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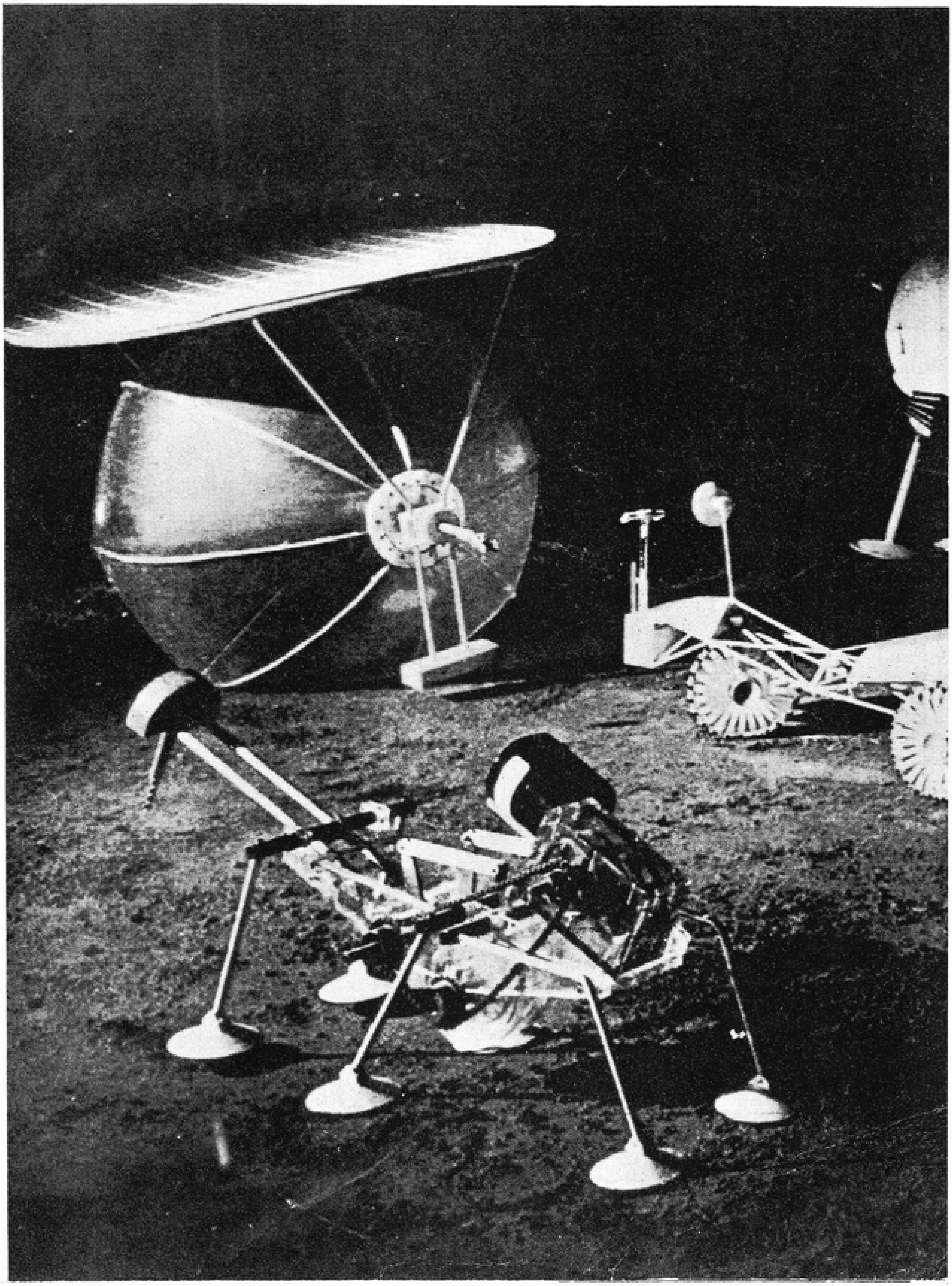

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Unorthodox Approach

Machines Can Walk

by A. C. Hutchinson, BSc (Member)*

There are byways of technical thought which have engaged inventive minds for many years. Suddenly one of them becomes fashionable and is hailed as a break-through; lucky the firm that can spot it in time. Other ideas continue their precarious existence in the backrooms of enterprising laboratories. One of these is the walking machine which is once again being iuvestigated for transport over rough ground. If this work doesn't yield a moon-horse, it may at least provide a stair-climbing invalid chair or a mountain-climbing truck.

