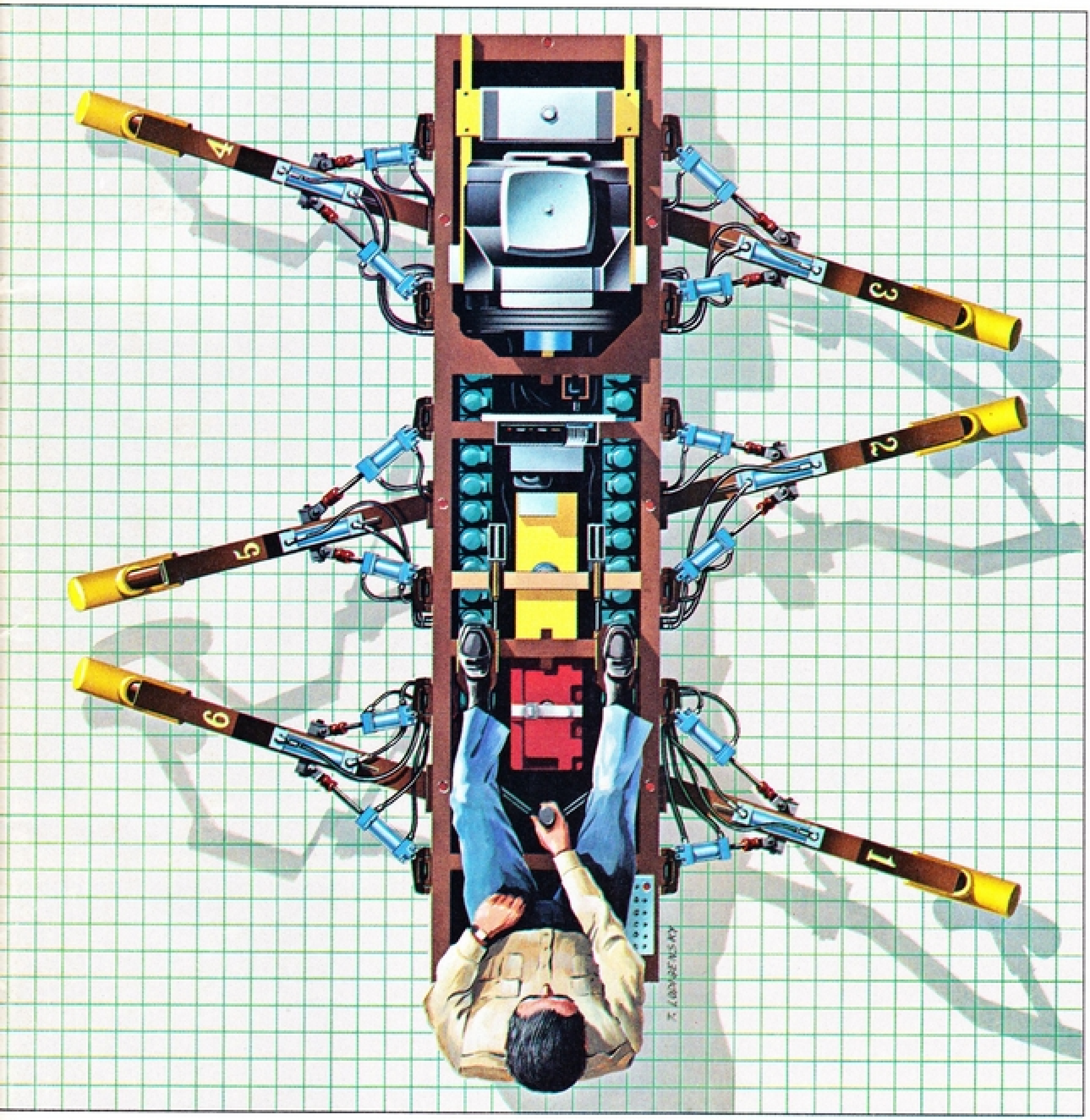
SCIENTIFIC AMERICAN



MACHINES THAT WALK

~~$2.50~~ 3.35

January 1983

Established 1845 **SCIENTIFIC AMERICAN** January 1983 Volume 248 Number 1

ARTICLES

DEPARTMENTS

SCIENTIFIC AMERICAN (ISSN 0036-8733), PUBLISHED MONTHLY BY SCIENTIFIC AMERICAN, INC., 415 MADISON AVENUE, NEW YORK, N.Y. 10017. SECOND-CLASS POSTAGE PAID AT NEW YORK, N.Y., AND AT ADDITIONAL MAILING OFFICES. AUTHORIZED AS SECOND-CLASS MAIL BY THE POST OFFICE DEPARTMENT, OTTAWA, CANADA, AND FOR PAYMENT OF POSTAGE IN CASH. SUBSCRIPTION RATE: $21 PER YEAR IN THE U.S. AND ITS POSSESSIONS; $27 PER YEAR IN ALL OTHER COUNTRIES. POSTMASTER: SEND ADDRESS CHANGES TO SCIENTIFIC AMERICAN, 415 MADISON AVENUE, NEW YORK, N.Y. 10017.

Machines That Walk

Locomotion on legs resists imitation, but modern control technology should be able to solve the problem. Experiments with machines that hop and crawl can also illuminate the mechanisms of natural walking

by Marc H. Raibert and Ivan E. Sutherland

Many machines imitate nature; a familiar example is the imitation of a soaring bird by the airplane. One form of animal locomotion that has resisted imitation is walking. Can it be that modern computers and feedback control systems make it possible to build machines that walk? We have been exploring the question with computer models and with actual hardware.

So far we have built two machines. One has six legs and a human driver; its purpose is to explore the kind of locomotion displayed by insects, which does not demand attention to the problem of balance. The other machine has only one leg and moves by hopping; it serves to explore the problems of balance. We call the first kind of locomotion crawling to distinguish it from walking, which does require balance, and running, which involves periods of flight as well. Our work has helped us to understand how people and other animals crawl, walk and run.

Unlike a wheel, which changes its point of support continuously and gradually while bearing weight, a leg changes its point of support all at once and must be unloaded to do so. In order for a legged system to crawl, walk or run, each leg must go through periods when it carries load and keeps its foot fixed on the ground and other periods when it is unloaded and its foot is free to move. This type of cyclic alternation between a loaded phase, called stance, and an unloaded phase, called transfer, is found in every form of legged system. As anyone who has ridden a horse at a trot or a gallop knows, the alternation between stance and transfer can generate a pronounced up-and-down motion. We believe legged machines can be built that will minimize this motion.

Our work and related work by others may eventually lead to the development of machines that crawl, walk and run in terrain where softness or bumpiness makes wheeled and tracked vehicles ineffective and thus may lead to useful industrial, agricultural and military applications. The advantage of legged vehicles in difficult terrain is that they can choose footholds to improve traction, to minimize lurching and to step over obstacles. In principle the performance of legged vehicles can be to a great extent independent of the detailed roughness of the ground. Our objective has been to explore the computing tasks involved in controlling and coordinating leg motions. It is clear that very sophisticated computer-control programs will be an important component of machines that smoothly crawl, walk or run.

As we have indicated, locomotion is possible with or without dynamic balance. The animals that crawl avoid the need for balance by having at least six legs, of which at least three can always be deployed to provide a tripod for support. High-speed motion pictures of insects show that they commonly crawl with an alternating tripod gait.

Although a crawling machine that does not need dynamic balance can be built with four legs, such a machine performs awkwardly because its weight must be shifted at each step to keep it from tipping over. Satisfactory performance without active balance calls for at least six legs, since six is the smallest number of legs that always provide a tripod for support even when half of the legs are elevated. Several six-legged machines have now been built, each differing in size and in mechanical design. All of them depend on computer control of the legs.

