PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

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Phil. Trans. R. Soc. Lond. B 1999 **354**, 863-868
doi: 10.1098/rstb.1999.0438

THE ROYAL
SOCIETY

Control of a robot dinosaur

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The Palaiomation Consortium, supported by the European Commission, is building a robot *Iguanodon atherfieldensis* for museum display that is much more sophisticated than existing animatronic exhibits. The current half-size (2.5 m) prototype is fully autonomous, carrying its own computer and batteries. It walks around the room, choosing its own path and avoiding obstacles. A bigger version with a larger repertoire of behaviours is planned.

Many design problems have had to be overcome. A real dinosaur would have had hundreds of muscles, and we have had to devise means of achieving life-like movement with a much smaller number of motors; we have limited ourselves to 20, to keep the control problems manageable. Realistic stance requires a narrower trackway and a higher centre of mass than in previous (often spider-like) legged robots, making it more difficult to maintain stability. Other important differences from previous walking robots are that the forelegs have to be shorter than the hind, and the machinery has had to be designed to fit inside a realistically shaped body shell. Battery life is about one hour, but to achieve this we have had to design the robot to have very low power consumption. Currently, this limits it to unrealistically slow movement.

The control system includes a high-level instructions processor, a gait generator, a motion-coordination generator, and a kinematic model.

Keywords: robot; dinosaur; walking; quadrupedal locomotion

1. INTRODUCTION

Many robots have been built during the past two decades that have walked on two, four, or six legs (see Raibert 1984, 1990). Some, frankly, have been experimental, while others have been conceived as prototypes for machines that could perform useful functions, such as vehicles for terrain too rough for wheels, or robots that could be sent into environments too hazardous for human workers. Some of these designs seem to have been inspired by the human body, by insects or by other animals, but none have been intended to simulate animal movement. During the same period, animatronic exhibits (many of them representing dinosaurs) have become popular in museums. These have been designed to look and move like real animals, but have so far been relatively unambitious; they have moved their heads and limbs, but they have not walked. In this paper we describe progress towards building an autonomous walking dinosaur suitable for museum display. We outline some of the problems we have faced, and our solutions, many of which involve compromises between realism and practicability.

The species we have chosen is *Iguanodon atherfieldensis*, an ornithopod dinosaur known from fossils of the Lower Cretaceous in Belgium and the Isle of Wight. The reasons for our choice are as follows.

(i) There are excellent fossils, which have been very fully described (Norman 1986).
(ii) It is small enough (5–6 m long) for us to contemplate building a full-sized robot, although the current prototype is only half the adult size (2.5 m).
(iii) Fossil footprints show that *Iguanodon* used quadrupedal as well as bipedal locomotion (Norman 1980; Thulborn 1990). Bipedal locomotion is more difficult to implement than quadrupedal, unless the feet are made disproportionately large. Our prototype walks only quadrupedally.
(iv) There is evidence for several patterns of movement that offer interesting opportunities for animation. *Iguanodon* could rear up on its hind legs. It had extraordinary hands with an immobile first digit that must have served as a weapon, and a highly mobile fifth digit that seems to have served for grasping, like the human thumb (Norman 1986). It had a chewing action unlike any modern animal (Norman & Weishampel 1985).
(v) It seemed appropriate to choose a European dinosaur for a project funded by the European Community.

Modern reptiles use a sprawling gait, placing their feet far lateral to their hip and shoulder joints. Thus, trackway width (the distance between the line of left footprints and the line of right footprints) is quite large compared to leg length. In contrast, mammals place their feet much closer under the body, using a narrow trackway. Fossil footprints and the anatomy of their joints show that dinosaurs walked like mammals, with a narrow trackway (Thulborn 1990).

The control problems discussed in this paper are not specific to *Iguanodon* or even to dinosaurs, but would arise in designing any quadrupedal robot with a narrow trackway and a high centre of mass. The project has the potential to make a much wider contribution to legged robotics than the development of a museum exhibit.