The story begins in about January 1940, in the middle of the 'phoney war'. That was a time when many people were anxious and frustrated because national resources were not being adequately employed. I had just read *The Defence of Britain* by the well-known military student, B. H. Liddell Hart in which he reiterates over and over again his conclusion that defence had so mastered attack that all warfare was bound to degenerate into trenches and mud on the 1917 pattern: mud and the anti-tank gun had devalued the tank. I must emphasise that the period was January 1940 and that the panzer war of movement was then unknown.

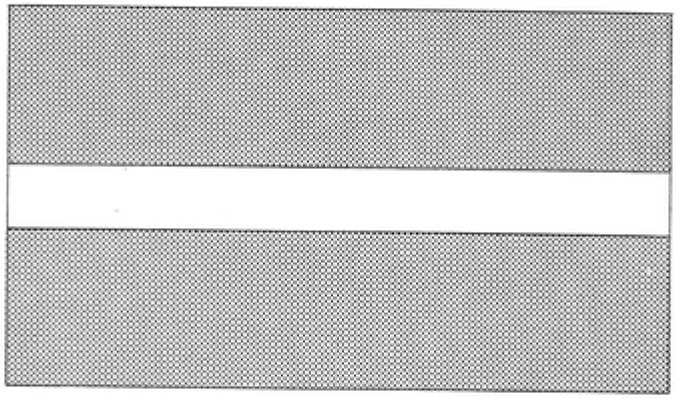
There was never much difficulty in appreciating the disadvantage of the caterpillar track when it sinks into soft ground or mud. The advancing track has continually to push its way against a ridge of ground. A less obvious difficulty follows from the scale effect. To defy shellfire, tank armour must be thick. Very thick armour dictates a large tank and increase of size increases the pressure of a track upon the ground. The result is shown in Fig. 1: on the left is the track plan of a 14-ton tank[1] of 1940 and on the right is the track of a geometrically similar tank weighing 1000 tons. The tracks of both vehicles are designed for the same ground pressure. In the big tank the tracks have to take up nearly the whole plan area.

Reflecting on Liddell Hart, it struck me that, in mud, farm horses are better than tractors. Not only does walking avoid the soil build-up in front of a track but it seems to permit higher ground pressures and promises greater mobility than the track in difficult conditions because legs can be lifted clear of obstructions. On top of all that, the legs of a really large walking vehicle might well be much more robust and resistant to shellfire than a track mechanism can be.

I shared these thoughts with a collaborator† and they started off a period of intense activity directed towards a walking fighting vehicle. We referred it to the War Department and attended examining committees. It was rejected on the grounds that walking machines cannot have the intrinsic stability of the caterpillar track. If their legs get in a muddle, they will fall over. The national resources were committed to developing tracked vehicles and there could be no thought of changing to a 'horse' mechanism in mid-war.

Finally, the battles in France and Belgium had completely shattered Liddell Hart's main premise about trench warfare and stagnation.

My collaborator and I were perfectly satisfied. We cut our losses and turned our minds back to ordinary things for the next 20 years. Then, around 1960, the whole subject suddenly got very topical with news of American walking machines to



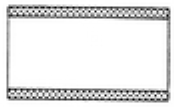


Fig. 1. The scale effect for caterpillar tracks: on the right a 14-ton tank, compared with a 1000-ton vehicle designed for the same ground pressure (above)

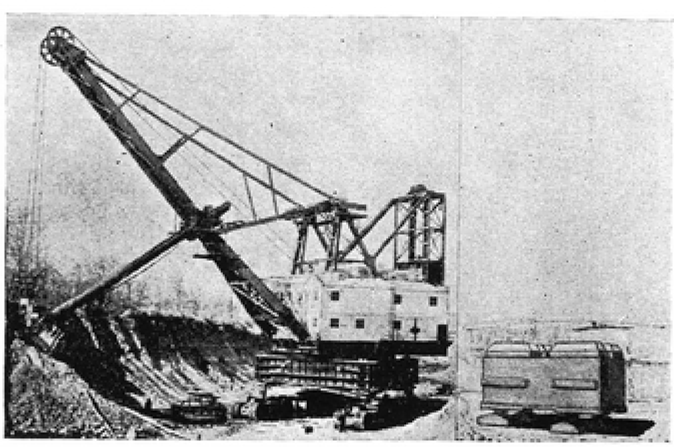


Fig. 2. A pre-war 1000-ton shovel excavator, compared with a 12 ton tank and the proposed walking fighting machine