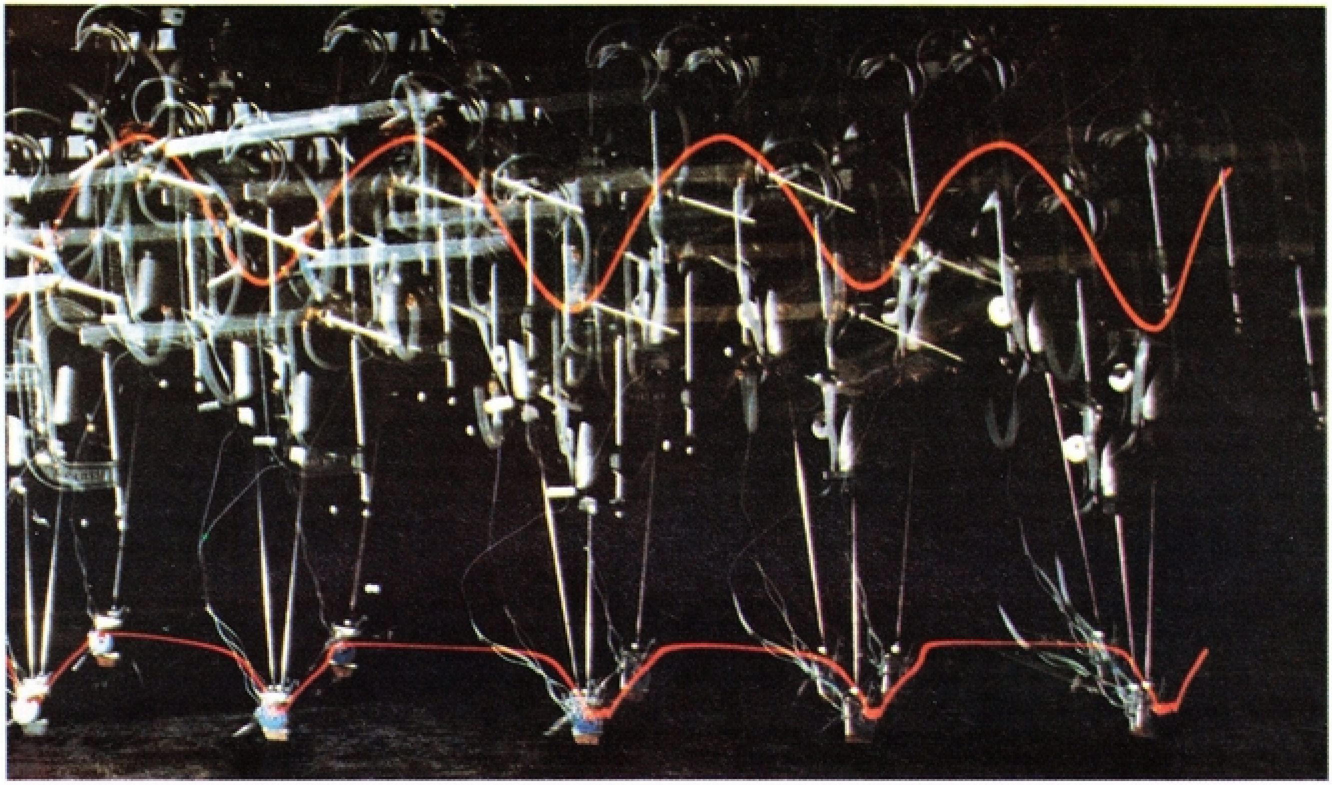
A computer program that controls such a machine accomplishes five tasks. First, it regulates the machine's gait, that is, the sequence and way in which the legs share the task of locomotion. Six-legged machines work with gaits that elevate a single leg at a time or two or three legs simultaneously.

The simplest gaits involve a regular sequence of leg motions. A gait can be described by noting the sequence. For example, the tripod gait can be recorded as (1,5,3;6,4,2;), with the commas designating the concurrent use of legs and the semicolons sequential use. Similarly, gaits that elevate a single leg at a time such as (3;2;1;4;5;6;) and (3;4;2;5;1;6;) are useful. A gait that elevates several legs at once generally makes it possible to travel faster but offers less stability than a gait that keeps more legs on the ground.

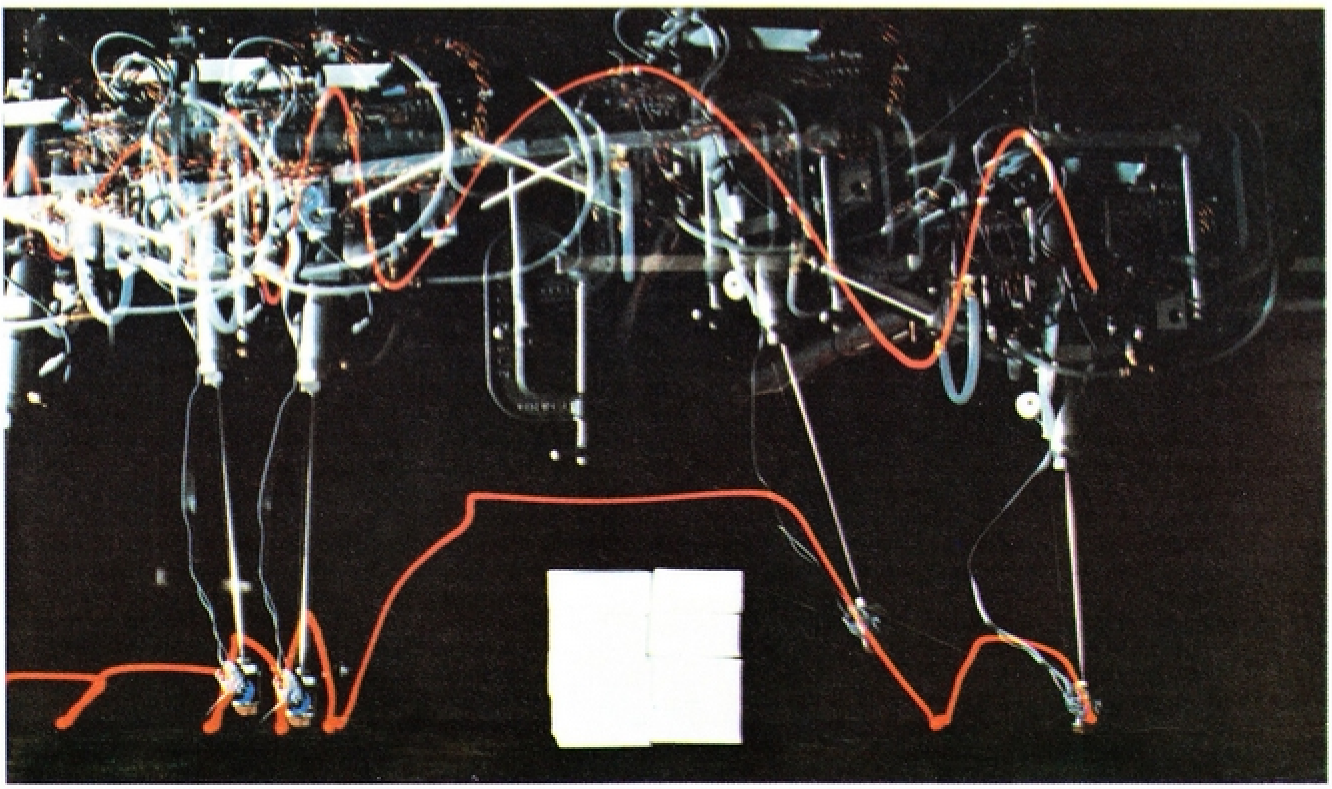
A second task of a computer program controlling a crawling machine is to keep the machine from tipping over. If the center of gravity of the machine moves beyond the base of support provided by the legs, the machine will tip. The computer must monitor the location of the center of gravity of the machine with respect to the placement of the feet to ensure that the base of support is always large enough. For simple gaits the geometry of the legs may suffice to keep an adequate base of support, but for more complex gaits a careful computation of static stability may be critically important.

Since many legs share the support of the machine, a third task of the control computer is to distribute the support load and the lateral forces among the legs. In the tripod gait, of course, the distribution of the support load is set by the geometry of the three supporting legs. With more than three supporting legs, however, the control computer must decide how to manage the distribution of loading in order to achieve higher-level objectives such as smoothness of ride and minimal disturbance of the ground.

Even when only three legs are supporting the machine, the control program must distribute the lateral foot forces. One way of looking at this task is to consider that the control system must keep the machine from simply doing isometric exercises against the ground. The amount of sensing and computation that is needed to distribute the lateral loads among many legs can be formidable. We have reduced this burden for the crawling machine we are building by providing passive hydraulic circuits that automatically distribute the sideways loads.