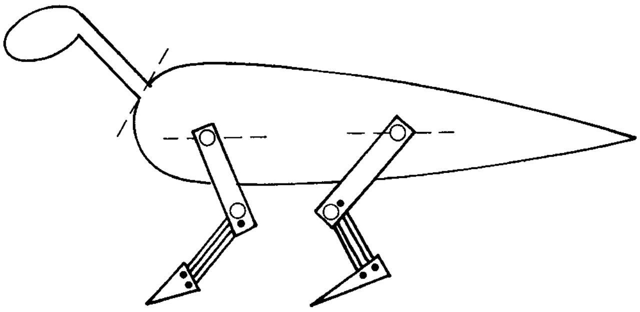

Figure 1. A diagram of the robot, showing the movable joints. The axes of joints moved by motors are indicated by circles (if at right angles to the plane of the paper) or by broken lines (if in the plane of the paper). Other joints in the four-bar mechanisms of the lower legs are indicated by dots.

2. JOINTS AND MOTORS

Dinosaurs are formidably complex structures, with a large number of joints that must have been powered by an even larger number of muscles. We have no means of counting dinosaur muscles, but they must have been similar in number to the muscles of humans, who have 38 effectively separate muscles in the hand alone. To design a feasible robot, we were obliged to simplify greatly.

We decided at an early stage that it would be difficult to control more than around 20 motors. Muscles can pull but cannot push and are generally arranged in antagonistic pairs. Some of our electric motors are connected to the segments they move by flexible cables, so they also cannot push, but by using antagonistic springs we have made each of them perform the function of a pair of antagonistic muscles. Even so, limitation to 20 or fewer motors implies gross simplification.

Figure 1 is a schematic representation of our prototype, showing the joints and their axes of movement. Walking involves leg movements in a parasagittal plane. As a minimum requirement, each leg must have two degrees of freedom of movement (for example, hinge joints at shoulder and elbow, or hip and knee) to enable the foot to be placed as required in this plane. However, we show in a later section that it will be useful for the robot to be able to move each foot a little to the left or right, to preserve its balance. To make this possible, we have given each leg an additional degree of freedom of movement, allowing abduction and adduction at the shoulder or hip. Each of these 12 degrees of freedom (three in each leg) is controlled by an electric motor.

A quadruped with movable joints only at the shoulder, elbow, hip and knee could walk effectively, but realism requires movement also at the wrist and ankle. We have implemented these movements without increasing the number of motors by means of four-bar mechanisms linking the wrist with the elbow and the ankle with the knee. This makes our robot's movements more stereotyped than those of an animal that could move all its joints independently, but allows reasonably close imitation of the gait of mammals such as dogs in which the ratios of segment lengths within each leg are similar to those of *Iguanodon* (see the sequences of photographs of walking mammals in Muybridge (1957)).

The mobility of our prototype allows each foot to be placed at the required point on the ground. Our final product will have realistically shaped feet, and we will need to ensure in addition that the feet are set down with their soles parallel to the ground. We plan to achieve this passively, by constructing feet with compliant toes that will conform to the ground.

Dinosaurs presumably looked from side to side as they walked, scanning the environment for obstacles, danger and food. This would have required pronounced head movements if the eyeballs of dinosaurs moved as little in their orbits as do those of their closest modern relatives, the birds and crocodiles. Our robot has no functional eyes, but depends on ultrasonic sensors mounted in its head to detect obstacles. The head moves from side to side as the robot walks, enabling these sensors to scan the environment. This is achieved by means of a hinge joint and a motor at the base of the neck.

We plan to add a few more motors and degrees of freedom in future versions of the robot. Some mobility will be given to the head and tail. In addition, we plan to simulate the remarkable chewing movements of *Iguanodon*, described by Norman & Weishampel (1985), and the presumed grasping action of the fifth digits (Norman 1980).

3. PRINCIPLES OF WALKING

A quadruped can be stable, standing on just three feet, even if each foot contacts the ground only at a single point. The necessary condition is that a vertical line through its centre of mass must pass through the triangle of support, that is the triangle of which the apices are the points of contact of the feet with the ground. With fewer than three feet on the ground, an animal cannot be stable unless the feet are large.

A regular gait involves repeated cycles of movement, in each of which every foot is lifted and set down just once. The distance travelled in one complete cycle is the stride length, and the duration of the cycle is the stride period. Any regular gait can be described in outline by specifying two quantities for each foot, the duty factor and the relative phase. The duty factor is the fraction of the stride period, for which the foot is on the ground. The relative phase is the stage of the stride at which the foot is set down, expressed as a fraction of the stride period after the setting down of an arbitrarily chosen reference foot. McGhee & Frank (1968) discussed the stability of quadrupeds with point feet, which move their legs in parasagittal planes. For such a quadruped to be statically stable at every stage of the stride, it must always have at least three feet on the ground, which implies that the duty factor (assumed to be the same for all four feet) must be at least 0.75. Further, a vertical line through the animal's centre of mass must pass through the triangle of support, at every stage of the stride. McGhee and Frank showed that for duty factors between 0.75 and 0.83, this could be the case only if the feet moved in the sequence left fore, right hind, right fore, left hind. This is the sequence actually used by walking mammals, and by our robot. If the duty factor is greater than 0.83, two other sequences allow static stability to be maintained throughout the stride.

