6] is a six-legged walking machine that is specifically designed for use in rough terrain. This human-operated robot successfully navigated various types of terrain, but its size (17-ft long) and weight (6000 lbs) limited its use. Additionally, the numerous sensors and actuators added to its complexity and cost. In 1992, a six-legged walking machine, not unlike the ASV, called MECANT I was built [7]. This self-contained, autonomous robot was designed for operation in rough and irregular terrain. Its successful operation has not been reported.

There are many areas that need further development before the design of a usable, fully autonomous bipedal, and even four- and six-legged, walking robot can be expected. These areas are terrain sensing, travel over unstructured terrain, actuator design, and system controls. We have already determined that a human will operate the machine, which places our design in the area of human-assisted robots. The design of such devices is grounded in the notion that a human's ability to perform physical tasks is limited by physical strength and not intelligence. As long as we have an intelligent operator, we should take advantage of the situation and use his/her abilities. The tasks that we can assign to the operator without causing excess mental or physical fatigue are balance and navigation. Thus, by combining the skills of the two machines, the human and the robot, and allowing each one to perform the tasks they are good at, we can simplify the design and improve the robot's effectiveness.

***Allowing the machine to be human-operated eliminated the need for a fully autonomous robot.***

## Bipedal Locomotion

Because the goal was to create a bipedal walking machine, it was only logical to study how humans successfully perform the task. The interest in this study is mainly to focus on the motion of the legs and the feet in the sagittal plane. The other motions of the legs and the motion of the rest of the body are for balance, momentum conservation, and energy storage. These tasks were not assigned to the legs of this machine; thus, the human leg motions that accomplish them were not considered.

There is an important hypothesis that may explain most leg and body motions during human walking. It states that, during walking, the human will integrate motions of the various segments and control the activity of the muscles so that the metabolic energy required for a given distance walked is minimized [8]. This hypothesis, which we can consider to be proved, is important in that it provides some insight into the motion of the legs, feet, and body. The human walking cycle, or gait, can be divided into various events [9]

- 0%—left-foot strike, left leg begins stance phase
- 12%—right toe-off, right leg begins swing phase
- 50%—right-foot strike, right leg begins stance phase
- 62%—left toe-off, left leg begins swing phase.

The foot-strike event is characterized by a very rapid loading onto the forward limb with absorption of the shock by the limb and body and a slowing of the body's forward momentum. This change in momentum is what researchers Dunn and Howe [10], [11] tried to eliminate in order to smooth bipedal walking.

We examined the path of the foot during walking across various types of terrain. A total of 23 plates (consisting of a chronological sequence of photographs) of males and females traversing level ground, ascending and descending an inclined plane, and ascending and descending a set of stairs was used [12]. To determine the path of the foot relative to the body, a marker was placed on the pelvis and another on the foot, and a line was drawn connecting them. This process was repeated for each frame of the walking sequence, then the lines were combined. The end points of the lines were connected to form the path of the foot. This foot path was constructed for both males and females on the various types of terrain (Fig. 1). One observation is that the path of the swing foot remains very close to the ground.