HOPPING MACHINE was built by one of the authors (Raibert) to explore the problems of controlling a machine that must balance as it moves. Its leg is actuated by compressed air and its motions are controlled by a computer that obtains feedback from position sensors. This version is held by a tethering arm and so balances in a single plane. A series of hops is recorded in this photograph, which was made while the camera lens was kept open. Red lights attached to the body and foot of the machine delineate the path of the hops.



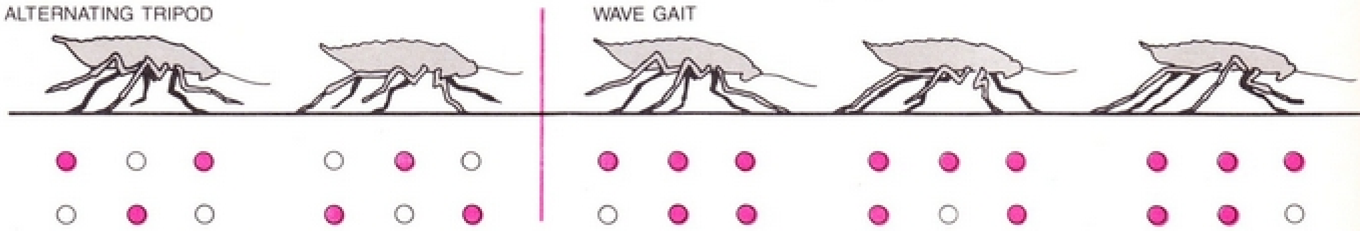
JUMPING MODE of the hopping machine shows it leaping over an obstacle. The machine approaches the obstacle from the right. When it is one step away, the operator pushes a "leap" button. As a result the maximum tension is generated in the drive actuator so that the altitude of the next hop will be increased. In flight the leg is shortened and its normal swinging motion is delayed to provide better clearance of the obstacle. A servomechanism controlling balance moves the leg to the correct landing angle and the leg is lengthened in preparation for landing. Thereafter the machine continues its normal hopping. The obstacle was 15 centimeters (six inches) high.

A fourth task of the control computer is to make sure the legs are not driven past the limits of their travel. The geometry of the legs may make it possible for one leg to bump into another; if legs can collide, the computer must limit their motion to prevent damage. To maximize the usefulness of each leg its placement on the ground must take into account the limits of the leg's motion and the expected motion of the machine during that leg's stance period. For example, if the machine is turning to the right, the forward legs should be placed farther to the right so that their sideways travel can be accommodated during the turn. For a vehicle with autonomous control the placement of the legs can be based on the planned future path of the vehicle. For a vehicle with a human driver the proper placement of each leg requires a prediction of the driver's commands for the next stance period.

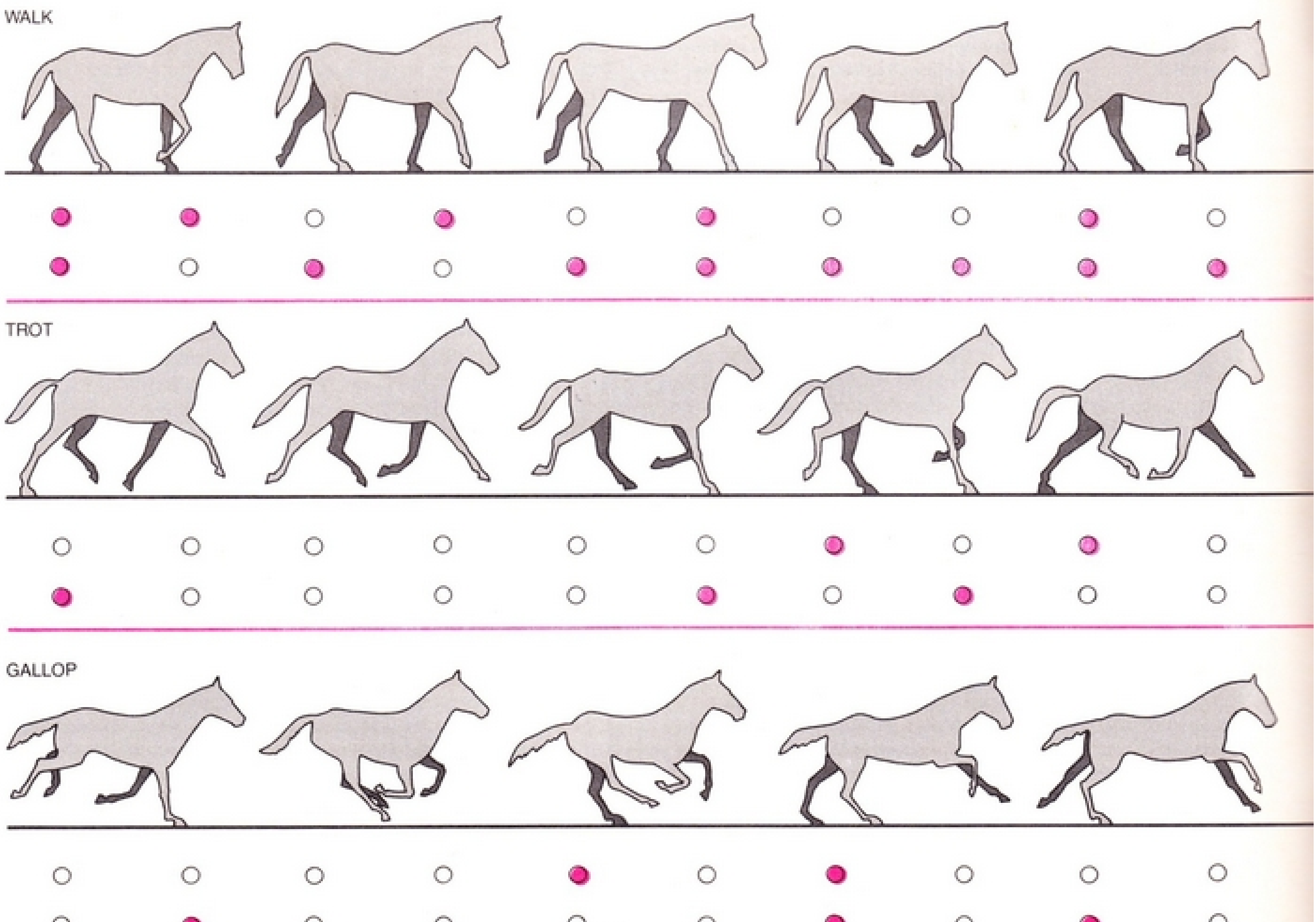
A fifth task for the control computer is to choose places for stepping that will give adequate support. On smooth ground the task is easy, but on rough terrain it may be exceedingly difficult. No system has yet been built that accomplishes this task. One can envision a terrain-scanning system that would survey the ground ahead of the machine and choose likely footholds. To make use of such a scanner the control computer would build an internal digital model of the terrain. Such a model would have to account only for bumps that are about the size of the machine's feet or bigger. Human input to the model might help in the evaluation of possible footholds.

One of us (Sutherland) is building a six-legged, hydraulically driven crawling machine. A gasoline engine provides its power and hydraulic actuators move its legs. There are six legs, so that dynamic balance is not needed.

A built-in microprocessor controls the legs by switching on or off the valves that regulate the flow of oil to the hy-



GAITS OF INSECTS provided a basis for designing the method of locomotion of the six-legged crawling machine portrayed on the cover of this issue. The circles below each drawing show whether the corresponding leg is on the ground or in the air: a filled circle represents



GAITS OF A HORSE represent the kind of locomotion in which balance is a factor. In the walk at least two of the horse's legs touch the ground at all times. In the trot and the gallop the animal periodically leaves the ground. The drawings are based on the stop-motion pho-

draulic actuators. Sensors in each leg report its position and the forces acting on it to the microprocessor. The machine is large enough to accommodate a human driver, who controls its speed and direction of motion and establishes the tilt of its body and its ground clearance. The vehicle's design speed is about two miles per hour.