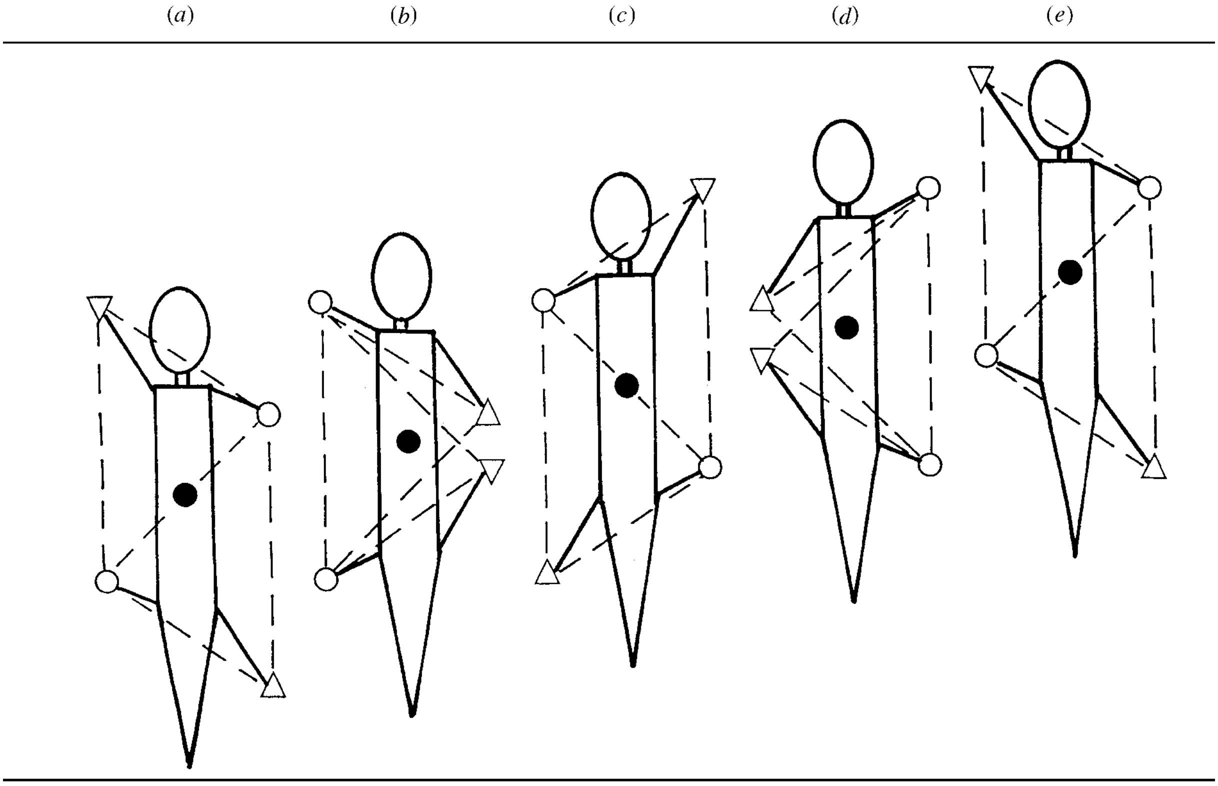

Figure 2. Diagrams of successive positions of a quadruped executing a statically stable walk. At each of these stages of the stride, the foot marked by a downward-pointing triangle is set down, and the one marked by an upward-pointing triangle is lifted. The triangles of support immediately before and after this change are shown by broken lines. The centre of mass (filled circles) never falls outside the triangle of support. This figure has been drawn with the centre of mass at a fixed position in the trunk, as if the mass of the legs were negligible. The robot has legs of substantial mass, so its centre of mass moves relative to the trunk as the legs step; but because the legs step in turn these movements are not large.