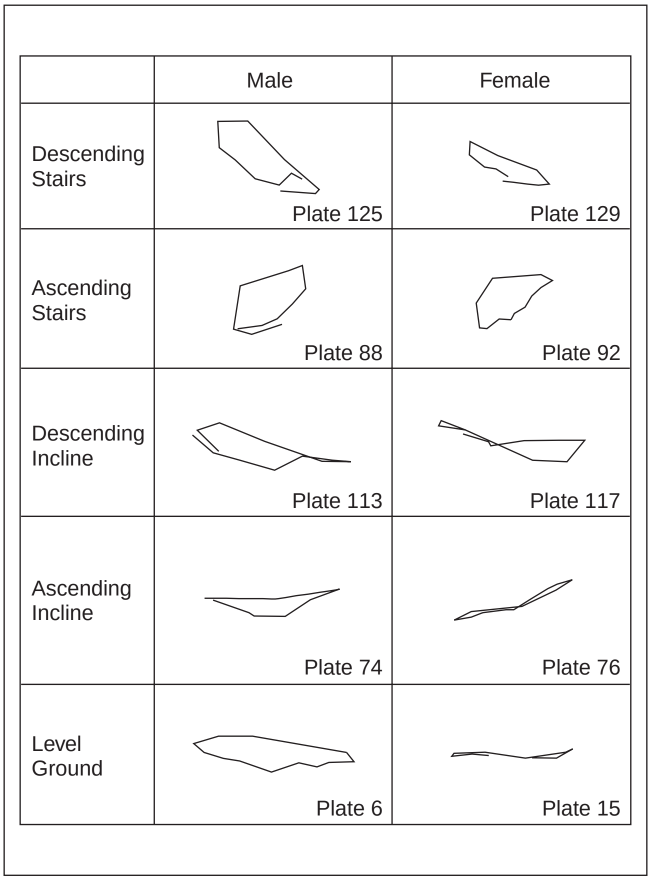


***Figure 1.*** *Path of foot for various terrain.*

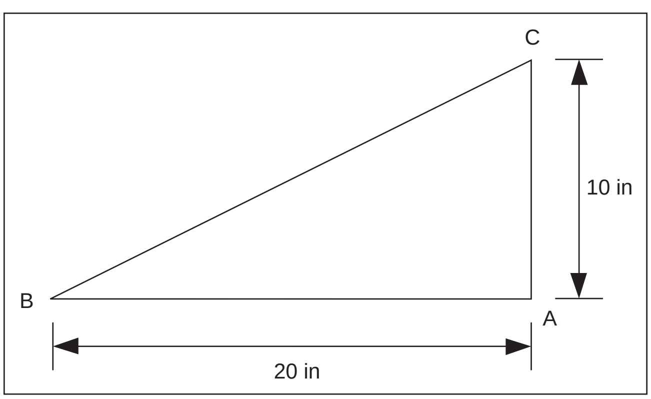


***Figure 2.*** *Desired foot path.*

The next step was to construct a desired foot path so as to achieve bipedal locomotion over the various terrain. Referring to Fig. 1, we see that the stance component of the path is generally straight and parallel to the ground surface. This feature was duplicated in the desired foot path by having the connection between points A and B (Fig. 2), the stance component of the foot path, be straight. The next step was to determine the form of the rest of the path (i.e., during the swing phase). We would like to have a single foot path that can be used to traverse all the different types of terrain, which would greatly simplify the machine's leg mechanism. If the foot of the machine needs to be able to reach any point in the vertical plane, each leg must have at least two powered degrees of freedom, for a total of four powered degrees of freedom (where each powered degree of freedom requires its own actuator). However, if we can find a single foot path that will accomplish what the two degree of freedom path can do, then we need only one actuator per leg for locomotion. Finally, it should be noted that if there is a fixed foot path, knowing the position of one of the legs automatically determines where the other leg will be, which is 50% of the gait cycle ahead/behind. Thus, there is only one degree of freedom necessary for both legs, and, as a result, only one actuator is necessary to drive the entire system. All these advantages depend on finding the single foot path which will accomplish the motion.

The movement of the foot during the swing phase differs between the various types of terrain. These differences exist because the human tries to traverse the terrain while avoiding excessive or unnecessary movements of the leg. Because the energy efficiency of the machine is not the main issue, the swing path of the foot for the machine is not as restricted as it is for a human. This leads to the desired path having the shape shown in Fig. 2. Note that the curve presented in Fig. 2 is the path that the foot traces out relative to a fixed point on the machine. The flat horizontal part is based on the common feature found in the human foot paths of Fig. 1. The swing component of the foot path (points B-C-A in Fig. 2) is similar to the swing foot path of the human ascending stairs (plates 88 and 92 of Fig. 1) but with the apex of the path shifted forward. The forward shift is to accommodate a step or rise in the terrain that occurs anywhere within the stride of the machine. In order for the machine to walk, the bottom flat part, from point A to point B, must last for at least 50% of the gait cycle (recall that for humans it is 62%). Also, the motion along the path should be smooth so that the velocity of the machine is relatively constant. We now have a single degree of freedom foot path for a biped that can traverse irregular terrain, including stairs.

## Double Four-Bar Linkage

The next step in the design was to produce a mechanism that achieved the desired foot path. Achieving the desired path has two components: a space constraint and a time constraint. Satisfying the space constraint means that we have produced a machine where the foot path matches the desired path in space only. The time constraint means that we reach every point in space along the path at the correct time as measured relative to the driving input. The time constraint is critical because we need to ensure that the duration of the stance phase is at least half the total cycle.

At this point, we are looking for a mechanism that will produce the desired foot path with a single input. Potential mechanisms that were evaluated included four-bar linkages, seven-bar linkages, and pantographs. Also, various design techniques for producing a straight line path [13] were evaluated. The four-bar linkage had the problem of not being able to satisfy the space and time constraint for matching the foot path. The seven-bar linkage and the pantograph mechanism both require two inputs, which violated the criteria of reducing the complexity of the robot by having only one powered input. From the available technology, there was no method to produce the desired motion while keeping within the design constraints. For this reason, we had to design our own mechanism, called the double four-bar mechanism, to satisfy the design.