One objective in the design of the vehicle was to minimize the amount of computation required to obtain a crawling movement. The hydraulic circuits are designed to make the legs move along useful paths without attention from the microprocessor, which merely selects one of the available paths for each leg. Thus the microprocessor is free to concentrate on selecting which legs to use for support and on deciding where to step next; it does not have to spend time computing the details of leg motion.

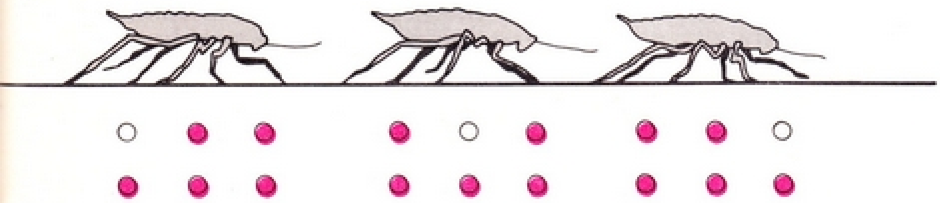
Each leg of the machine can swing fore or aft and up or down on the universal hip joint that attaches it to the frame of the machine. These motions are executed by lengthening or shortening the two hydraulic actuators per leg that are arranged in a *V* configuration above the leg. One setting of the valves provides that oil leaving one actuator will enter the other, so that as one actuator shortens, the other actuator lengthens by the same amount. Because of the geometry of the pivots this connection provides horizontal leg motion.

The horizontal motion can be powered or unpowered depending on the valve settings, so that some legs can serve to drive the machine forward while others coast. As legs are placed on the ground and accept load they are able to coast forward or backward as dictated by the motion of the legs already on the ground and driving. Hence the control computer does not need to compute the precise instant when a leg will touch the ground or the details of the motion required at the time of contact to obtain a smooth forward motion.

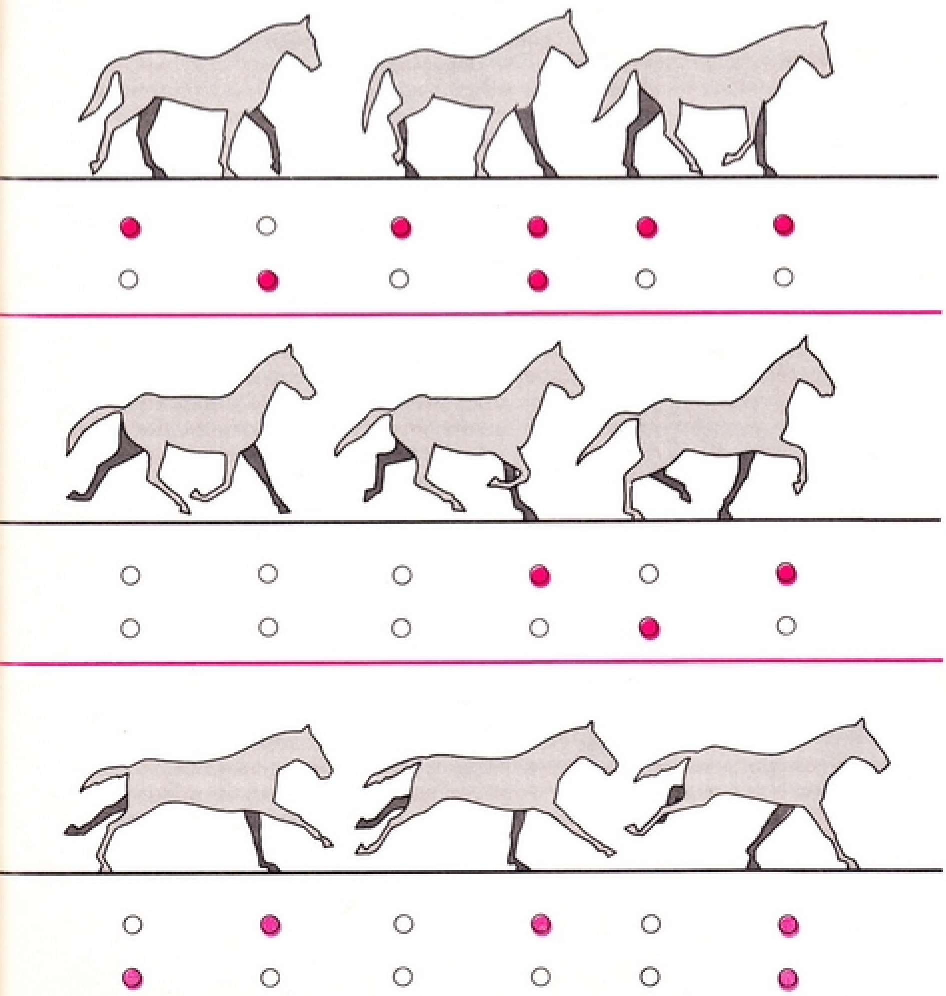
The knee joint of each leg is powered by a separate hydraulic actuator mounted horizontally along the leg. This actuator can be powered while the leg is raised in order to position the foot sideways for the next step. When the foot is on the ground, the knee joint must move slightly to match the circular path of the knee about the hip to the straight path of the foot on the ground. It is a complex motion, but it does not call for action by the computer; instead a simple parallel connection of the knee-joint actuators enables all the knees to accommodate to the average motion of the vehicle. An additional hydraulic pump provided in the system can force a collective sideways motion of all the knee joints, making the machine crawl sideways like a crab.

The human driver of the machine has three kinds of control. First, he can regulate the amount of oil flowing in the system because he can control the displacement of the hydraulic pumps. Separate pumps are provided for the legs on the left and right sides so that the driver can steer by making the machine crawl faster on one side than on the other. The settings of the steering controls are reported to the microprocessor so that it can position the feet properly. For example, if the machine is turning to the right, the front feet must be transferred to the right and the rear ones to the left to accommodate to the turn. If the machine is walking backward, which is achieved by reversing the flow of oil, the feet must be transferred backward with each step rather than forward. As each foot is lifted from the ground the control computer picks a target position for it based on the current rate and direction of oil flow set by the driver. When a supporting foot nears the limit of its travel, the control computer initiates its lift and transfer to a new foothold. If any supporting foot actually reaches the limit of its travel, the microprocessor stops the vehicle until that foot can be lifted from the ground and transferred to a new foothold where it has room to move.

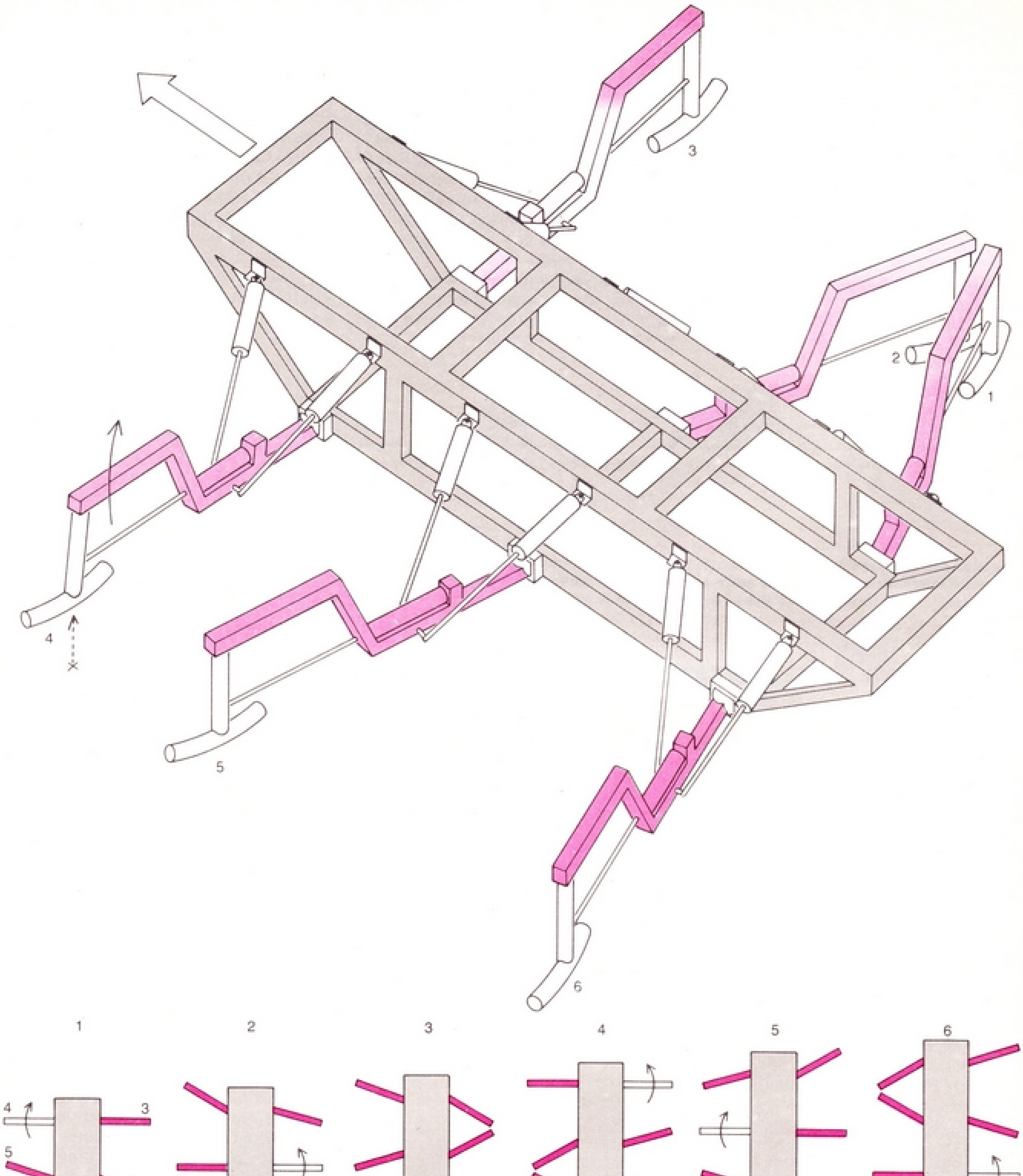
The second kind of human control of the vehicle establishes the attitude and