Adapted from his Chairman's Address to the Eastern Branch in 1962.
†*Mr. F. S Smith of Bedford.*

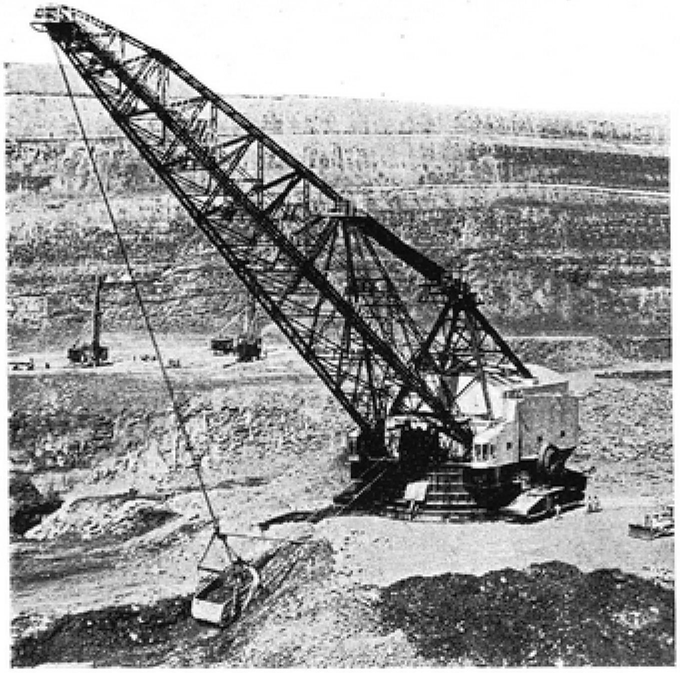
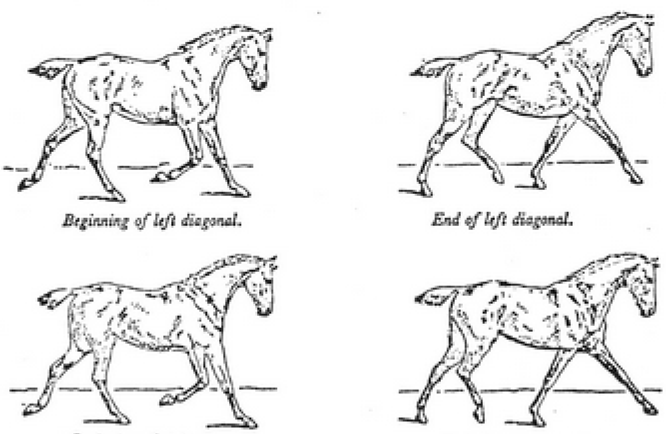


Fig. 3. This walking dragline half-raises itself off the ground on its flat feet, then slithers backwards to a new position: speed $\frac{1}{8}$ mile/h



[Courtesy: Hurst and Blackett]

Fig. 4. In the trot, diagonally opposite legs move together and there is no body-sway

explore the surface of the moon. The essential problem of transport on the moon at that time was that its surface was supposed to be covered with soft light dust.

The cover shows a selection of moon vehicle models taken from the American magazine *Life* (27th April, 1962). Two of the models progress by rolling but rely on such low ground pressures that they could almost be said to float on moon dust. The other two models are walkers. The one in the foreground is six-legged and two legs of a four-legged walking machine are shown at the back (right).

An early attempt

The moon-inspired revival of interest in walking machines is the justification for this account of the design of a walking machine in 1940. In that development, an early decision had to be made about dimensions. As already mentioned, resistance to shellfire and great size were the key ideas. We had to start somewhere. Drawing on naval background, we selected six-inch armourplate. Observing that an inverted steel box, 42 ft by 30 ft by 18 ft high and 6 in. thick weighs about 500 tons, we set 1000 tons as the all-up weight for our fighting vehicle.

We were much helped at this stage by noting that 1000-ton vehicles were already in existence for moving about on land. Fig. 2 shows a 1000-ton shovel excavator[3], compared with a 12-ton tank of the 1930s and with what our finally evolved walking machine might have looked like without any armament. That excavator was mounted on caterpillar tracks which inevitably limited it to operation of hard ground.

Even then excavators for soft or swampy ground had already discarded the track in favour of a walking system, if rather a primitive one. Fig. 3 shows a walking dragline excavator, made by Ransomes and Rapier, which, in 1962, held the world record weight at 1800 tons. During operation, the dragline excavator sits on a very large flat circular base. When it has accomplished its task on one part of its site, the two flat feet at its sides are driven downwards and sideways on to the ground. The excavator is then partly raised on these feet and the whole machine slithers backwards. In this way it achieves a cruising speed of fully one-eighth of a mile per hour.