The double four-bar mechanism consists of two four-bar linkages, connected in a novel way that will be discussed below. The first four-bar linkage, which we will call the *thigh linkage*, is shown in Fig. 3. The thigh linkage consists of the *thigh driver-link* having length $r_{t\_d}$; the *thigh rocker-link* having length $r_{t\_r}$; the *thigh coupler-link*, having length $r_{t\_c}$, which couples the thigh driver-link and the thigh rocker-link; the *thigh ground-link* having length $r_{t\_g}$, so called because it is usually grounded to a fixed component; the *thigh leg* having length $L_t$; and the *rigid connecting link*. The thigh leg has one end pinned at point a in Fig. 3, which is where the thigh rocker-link and the thigh ground-link are pinned together. The thigh leg is also connected to the thigh rocker-link by means of a rigid connecting link so that the rotational motion of the thigh rocker-link is transferred to the rotational motion of the thigh leg with an offset angle of $\theta_{\text{thigh\_offset}}$. When the lengths are such that they satisfy

$$r_{t\_r} + r_{t\_d} < r_{t\_c} + r_{t\_g} \tag{1}$$

as the thigh driver-link completes a full revolution, the thigh rocker-link rocks back and forth. This type of four-bar linkage is known as a crank-rocker mechanism.

The second four-bar linkage, which we will call the *shank linkage*, is shown Fig. 4. The shank linkage consists of the *shank driver-link* having length $r_{s\_d}$; the *shank rocker-link* having length $r_{s\_r}$; the *shank coupler-link* having length $r_{s\_c}$, which couples the shank driver-link and the shank rocker-link; the *shank ground-link* having length $r_{t\_g}$; and *sprocket 1*, which is rigidly connected to the shank rocker-link at point c. As the shank rocker-link rotates, it also rotates sprocket 1 through the same angle. As with the thigh linkage, when the lengths of the shank linkage links are such that they satisfy

$$r_{s\_r} + r_{s\_d} < r_{s\_c} + r_{s\_g}, \tag{2}$$

the linkage behaves as a crank-rocker mechanism. Grasshoff's theorem can be used to guarantee the rotatability of the device. However there are other concerns that need to be addressed before the use of this theorem.

The two linkages are then connected together (Fig. 5). Note that the thigh ground-link and the shank ground-link have been combined into the same element. Additionally, a shank leg is added to the base of the thigh leg. The shank leg, which has length $L_s$, has *sprocket 2* rigidly connected to it, so that as the shank leg rotates, sprocket 2 rotates with it. Point c (Fig. 4) of the shank linkage is connected at point a (Fig. 3) of the thigh linkage so that the thigh rocker-link, the shank rocker-link, and the thigh leg all have the same pivot point.