a leg touching the ground, an open circle a leg in the air. The alternating-tripod gait always provides stability. In creeping with a wave gait the insect's adjacent legs move successively.



tographs made by Eadweard Muybridge 100 years ago that settled a long-standing debate on whether a horse in a trot leaves the ground. Many other animals also do so in running.



SIX-LEGGED MACHINE built by one of the authors (Sutherland) moves by crawling. It does not have to balance. The six legs are controlled by a built-in microcomputer. Power comes from an 18-horsepower gasoline engine that drives separate hydraulic pumps for the left and right legs. A human driver steers the machine by making the oil flow at different rates on the two sides. Sensors report the driver's commands as well as the position of each leg and the forces on it to the microcomputer, which employs the information to choose the order and path of leg motion. Six legs ensure stability because at least three are always on the ground. Passive hydraulic circuits simplify the computing task; a leg that is supporting weight can either be connected to the drive unit or can coast, being pushed by the ground according to the motion generated by the other legs. The diagram at the bottom indicates the position of the legs in a walking cycle, which can be denoted as (4;2;6;3;5;1;). A solid rectangle represents a leg touching the ground and an open rectangle represents a raised leg moving forward as indicated by the arrow. In the numbered walking cycle the semicolons denote the sequential use of the machine's six legs.

ground clearance of the machine. The driver can set a control that changes the vertical support position for the left and right feet to make the vehicle roll left or right. Similarly, he can indicate different vertical support positions for front and rear feet to make the machine pitch forward or back. Another control enables him to indicate that the vertical support positions for all six legs should be raised or lowered collectively to change the ground clearance of the vehicle.

The third kind of human control will achieve careful placement of the feet for operation on very rough terrain. We have not yet decided how to provide this kind of control. A walking truck built some years ago by Ralph Mosher at the General Electric Company depended exclusively on manual control of foot placement and was therefore quite tiring to drive. We believe selection of the gait may also be important, but we have not yet had enough experience to know whether it could be done automatically or whether human inputs will be needed. It is precisely to answer such questions that we have built the machine.

The other subject of our attention is walking and running where balance plays a role. Until a century ago people still debated whether or not a horse in a trot had all its legs off the ground simultaneously. The stop-motion photography of Eadweard Muybridge settled the debate, showing that a horse does leave the ground entirely during a trot. A running person does so too, as do the dog, the cheetah and of course the kangaroo. Such animals not only walk, which requires dynamic balance, but also run, employing ballistic motions effectively to increase their rate of travel.

There are two fundamental differences between a crawling vehicle that is statically balanced and one that is dynamically balanced. The first difference is in the definition of stability. A crawling vehicle is stable if its legs provide at least a tripod of support at all times to ensure that it does not tip over; a dynamically balanced walking or running vehicle can be allowed to tip for brief intervals. Motions of the legs and the body ensure that a single tipping interval is brief and that an adequate base of support is maintained on the average. For example, a running man touches the ground alternately with his two legs, providing a base of support for his body only over time.

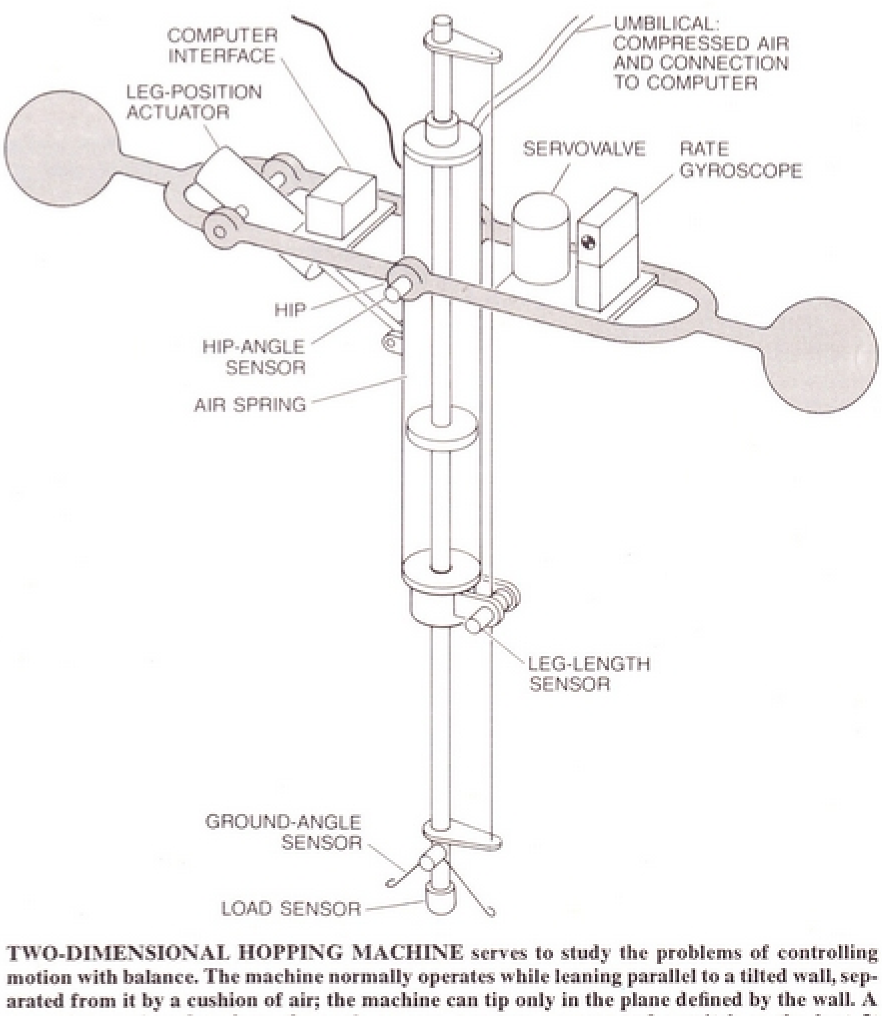
The second difference between static and dynamic balance is in the consideration of speed and momentum. Static balance assumes that the configuration of the supporting legs and the position of the center of gravity are adequate to specify stability; it ignores the vehicle's motion. Such static computations are not always sufficient. For example, a fast-moving vehicle might tip forward if it stopped suddenly with the center of gravity too close to the front legs. In order to understand the greater mobility of walking and running systems one must both relax the definition of stability and account for velocity in computing balance.