The first thing in the design of a walking machine is choice of foot pressure. Six lbf/in^2 seems to be a bogey figure for crawler tractors on farms. Walking excavators are generally designed for about 24 lbf/in^2 on their feet or 12 lbf/in^2 on their bases or bottoms. There was a four-ton elephant in Whipsnade Zoo whose feet had likewise been designed for 12 lbf/in^2. As this design had to be suitable for operation on soft jungle ground, there would seem to be scope for going higher in most walking machines. We planned to give our machine rather small feet with a designed pressure of 50 lbf/in^2 but to cope with really soft ground by fitting overshoes which would reduce the ground pressure to 15 lbf/in^2.

There were plenty more decisions to take. The walking excavators with their two feet and sliding bottoms might be thought of as three-legged creatures. We never had much doubt that four was the best number of legs but we had a good look at six, the insect system. There is a lot to be said for six legs, but there was not time then to analyse leg numbers in depth, so we followed our intuitions and concentrated on four legs.

The question of gait

Next choice was the gait. There are five known gaits for four-legged animals. In ascending order of speed, they are the walk, trot, amble, canter, and gallop. The simplest are the intermediate speed gaits, the trot and the amble. The amble, which is natural to the camel, is the simplest of them all. Two legs on each side move together as if joined by coupling rods, the animal's body swaying from side to side as it goes along. This gait is the exact four-legged equivalent of the human two-legged walk. In the trot, which can be easily studied by watching a dog, diagonally opposite legs move together and there is no body sway. Fig. 4 shows a horse trotting. Unfortunately for machine design, neither of these simple gaits can easily be started from rest. A horse has to 'break into a trot' from a walk, that being the slowest and most stable four-legged motion.

With the idea that our machine must be able to walk before it could run or trot, we concentrated all our effort on the walk. The four-legged walk, which anyone can study in a cow, or in himself by crawling on hands and knees, is more complex than it looks: all four legs move in different phases,

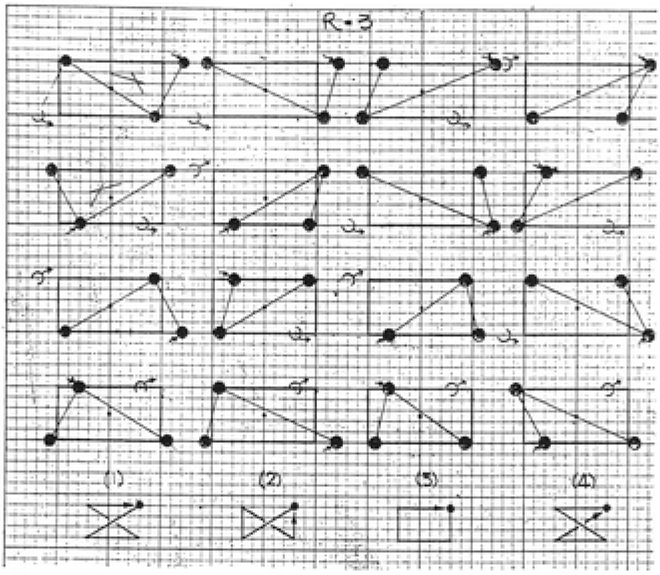


Fig. 5. Even in the most stable stepping order, shown in col. 1, the centre of gravity is never over the centre of the supporting triangle (Full circles represent feet on the ground, the rectangle the machine body)

one quarter of a cycle apart. One foot is always off the ground so that progress is on a continuously changing pattern of three-point support.

There are four possible stepping orders, but even in the best which, needless to say, is the one chosen involuntarily, the centre of gravity is never over the centre of the triangle of support. Fig. 5 is an idealised diagram of the four stepping orders. The rectangle indicates the body of a walking machine. The circles indicate foot positions relative to that body. A broken circle is a foot just about to take off. A full circle with an arrow is a foot just returning to earth. In every case, the three feet supporting the body are indicated by a triangle.

Each column in the figure shows four successive foot positions for one stepping order. The four different stepping orders are indicated by the diagrams at the bottom of each column. Only one stepping order is at all satisfactory, the one in the first column, the centre of gravity of the rectangular body being shown by the black dot. Even then the centre of gravity never comes over the centre of the support triangle. In the other orders, the situation is even worse, the walking creature being often in unstable equilibrium.