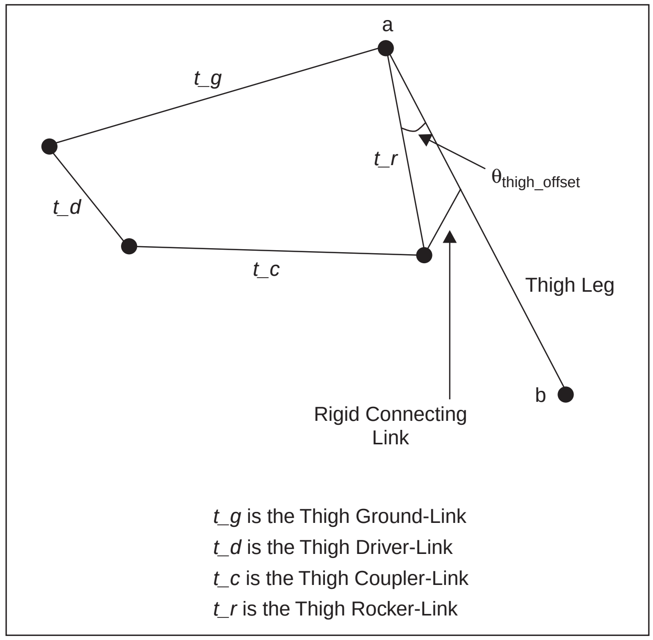


***Figure 3.*** *Thigh linkage.*

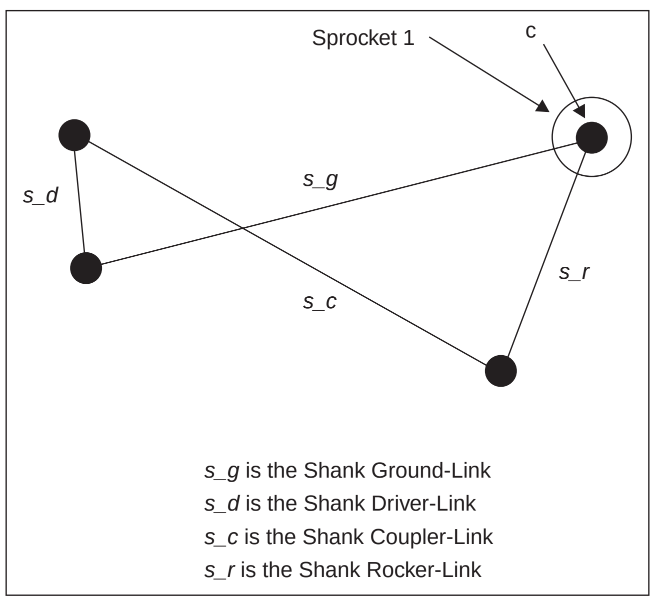


***Figure 4.*** *Shank linkage.*

Next a *chain* is used to connect sprocket 1 and sprocket 2. This chain transfers the motion of the shank rocker-link to the shank leg. The movement of the *foot* is considered to be the output of the double four-bar linkage. This movement is dictated by output of the two four-bar linkages. As the thigh driver-link rotates, the thigh rocker-link rocks back and forth, which in turn causes the thigh leg to rotate (resulting in a change in angle $\theta_{\text{thigh}}$). As the shank driver-link rotates, the shank rocker-link rocks back and forth, which in turn causes sprocket 1 to rotate, which causes sprocket 2 to rotate, resulting in a rotation of the shank leg (a change in angle $\theta_{\text{shank}}$). The double four-bar linkage system has one degree of freedom on the input (i.e., the position of the shank driver-link/thigh driver-link) and one degree of freedom on the output (i.e., the position of the foot along the curve that it traces out in space). The output (i.e., the position of the foot) of the double four-bar linkage is governed by a total of 15 independent parameters.

In addition to producing an acceptable foot path, there were certain conditions that had to be met by the linkages. To satisfy the overall size constraint, the linkages had to stay within a circle one and a half times the length of the foot path. Additionally, the minimum transmission angle for each linkage had a lower limit of 35°, but, ideally, we wanted it to be even larger than that.

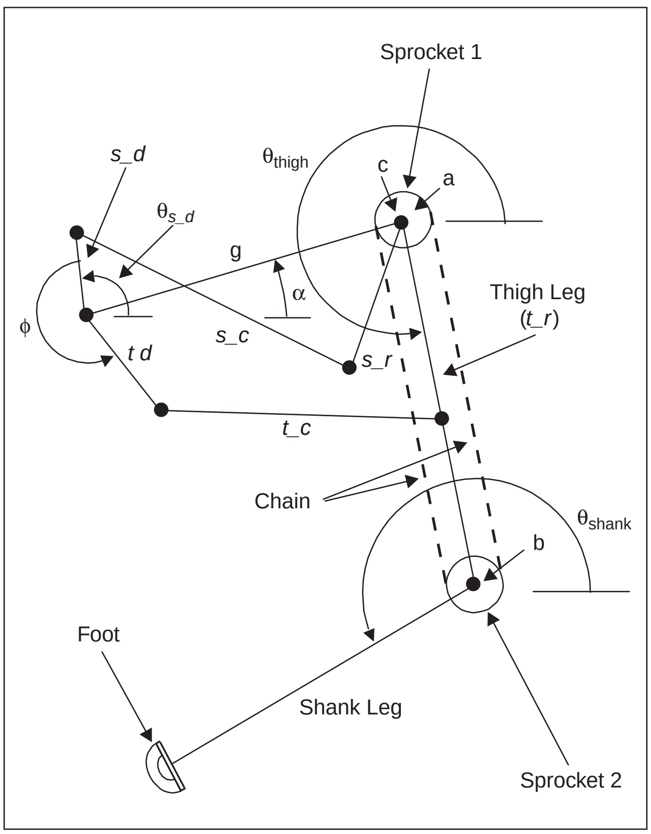


***Figure 5.*** *Double four-bar linkage.*

| **Table 1. Linkage Lengths** | | | | |
|---|---|---|---|---|
| **Linkage** | $r_d$ | $r_c$ | $r_r$ | $r_g$ |
| **Thigh** | 4.0 in | 15.0 in | 5.8 in | 15.5 in |
| **Shank** | 4.0 in | 13.0 in | 9.7 in | 15.5 in |

Due to the large number of governing parameters, a combination of four-bar linkage synthesis and a brute force search technique was required to solve for the feasible set of parameters. The feasible set is one that produces a foot path that best satisfies the space and time constraints. We first set the lengths of the thigh leg and the shank leg to be 17 in each, as above. Next, we decided to match only three points on the desired path. The points chosen were foot-points A, B, and C in Fig. 2, which are the vertices of the foot path. This simplification permits the use of the four-bar linkage function generator synthesis method with three-point matching. The input to this function generator was considered to be the angle of the driver-link and the output was the angle of the rocker-link.