In a gait that is not statically stable, unbalanced forces result in accelerations of the body, making it rise and fall, pitch or roll in the course of each stride. If the stride frequency is sufficiently high, the amplitudes of these unwanted displacements will be small, and they will cause no inconvenience. However, if the stride frequency is low, their amplitude may be large enough to make a gait impracticable. Alexander (1981) suggested that the parameter $g/2f^2h$ is a useful indicator of the need to avoid departures from equilibrium: here g is the gravitational acceleration, f is the stride frequency and h is leg length. The parameter is the distance the animal would fall if it were unsupported for one stride-period, expressed as a fraction of leg length. A low stride frequency or short legs may result in a high value of the parameter, indicating that departures from equilibrium must be kept small.

Living quadrupeds seldom, if ever, use statically stable gaits. Mammals seldom use duty factors as high as 0.75, and then only at very slow walking speeds (Alexander & Jayes 1983). Turtles often use duty factors higher than 0.75, but move their feet with relative phases that leave only two feet on the ground at certain stages of the stride (Jayes & Alexander 1980). Their short legs and low stride frequencies make the parameter introduced in the previous paragraph large, but even for them, provided departures from equilibrium are kept small, there is no need for static stability to be maintained throughout the stride. Jayes & Alexander (1980) showed that the gait used by turtles made walking practicable with slower muscles than would have been needed for a statically stable gait.

The parameter $g/2f^2h$ is approximately one for a galloping dog, five for a dog walking slowly and 200 for a turtle (Alexander 1981). Our robot has legs 0.6 m long and walks with stride frequencies down to about 0.1 Hz, giving the parameter a value of *ca.* 800. It is therefore even less tolerant than turtles of departures from equilibrium. We have chosen to implement a statically stable gait.

Figure 2 represents a plan view of a quadruped at four stages of a statically stable walk with a duty factor of 0.75. Each shows the instant at which one foot is been lifted and another set down. At stages (*a*) and (*c*), diagonally opposite feet remain on the ground while one of the other two feet is set down and the other lifted. At these stages the centre of mass is necessarily over an edge of the triangle of support, so the animal is barely stable (but at intermediate stages the centre of mass would be within the triangle). If the centre of mass can be moved a little from side to side, the time for which it is near an edge of the triangle can be reduced, and errors that would take it outside the triangle can be corrected.

4. ADJUSTMENT OF THE POSITION OF THE CENTRE OF MASS

The centre of mass could be moved transversely in either of two ways. The first (option (a)) is by lengthening

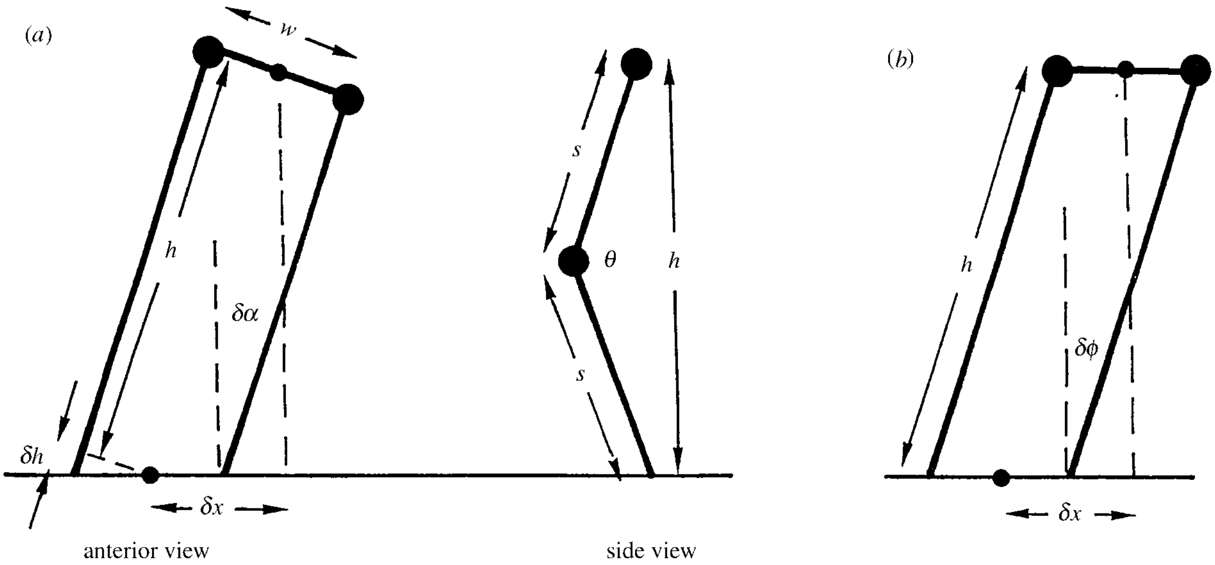

Figure 3. Diagrams illustrating the discussion of transverse movements of the centre of mass.