It is in this matter of equilibrium where the six-legged insect scores so heavily. Nevertheless, in nature, the higher up the scale of evolution, the fewer the legs. We thought that, following nature, there would be ways round the stability problem. We had settled for four legs and we took the walk as our basic target, with the remote hope that from that we might get to a trot which ideally is three times as fast.

Incidentally, nature becomes really complex in the fastest four-legged gait of all, the gallop, which is a series of leaps. In one phase, the animal is completely airborne or rather momentum-borne. What a six-legged gallop would be like shatters the imagination!

The mechanism

Going from flesh to hardware, any walking mechanism for a leg must be able to lift a foot up and down and to traverse it backwards and forwards. Relative to the body of the machine,

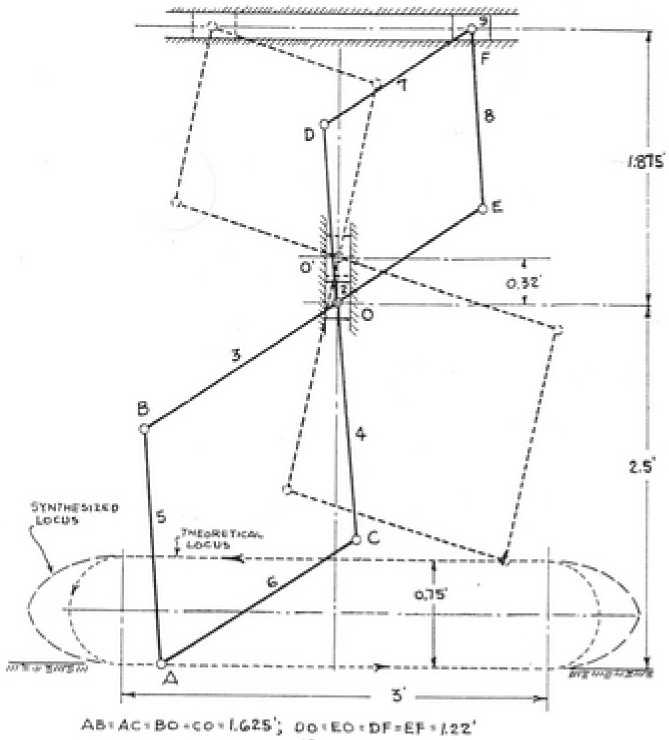


Fig. 6. Prof. Shigley's pantograph mechanism: the dotted oval at the bottom is the desired foot locus