It is to study the problem of balance in its simplest form that one of us (Raibert) and his co-workers at Carnegie-Mellon University have built and demonstrated a machine that hops on its single leg and runs like a kangaroo, in a series of leaps. The device can be thought of as a computer-controlled pogo stick. We have been encouraged by the remarkable simplicity of the balancing algorithm. In its present form the machine is limited to movement in a single plane, so that it can tip over in only one direction.

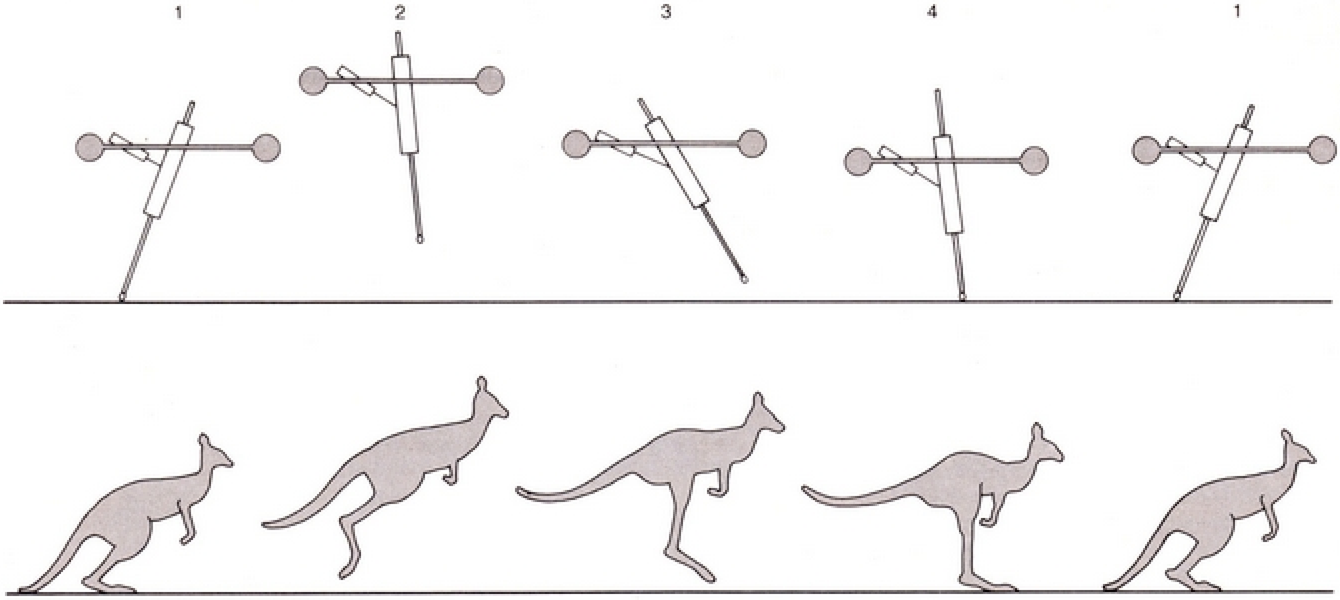
The machine has two main parts: a body and a leg. The body provides the main structure and carries valves, sensors and electronics. The leg is a simple mechanism that not only changes length along its axis but also pivots with respect to the body at a hinge called the hip. The leg bounces on a spring with adjustable tension, much like a human leg with its springy muscles and tendons. The spring is an air cylinder in which pressures are controlled with sensors and valves. At the bottom of the leg is a small foot.

The pivoting motion of the leg is controlled by a second air-operated actuator that applies torques at the hip hinge. A simple on-off valve controls the leg spring, but control of the pivot angle of the leg requires a proportional servovalve, that is, a feedback device that responds in proportion to the strength of the signal it receives. Because the moment of inertia of the leg is less than 10 percent of the body's moment of inertia the leg can pivot during flight without imparting much motion to the body. The tilt of the body is measured by a gyroscope, enabling the control computer to maintain the body in a level attitude. Other sensors measure the angle of the hip, the length of the leg, the air pressure in the leg spring, the angle between the leg and the ground and the force of the leg's contact with the ground.

Three separate servo-control loops



TWO-DIMENSIONAL HOPPING MACHINE serves to study the problems of controlling motion with balance. The machine normally operates while leaning parallel to a tilted wall, separated from it by a cushion of air; the machine can tip only in the plane defined by the wall. A computer receives data from the angle sensors, a pressure sensor and a switch on the foot. It controls hopping by adjusting the pressure in the pneumatic chamber that functions as a spring. The computer also applies torque between the leg and the body to regulate the angle of the hip. This angle determines the horizontal displacement of the foot and therefore influences balance.



HOPPER IN MOTION operates cyclically, as all legged systems do; the leg alternates between periods of support and periods of flight. At the left the machine is about to begin a leap. While it is in the air the leg swings forward at the hip in preparation for the next landing. At touchdown the leg spring shortens to its minimum length to provide for the next leap. A ground-contact sensor acts as a trigger for the vertical-control program. The machine also has feedback loops to control attitude and balance in synchrony with the vertical control. Like a pogo stick, the machine can balance only while it hops. The hop is like the kangaroo's movement Muybridge called a ricochet.

regulate the machine. One loop controls vertical motion, one balance and one body attitude. Each loop is synchronized with the basic hopping motion.

The first loop controls the height of the hopping motion. It adds or removes energy from the motion in order to achieve the correct hopping height and makes up for the energy lost during each hop. The height control does both tasks by periodically adding air to or releasing it from the main drive cylinder to adjust the effective tension of the air spring. In other words, the height control governs the timing and the magnitude of the power delivered to the hopping drive mechanism, thereby achieving the desired hopping height. When a desired hopping height has been achieved, most of the energy needed for the next hop is recovered from the spring, in which it was stored during the previous landing. As long as the hopping motions are relatively stable the task of managing the hopping energy of the machine is not particularly difficult.

The second servo-control loop provides for the balance of the machine by positioning the foot while the machine is in flight so that the next landing is made in a balanced posture. The calculation of the correct foot position takes into account both the forward speed of the vehicle and the inclination of the body. A single computer algorithm for balance works when the machine is hopping in place, accelerating to a run, running at a constant velocity, leaping over objects and slowing to a stationary hop.

When the machine is hopping in place, the leg and foot are moved small distances to compensate for external disturbances and the errors of previous hops. When the machine is to start running, say to the right, the foot is moved first to the left to unbalance the vehicle so that it starts to tip in the desired direction. Stable running is just like hopping in place except that the balancing adjustments supplement large sweeping motions of the leg, which are determined by the rate of travel. Stopping is much like starting except that the machine is made to tip in the direction opposite to the direction of movement.

The third servo-control loop stabilizes the attitude of the body to keep it upright. It provides torques between the leg and the body while the foot is on the ground in order to achieve the desired attitude during the next flight. The effectiveness of this servo depends on good traction between the foot and the ground. The attitude servo that operates when the foot is on the ground shares the hip-drive mechanism employed by the balance servo that operates while the machine is in flight. Certain subtle details of the change from one control mode to the other are associated with detecting the start and finish of each flight. The torquing mechanism must be idle during these events lest the foot slip on the ground.

When an animal runs, its legs swing back and forth through large angles to provide balance and forward drive. We have found that such swinging motions of the leg do not have to be explicitly programmed for a machine but are a natural outcome of the interactions between the controllers for balance and attitude. Suppose the vehicle is traveling at a constant horizontal rate and is landing with its body upright. What must the attitude controller do during stance to maintain the upright attitude? It must make sure that no torques are generated at the hip. Since the foot is fixed on the ground during stance, the leg must sweep back through an angle in order to guarantee that the torque on the hip will be zero while the body moves forward.

On the other hand, what must the balance servo do during flight to maintain balance? Since the foot must spend about as much time in front of the vehicle's center of gravity as behind it, the rate of travel and the duration of stance dictate a forward foot position for landing that will place the foot in a suitable spot for the next stance period. Thus during each flight the leg must swing forward under the direction of the balance servo, and during each stance it must sweep backward under the control of the attitude servo; the forward and back sweeping motions required for running are obtained automatically from the interplay of the servo-control loops for balance and attitude.