the legs of one side of the body (by extending the elbow and knee joints) and shortening the legs of the other side (figure 3*a*). In the figure, a pair of legs is seen in anterior view. The lengths of the legs projected onto the transverse plane were h when it stood symmetrically, but one has been lengthened and the other shortened by δh, tilting the animal through an angle $\delta\alpha$ and moving its centre of mass laterally by δx.

$$\delta x \approx h\delta\alpha,$$

and

$$\delta\alpha \approx 2\delta h/w,$$

where w is the width (figure 3*a*). Hence

$$\mathrm{d}x/\mathrm{d}h = 2h/w.$$

Now suppose for simplicity that each leg has just two segments, each of length s, and let the angle of the knee joint be θ. If the foot is in the same transverse plane as the hip,

$$h = 2s\ \sin(\theta/2),$$
$$\mathrm{d}h/\mathrm{d}\theta = s\ \cos(\theta/2) = (h/2)\ \cot(\theta/2),$$

and

$$\mathrm{d}x/\mathrm{d}\theta = (\mathrm{d}x/\mathrm{d}h)(\mathrm{d}h/\mathrm{d}\theta) = (h^2/w)\ \cot(\theta/2). \qquad (1)$$

The second way (option (b)) is by adducting the legs of one side of the body and abducting the legs of the other side (figure 3*b*). The figure shows the legs adducted and abducted by angles $\delta\phi$, while the lengths of the legs are unchanged:

$$\begin{aligned} \delta x &= h\delta\phi, \\ \mathrm{d}x/\mathrm{d}\phi &= h. \end{aligned} \qquad (2)$$

In equations (1) and (2), $(\mathrm{d}x/\mathrm{d}\theta)$ and $(\mathrm{d}x/\mathrm{d}\phi)$ represent the gain of the mechanism for displacing the centre of mass laterally. If the trackway is narrow (small w) and the knees are not too straight ($\theta \ll 180°$), option (a) will have high gain; small adjustments of knee angle will result in large displacements of the centre of mass. Option (b) will have lower gain, making precision of control easier. This applies to our robot which, like the dinosaur it represents, has a narrow trackway. For this reason, we have designed our control algorithm to use option (b) unless very large or fast lateral displacements are required, in which case option (a) is brought into use.

The anatomy of the leg joints of dinosaurs suggests that both options (a) and (b) would have been available to them, and we have no direct evidence of which they used. Humans standing with their feet on separate platforms, which move up and down unexpectedly, use option (a) to maintain their balance (Nashner & Woollacott 1979).

Anterior–posterior adjustments of the position of the centre of mass may also be required, especially if the robot encounters sloping ground. In this case our control algorithm adjusts knee and ankle angles (similar to option (a) for transverse displacements). In this case there is no problem with excessive gain, because the length of the trunk from shoulder to hip is much greater than the trackway width.

5. CONTROL ALGORITHM

Figure 4 represents the control algorithm for the legs. Each leg has three degrees of freedom (as described above), controlled by three motors operating under position control loops. Force feedback loops are scheduled to be implemented through additional processing layers dealing with the dynamic model of the system. The position and force signals are recovered from the structure of the system and fed back to the processing unit through analogue to digital conversion. The modules shown in figure 4 operate as follows.

(a) *High-level instructions processor*

This module generates 'strategic' decisions for the overall motion of the system. It receives data from the on-board programme selector (which permits a selection