The function generator synthesis method produced four equations each for the thigh linkage and the shank linkage. If we had used four or more points for matching, that would have yielded at least two more equations for each linkage. The number of unknown parameters for each linkage was 12. For the thigh linkage, five parameters were given based on the location of the three points to be matched and how these points occurred in time relative to each other. For the shank linkage, only four parameters were known. This meant that there were three free parameters governing the thigh linkage and four free parameters governing the shank linkage.

The search method involved systematically varying the free parameters and then solving the function generator equations for the remaining four parameters. Each combination was examined for compliance with the design specifications. The satisfactory linkages were then combined to form the double four-bar linkage, and the resulting foot path was then checked. The result was that only a few parameter combinations yielded potential solutions. Fine-tuning was performed on the final parameter combination so as to produce an acceptable foot path with high transmission angles. The final link lengths are given in Table 1.

The linkages were scaled so that they had the same length ground-link, and that the smallest link (which turned out to be the driver-link for both linkages) was the smallest acceptable value. If the driver-link was set to be any shorter than 4 in, it would have been difficult to implement in practice. For comparison, the desired and actual paths of the foot are presented in Fig. 6.

## Machine Components

The approach to designing the machine was to use technology that was developed for rugged terrain and outdoor environments. This approach is in contrast to what is commonly used for robotic walking machines, where the main technology in use is developed for laboratory and research purposes.

In order to achieve our design goal of an untethered machine, a power source was necessary. Given the current state of battery technology, an internal-combustion (IC) gasoline engine was the only possible solution. A two-stroke chainsaw engine was chosen for two reasons, the first being that chainsaw engines have been specifically designed to operate in harsh environments, similar to the type for which the robotic machine is being designed for. The other key feature is that the engines include a centrifugal friction clutch, which is designed to engage the load at a speed above the idle speed. This feature allows the engine to idle while the machine is not moving; in addition, it automatically prevents the load from stalling the engine while the machine is accelerating and other times when significant torque is required.

A single-stage worm gearbox was chosen to provide a reduction of 40:1 and to split the power to the two sides. A worm gear was chosen because it provides a space-and-weight-efficient way of achieving large gear ratios. Also, the worm gear cannot be back driven. This allows the legs of the machine to stop in any position without the need for a brake.

When the foot contacts the ground, the impact force is transferred to the machine and then to the user who is in direct contact with the machine. Because this force can be high and sudden, a means of isolating the user from this load was necessary. A self-compensating shock absorber, which provides a relatively constant force over a range of masses and impact velocities, was used in the shank leg.

A rigid foot with a vulcanized rubber pad was used in the design. The shape and surface coating of the foot was chosen for use on hard surfaces. The foot was designed such that it screws into the base of the leg, allowing for easy removal and the installation of other foot designs. Thus, one can substitute alternative designs for specific types of terrain, such as snow, sand, mud, etc.

A photograph of the robot in operation is shown in Fig. 7. The total weight of the unloaded machine is 125 lbs, with overall dimensions of 3-ft high, 2-ft wide, and 2-ft long.

## Operation

There are two ways to control the walking speed of the machine. One is open-loop or manual control, and the other is closed-loop control. In open-loop control, the operator serves as the controller. To go faster, the operator actuates the engine throttle to increase the engine torque, ultimately increasing the speed of the machine. In a similar manner, the user can slow the machine down. In closed-loop mode, the throttle actuation is governed by an electronic controller, which uses feedback to regulate the speed of the machine. There are three main components involved in closed-loop speed regulation: the input device, the controller, and the plant. The input to the controller comes from the operator, who ultimately decides the speed. A rotary switch with multiple positions was used for the operator to select the desired speed; each position of the switch corresponded to a different speed.

The controller was an onboard embedded computer with a 386 microprocessor and built-in analog input-output (I/O) and digital I/O capabilities. A dc motor, controlled by the microprocessor, was used to actuate the spring-loaded throttle lever on the engine. These two electrical devices were powered by an onboard 12-V dc battery. The speed feedback was provided by a tachometer that was mounted on the output shaft of the worm gear transmission. The tachometer provided a voltage proportional to the speed of the shaft that was then read by an analog input channel on the microcomputer.