We are now building a version of the machine that will balance in three dimensions and therefore be able to move around on an open floor. We have written and tested a computer simulation of the motion of such a machine and have found that control in three dimensions can be broken down into the same three servo-control loops we have described.

Our work in making the one-legged machine run was greatly aided by a thought that came to us as we went along. It was that running can best be understood by breaking it down into the three parts we have discussed here: height control, balance control and attitude control. Partitioning the control into these three parts has made the complex behavior of legs in walking and running much easier to understand. This insight has led to a fairly simple control system that makes the one-legged machine balance and run.

Our success in this effort encourages us to think about building dynamic-motion machines with more than one leg. We believe the right way to think about such machines is to focus first on their up-and-down and balancing behavior, postponing the complications introduced by forward motion. The notion that hopping is the main activity was natural to the one-legged machine and provided an effective way to think about its behavior, but it seems less natural for machines with several legs. Perhaps it seems less natural because we are accustomed to seeing animals run and want to understand their behavior all at once.

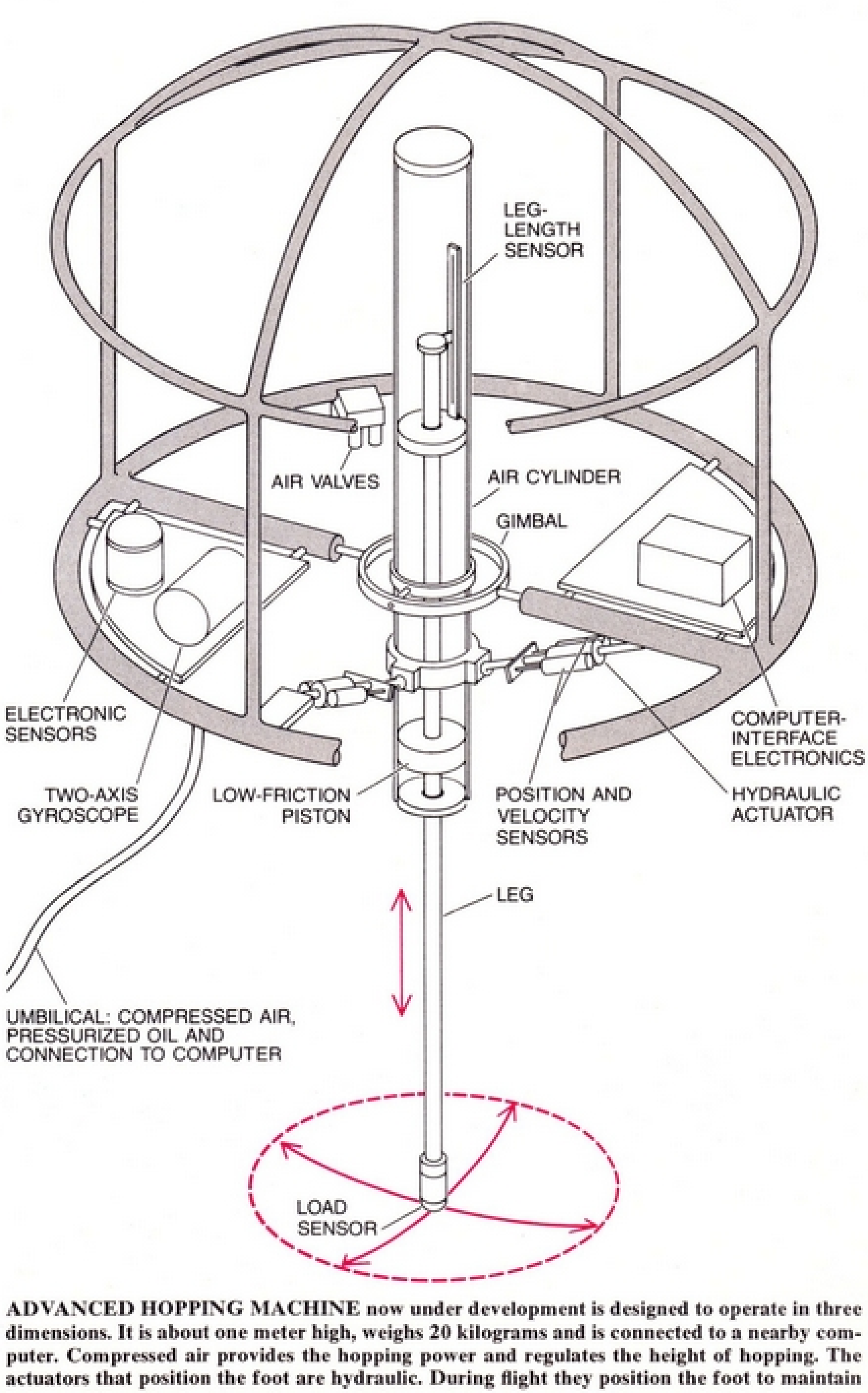
A four-legged machine hopping in place might use any of several sequences of leg activity. The simplest pattern would be to hop simultaneously on all four legs. It is not hard to imagine that the same three servomechanisms that control the one-legged hopping machine might control the motion of a four-legged vehicle in this mode. In fact, the attitude-control loop that keeps the body upright might be substantially simpler because of the broader base of support. When the machine moved forward, the legs would swing together in a pattern of motion that could easily be generated by the same control mechanisms as those that serve the one-legged machine.

Another possible gait for a four-legged machine hopping in one place is bouncing on diagonally opposite pairs of feet. Again it does not stretch the imagination too much to see how one might separate the control of such a vehicle into a height control, a balance control and a body-attitude control. The height control would add energy to the hopping motion to keep the hopping height at the desired level. The balance control would position the two raised legs in such a way as to maintain balance. The body-attitude control would apply appropriate torque to the pair of legs on the ground. The attitude and balance controls would alternate in the use of the same leg actuators, as they do in the one-legged machine. Moreover, just as we have found in that machine, forward motion could easily be accommodated by moving each raised foot to a forward position chosen to make the average balance force of the leg zero during the next stance period. The resulting motion is a trot of the kind common among four-legged animals.