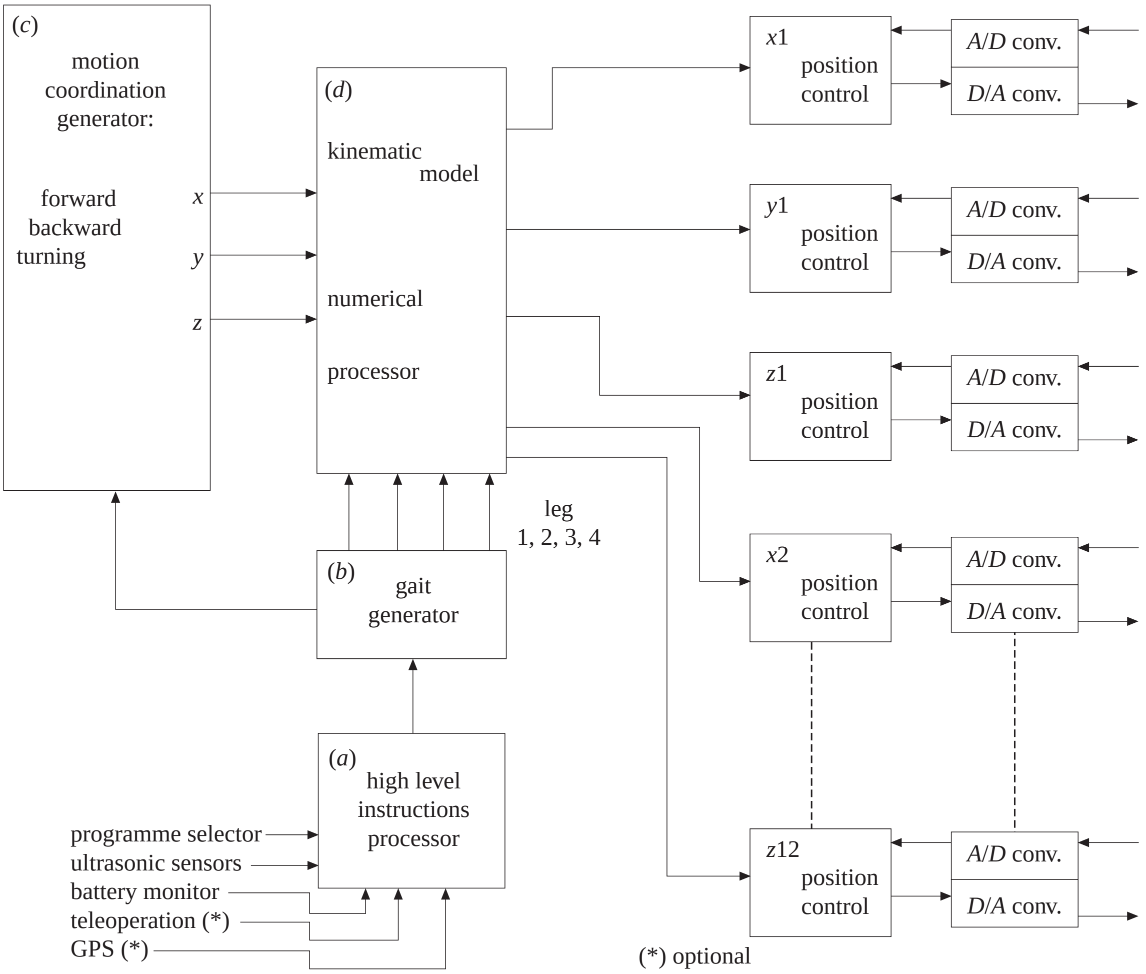

Figure 4. A diagram of the control algorithm of the legs.

of pre-installed 'behaviour' routines), or from the proximity (ultrasonic) sensors, which indicate the presence of obstacles.

Additionally, the module receives data from the on-board battery monitors, and prepares the system for a 'graceful' shutdown in case of battery power failure.

Further, the same module can optionally receive data from a tele-operator, using a radio link with a remote controller, and could be supplied with absolute position data using a global positioning satellite (GPS) receiver.

(b) *Gait generator*

This is a basic gait generator, adaptable to a number of different gaits. The module produces the gait pattern and rate according to the high-level instructions processor. The gait generator instructs the motion-coordination generator.

The different types of gait that can be generated are (i) from standing position commence walking gait, with gradually increasing step length; (ii) from walking slow down to standing, with gradually decreasing step length; (iii) turning during motion; (iv) turning on the spot; (v) moving backwards; and (vi) modifying the step height during operation.

(c) *Motion-coordination generator*

The motion-coordination generator produces motion instructions regarding the desired x, y, z motion of each foot. However, it does not generate motor-related instructions, since it does not include the kinematic model of the system. This means that the aforementioned modules (*a*), (*b*) and (*c*) are generic and can be adapted to any quadrupedal system, irrespective of its kinematic configuration.