The model of the plant, for purposes of feedback control, is based on many parameters and states of the system. The basic model of the two-stroke engine has the throttle angle as the input, the load torque as a disturbance, and the engine speed as an output. A state feedback controller is entirely impractical for this application because of the requirement for numerous sensors, including engine speed, terrain angle of inclination, temperature, throttle position, air and fuel flow rates, and pressure [14], [15]. Additionally, it was not required that the controller track perfectly with fast response time. The combination of the engine dynamics and the inertial effects of the

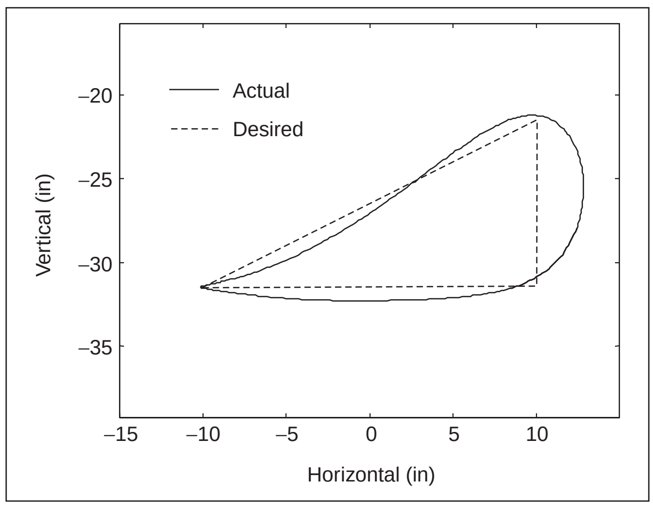


***Figure 6.*** *Actual and desired foot paths.*

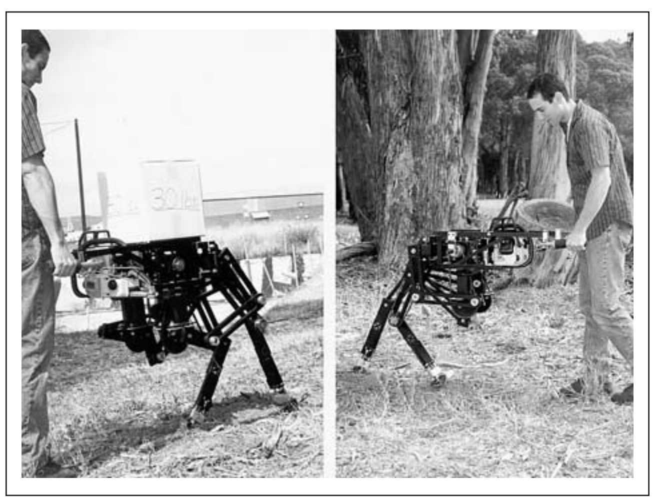


***Figure 7.*** *Photographs of the robot transporting a load.*

machine provides for a very slowly responding system, allowing for a simple controller. The control law developed was a standard proportional controller of the form