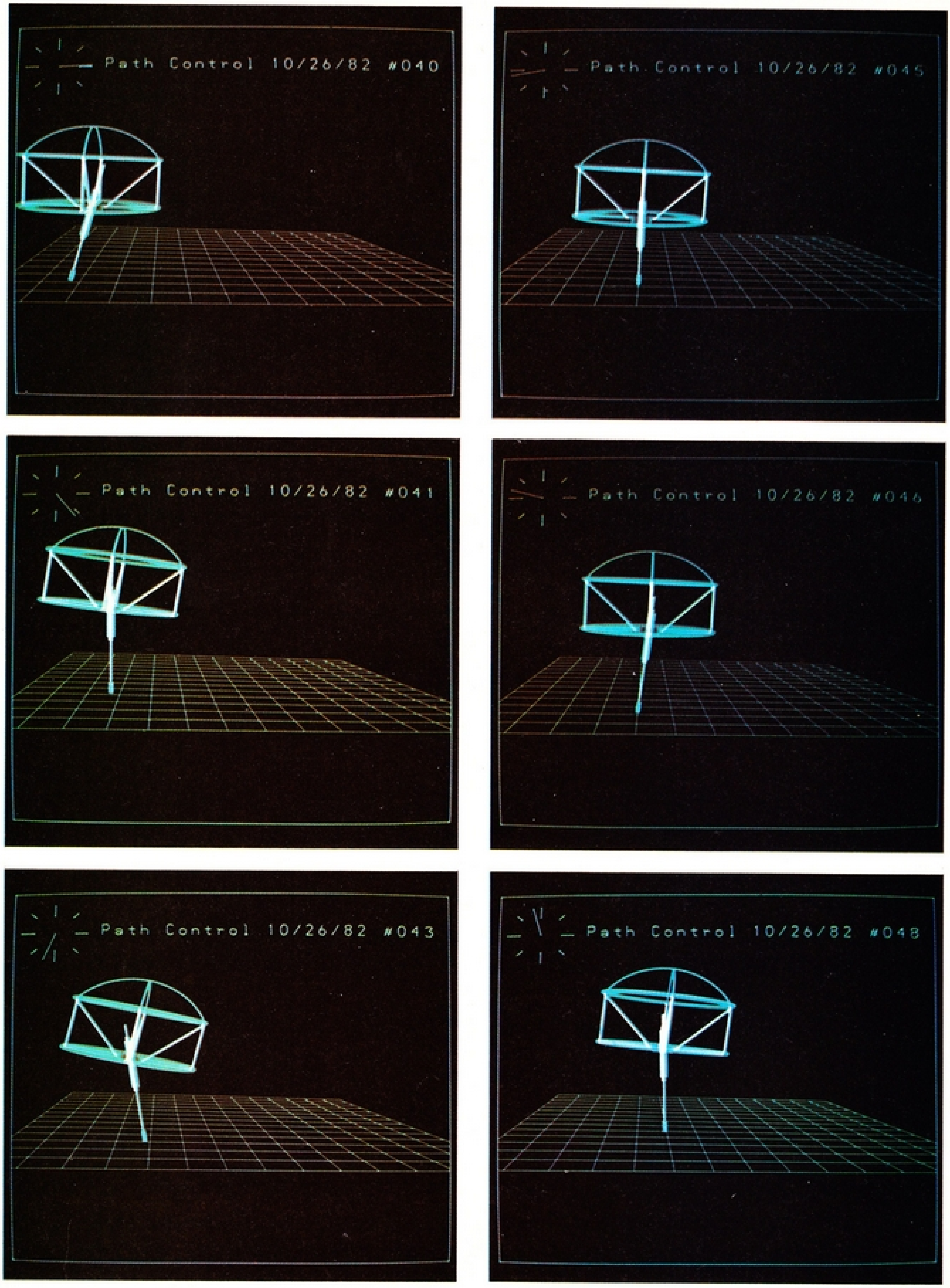
Two other gaits can similarly be understood by separating the control of each leg into vertical, balance and body-attitude components. In the gallop the rear legs land slightly sooner than the front ones. The body attitude is allowed to change during flight so that a nose-up attitude is seen as the rear legs touch down and a nose-down attitude develops as the front legs take off. The bound is a variation of the gallop in which the front legs operate nearly in unison and so do the rear legs but the front and rear actions are equally spaced in time. It is the bound that enables the cheetah to sprint at speeds of more than 60 miles per hour.

Efficient motion over the ground requires that little energy be lost during each motion of the machine. We have already mentioned how the vertical motions of legs can be made efficient by storing energy in elastic elements. What about fore-and-aft leg motions?

At high speeds over the ground the legs of a vehicle will have to move forward and back quite rapidly. Most of the energy expended by a running animal goes into generating these leg mo-



ADVANCED HOPPING MACHINE now under development is designed to operate in three dimensions. It is about one meter high, weighs 20 kilograms and is connected to a nearby computer. Compressed air provides the hopping power and regulates the height of hopping. The actuators that position the foot are hydraulic. During flight they position the foot to maintain balance. When the foot is on the ground, they maintain the machine in an upright body posture.



SIMULATED MOTION of the three-dimensional hopper is shown in these photographs from the display of the computer that worked out the motion. Here over a period of approximately .7 second the machine is shown balancing itself while it lands and takes off again.

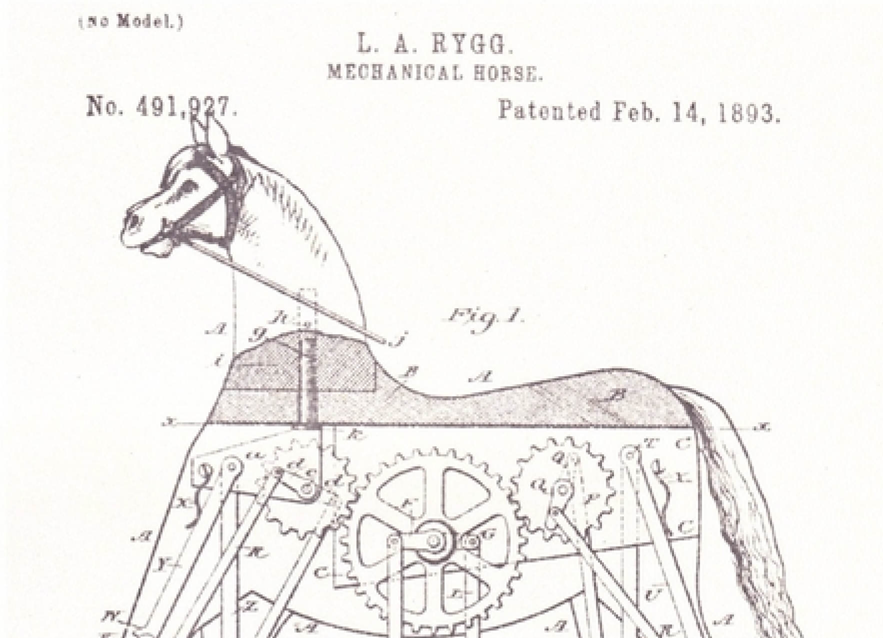
tions. In our one-legged machine these motions are provided by a conventional proportional servomechanism. In such a system the kinetic energy of the leg as it swings is entirely lost as the leg is brought to rest momentarily at each extreme angle. The hopping motion, on the other hand, is obtained by a self-resonant system made up of the leg spring and the mass of the machine, so that the height servo need only add or subtract a small amount of energy to maintain the hopping height. It is obvious that if a machine with several legs is to be made efficient as well as fast, it will have to incorporate some kind of self-resonant system for the fore-and-aft motion of the legs as well. One might design such a mechanism with springs between the legs to make the legs oscillate like a tuning fork at a frequency appropriate to the vertical bouncing rate.

Although we believe we understand how to build a four-legged machine that can run with any of the common gaits we have described, there remain many interesting questions associated with starting and stopping such a machine and selecting its gait. We can easily see how to start forward if the machine is already hopping in place. What is much less obvious is how to coordinate the transition from a standing start to full-speed running. Similarly, how and when should such a machine change from one gait to another? A running horse switches its lead as it turns, that is, it changes which of the two front legs slightly precedes the other. What computations should be done to make such minor changes in the pattern of leg motion? We find these problems fascinating, both as engineering questions in the form "What should we build?" and as scientific questions in the form "How do living systems work?"

A much more difficult problem is how to choose footholds for the machine. The function of vision in walking and running by people and animals, particularly the ability to choose sensible places to put the feet, is not well understood. One can imagine avoiding this problem by having the machine run fast only over smooth ground and by having some kind of human assistance to choose a safe path. It will probably be desirable to scan the ground ahead of the vehicle for holes. Still, just as a galloping horse runs the risk of stepping into a gopher hole, so we must expect that a running machine will also get into that kind of trouble.

The mobility of off-road vehicles is limited by two factors. First, the continuous footprint of wheels and tracks prevents wheeled and tracked vehicles from making use of the discontinuous points of support that are available to a legged vehicle. We are encouraged to think that the state of the computer art is now sufficiently advanced to allow the construction of adequate control systems for legged vehicles, and so the legged alternative for high-mobility vehicles can be seriously considered. Indeed, the Defense Advanced Research Projects Agency is already sponsoring research on such vehicles, including partial support for our projects.

A second source of mobility is narrow width: a motorcycle can get into places a jeep cannot reach. Narrow legged vehicles can be built, but they will have to balance, at least in the sideways direction. Involved as we are both in the construction of a six-legged vehicle that can crawl without attention to balance and in studies of walking and running with balance, we believe the effort to understand balance is much more important. We think the experiments with six-legged crawlers now under way in our laboratory and elsewhere are mainly exercises in the control of multiple legs and are not in themselves useful; such crawlers will ultimately be replaced by machines with fewer legs that can balance. Mastery of balance will be the key to building high-mobility machines that walk and run.



MECHANICAL HORSE was the subject of a patent obtained by Lewis A. Rygg in 1893. The lower drawing is a plan view along the line *x–x* of *Fig. 1*. The stirrups doubled as pedals that were to enable the rider to power stepping motions. Steering was to have been done with reins that moved the head and forelegs from side to side. Apparently the machine was never built. It would have been similar to many modern walking toys. Since they have no sensing or computing facilities, they cannot adapt to variations in terrain. They only crawl on flat surfaces.