(d) *Kinematic model and numerical processor*

This module customizes the gait patterns produced by the motion-coordination generator to fit the kinematics of the specific machine. The numerical processor generates the desired positions for each of the 12 motors, using the inverse-kinematics model derived from the segment lengths and the kinematic geometry of the machine. The desired positions are then fed to 12 numerical proportional + integral + derivative (PID) controllers, which drive the power stages of the motor-controller cards. Data from the motors' motion are fed back to the numerical PID controllers via analogue potentiometers on the motor output shafts or via direct measurements of joint movements by using precision linear potentiometers.

6. ENERGETICS

The power consumption of the robot is a matter of great concern to us, because it carries its own power supply as batteries of limited energy capacity. The current prototype has a mass of 12 kg and consumes *ca.* 20 W when walking and 12 W when standing still. Its batteries (mass 2 kg) enable it to walk for about one hour before requiring recharging. These are classical lead–acid batteries, chosen for their low cost and for their stability in rapid charge–discharge cycles.

The requirement for reasonable battery life currently restricts us to unrealistically slow walking speeds. Analysis of fossil footprints indicates that dinosaurs commonly walked at speeds of the order of $1\,\mathrm{m\,s^{-1}}$ (a slow human walking speed), and that small- to medium-sized dinosaurs sometimes ran fast (Alexander 1989). Our prototype walks at only $0.05\,\mathrm{m\,s^{-1}}$. We hope to achieve higher walking speeds, but see no prospect of being able to make it run. Modern mammals of equal hip height (0.6 m) break into a run at about $1.7\,\mathrm{m\,s^{-1}}$ (Alexander & Jayes 1983).

Modern mammals save energy in walking by the pendulum principle (by exchanging kinetic energy with gravitational potential energy), and in running by the principle of the bouncing ball (exchanging kinetic and gravitational potential energy with elastic strain energy; Alexander 1992). The pendulum principle will be effective also in our robot if it walks realistically, but we have not specifically designed its motion to exploit the principle. A gait that used springs to save energy in the manner of a running mammal would be highly unrealistic for slow walking. Another possibility for recycling and so saving energy would be to use back-driveable motor generators, but this is not an option for us because the standard low-power motors we have chosen (for reasons of availability and cost) work through gearboxes of considerable ratio.

Muscles consume power whenever they exert tension, even when they are not shortening and therefore doing no work. For this reason, an animal requires power simply to stand still. Similarly, power is required to maintain torque in our motors when the robot stands. This power requirement is high in the knee and elbow joints, where joint extension is operated by cables. These can pull but cannot push, so we have to depend on retraction springs to reverse motion. Thus, when the robot is standing, the motors have to counteract spring torques in addition to gravitational torques. A possible alternative design, with two motors arranged like antagonistic muscles at each knee or elbow, was rejected on grounds of weight.

We will compare the power consumption of our robot with that of modern animals of similar size. The mass of adult *Iguanodon bernissartensis* (a larger species than our robot represents) has been estimated as 5000 kg (Alexander 1989) for a specimen 9 m long, 3.6 times the length of our prototype. We can estimate the mass of an *Iguanodon* of the length of our prototype as $5000/3.6^3 \approx 100$ kg. The mass of the prototype is only 12 kg, but a completed robot even of the same scale would be much heavier because the prototype lacks the shell and skin that will give the robot the external shape of a dinosaur. A 100 kg mammal would be expected to consume 150 W of metabolic power when standing still, 160 W when walking at $0.05\,\mathrm{m\,s^{-1}}$ (the speed of our prototype) and 400 W at a more normal walking speed of $1\,\mathrm{m\,s^{-1}}$ (Taylor *et al.* 1982). A modern reptile of the same mass would be expected to use only *ca.* 30 W when standing, 40 W at $0.05\,\mathrm{m\,s^{-1}}$ and 280 W at $1\,\mathrm{m\,s^{-1}}$ (estimated from data in Taylor (1973) and Full (1989); note that although the cost of standing would be much less than for mammals, the additional cost of moving would be about the same, $250\,\mathrm{J\,m^{-1}}$). The question, whether the metabolic rates of dinosaurs were more similar to those of mammals or to those of modern reptiles of equal mass, remains controversial, but some recent evidence favours reptile-like metabolism (Ruben *et al.* 1996). Our prototype uses 12 W when standing and 20 W when walking at $0.05\,\mathrm{m\,s^{-1}}$, so it is more economical than dinosaurs of the same linear dimensions seem likely to have been.

This work was supported by a grant from the European Community Brite/Euram Programme.

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