$$u = k_p\, e, \tag{3}$$

where

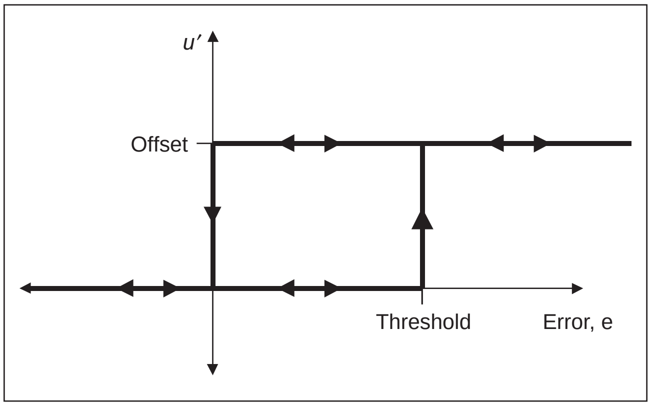


**Figure 8.** *Function* u′.

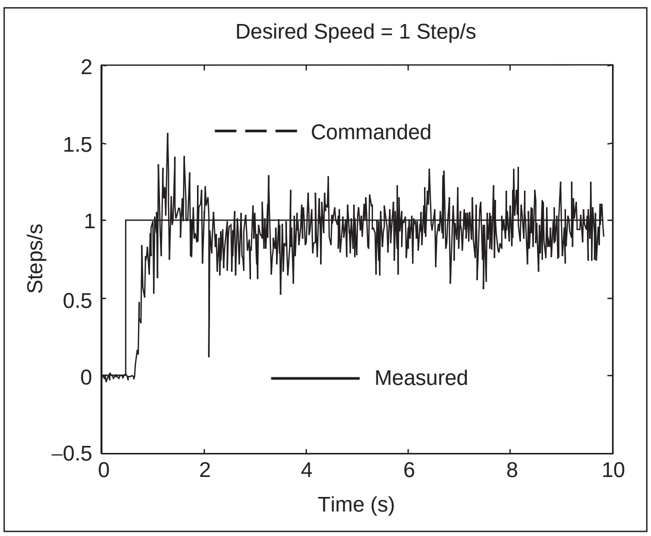


**Figure 9.** *Closed-loop step response.*

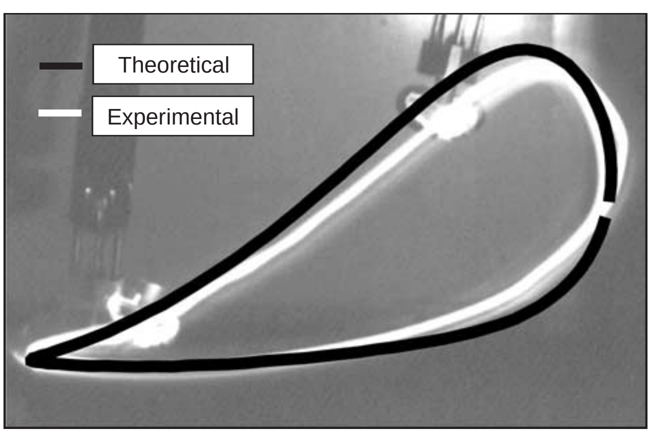


**Figure 10.** *Theoretical and experimental foot path.*

$$e = \omega_{des} - \omega_{act}, \tag{4}$$

$\omega_{des}$ is the desired speed, $\omega_{act}$ is the actual angular speed, and $k_p$ is a proportional gain constant. In order to overcome stiction in the throttle and motor, and to counteract the spring force of the throttle lever, offset term $u'$ was added. Because the spring force was only in one direction, the offset term also was only needed in one direction. To prevent rapid switching of this offset term, hysteresis was added. The function for $u'$ is shown in Fig. 8, where the threshold and offset values were empirically determined. The resulting control law is

$$u = k_p\, e + u'. \tag{5}$$

The role of the operator is critical to the function of the machine. Recall that the simplicity of this walking robot was due to the dividing of tasks between the operator and the machine. The operator must provide the forces necessary to keep the machine upright. The operator, through the handles, applies these forces to the machine. One of the forces prevents the rolling motion of the robot. The magnitude of this force was determined to be less than 10 lbs, as long as the machine remained within 5° of vertical. The other force, which prevents pitching motions of the machine, was determined to be a maximum of 25 lbs.

The other critical role the operator must perform is that of navigation. The operator needs to select a path such that there will be acceptable footholds for the machine; a relatively easy task for a human to perform, but extremely difficult for a machine. The final task for the operator is that of speed regulation. If the operator decides to use the closed-loop method, then he/she needs only to dial-up the desired speed on the multiple-position switch. If the operator decides to use the open-loop method, then he/she has to actuate the throttle lever to achieve the desired speed.

## Results

The machine was tested using the controller described above. Tests were conducted with the machine suspended off the ground, which we will call *suspended-mode* testing, and with the machine walking on the ground, which we will call *walking-mode* testing. Both types of tests were implemented with the machine starting at rest. A command signal of a desired speed was then issued (a step input). The resulting speed of the machine, as measured by the rotational speed of the transmission output shaft, was then recorded for 10 s. A typical plot of the performance from the suspended-mode performance is shown in Fig. 9. The results for various speeds, as well as the walking-mode testing, compare similarly with the results shown in Fig. 9.

To verify that the actual mechanism operated as it was designed to, a trace of the foot's path was generated by attaching a light bulb to the end of the foot. While the suspended machine moved its legs, the shutter of the camera was opened.

For comparison, the theoretical (or predicted) foot path is overlapped onto a photograph of the actual foot path (Fig. 10).

The performance of the machine was quantitatively determined on level ground and inclined surfaces. Because the fixed foot path produces a fixed step size of 20 in, the variable in performance between the various types of terrain is the step frequency, which governs walking speed. Walking on level ground, the machine reached a maximum speed of 1.57 steps/s. Walking up a 12% grade incline, the machine sustained 1.5 steps/s. And, finally, on a 23% grade incline, the machine sustained 1.48 steps/s. The only barrier to climbing steep grades is ensuring that the friction forces between the foot and the ground are sufficient to propel the machine forward. The machine's performance in walking up and down stairs is hard to quantify. It can be said that some navigation on the part of the operator is necessary as the machine ascends the stairs. The machine ascends the stairs better if the operator slows the machine down slightly before having it step on the first step and then making sure that each successive stair is safely reached

The walking performance of the machine is summarized in Table 2.

**Table 2. Summary of Walking Performance**

| Terrain | Walking Speed |
|---|---|
| Level Ground (0% Grade Incline) | 1.57 steps/s |
| 12% Grade Incline | 1.50 steps/s |
| 23% Grade Incline | 1.48 steps/s |

## Conclusion

We have invented and designed a bipedal walking machine to solve the challenges of transporting loads in remote and isolated areas. The problem of autonomous walking has been reduced by having the operator navigate the robot and provide the balancing forces. The novel mechanism is the double four-bar linkage, which enables a single powered degree of freedom to produce a walking motion. The resulting machine is simple and robust enough to successfully operate in harsh environments and on rugged and irregular terrain. The new leg mechanism can be adapted to reduce the complexity of four- and six-legged walking machines. The next step in this research is to reduce the effort of the operator in maintaining balance of the robot. This can be achieved by monitoring the forces between the operator and the machine and mechanically altering the location of the center of mass accordingly.

## Keywords

Robots, human assisted, walking machines, augmentation, enhancer, extender.

## References

[1] "Logistical vehicle off-road mobility," U.S. Army Transprotation Combat Developments Agency, Fort Eustis, VA, Project TCCO 62-5, 1967.

[2] M.G. Bekker, *Off-The-Road Locomotion*. Ann Arbor, MI: Univ. of Michigan Press, 1960.

[3] S. Kajita and K. Tani, "An analysis of experimentation of a biped robot Meltran II," presented at the 3rd Int. Workshop Advanced Motion Control, Berkeley, CA, 1993.

[4] S. Kajita and K. Tani, "Experimental study of bipedal walking," *IEEE Control Syst. Mag.*, vol. 16, pp. 13-19, Feb. 1996.

[5] J. Yamaguchi, A. Takamishi, and I. Kato, "Development of a biped walking robot adapting to a horizontally uneven surface," in *Proc. IEEE/RSJ/GI Int. Conf. Intelligent Robots and Syst.*, Munich, Germany, 1994, pp. 1156-1163.

[6] S. Song and K. Waldron, *Machines That Walk: The Adaptive Suspension Vehicle*. Cambridge, MA: MIT Press, 1989.

[7] K.K. Hartikainen, A.J. Halme, H. Lehtinen, and K.O. Koskinen, "MECANT I: A six legged walking machine for research purposes in outdoor environment," in *Proc. 1992 IEEE Int. Conf. Robotics and Automat.*, Nice, France, pp. 157-163.

[8] V.T. Inman, H.J. Ralston, and F. Todd, in *Human Walking*, J.Rose and J.G. Gamble, Eds, 2nd ed. Baltimore, MD: Lippincott, Williams & Wilkins, 1994, ch. 1, pp.1-22.

[9] D.H. Sutherland, K.R. Kaufman, and J.R. Moitoza, in *Human Walking*, J. Rose and J.G. Gamble, Eds, 2nd ed. Baltimore, MD: Lippincott, Williams & Wilkins, 1994, ch 2, pp.23-44.

[10] E.R. Dunn and R.D. Howe, "Towards smooth bipedal walking," in *Proc. 1994 IEEE Int. Conf. Robotics and Automat.*, Los Alamitos, CA, 1994, vol. 3, pp. 2489-2494

[11] E.R. Dunn and R.D. Howe, "Foot placement and velocity control in smooth bipedal walking," in *Proc. 1996 IEEE Int. Conf. Robotics and Automat.*, Minneapolis, MN, vol. 1, pp. 578-583.

[12] E. Muybridge, *Muybridge's Complete Human and Animal Locomotion*. New York: Dover, 1979.

[13] J.P. Vidosic and D. Tesar, "Selection of four-bar mechanisms having required approximate straight-line outputs," *J. Mechanisms*, vol. 2, no. 1, Spring 1967.

[14] Y. Kubota, S. Hayashi, S. Kajitani, and S. Norihiro, "A study of the transient characteristics of a small two-stroke spark-ignition engine," presented at the SAE Int. Congr. and Exposition, Detroit, MI, 1991.

[15] D. Margolis, "Modeling of two-stroke internal combustion engine dynamics using the bond graph technique," *SAE Trans.*, vol. 84, no 3, 1975.

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