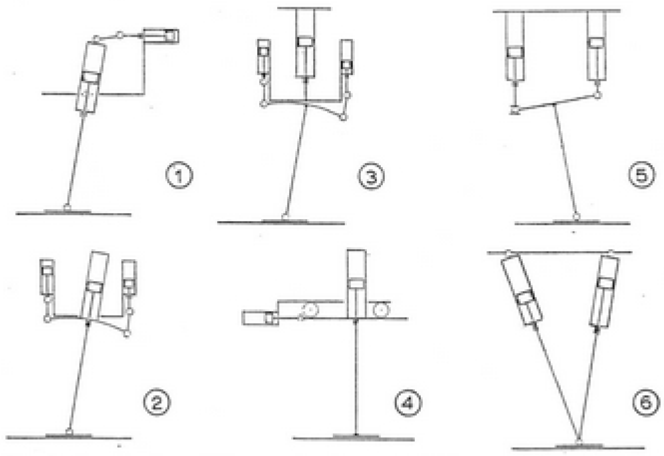


Fig. 8. A selection of leg mechanisms studied. No. 2, was thought most promising

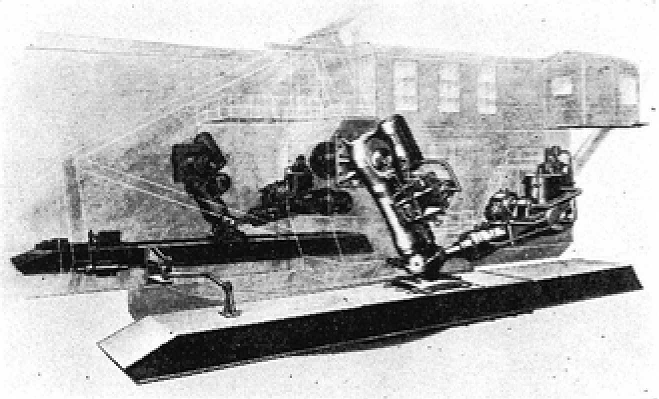


Fig. 7. The walking mechanism of a Russian excavator

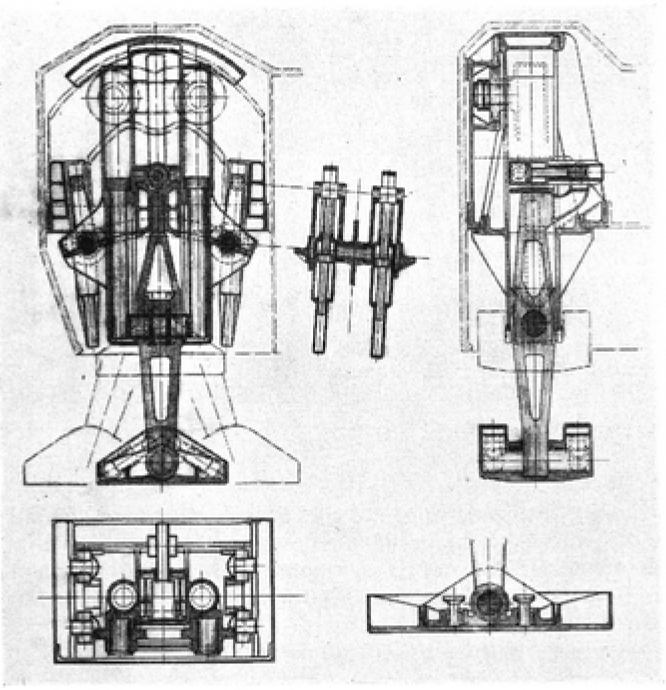


Fig. 9. The proposed armoured fighting machine in a partly engineered state ◀

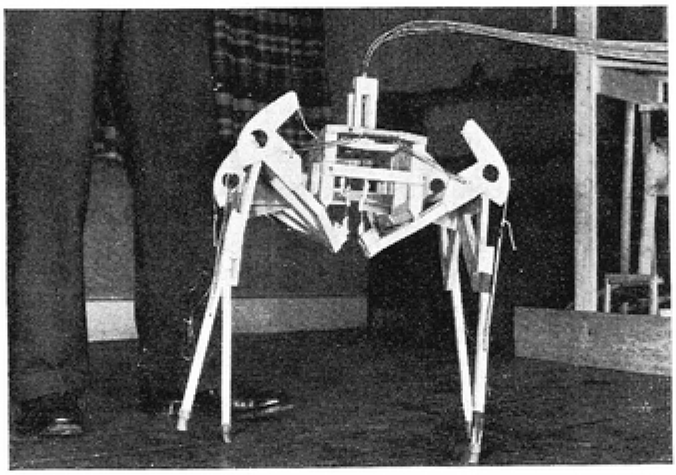


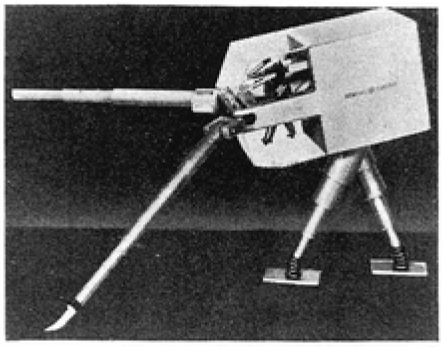
Fig. 10. This demonstration model was remotely controlled by means of flexible cables: the operator used one limb to control each leg

a foot will trace out a roughly elliptical locus. Various linkage mechanisms will give the kind of properties required. One example, used by the walking excavator in Fig. 3, belongs to the family of linkages which includes the well-known Whitworth quick-return mechanism.

A more elegant general solution of the walking mechanism problem, due to Professor Shigley[4], is shown in Fig. 6. The dotted curve at the bottom of the figure is the desired foot locus.

Horizontal components of this locus are determined by movement backwards and forwards along the horizontal slide path at the top of the figure. Vertical components of the locus are determined by up-and-down movements in the slide path in the middle of the figure. The pantograph linkage combines the two components. The sliders could be driven mechanically or, as Professor Shigley proposed, they could be driven hydraulically. Once hydraulic action is entertained the whole horizon expands. Individual foot control can then be effected easily.

Fig. 11. An idea from International GEC in 1962, for a two-legged walking machine ▶



[Courtesy: Desbrow Public Relations]

Fig. 7 shows a hydraulic walking mechanism used on a Russian excavator. I am glad to say, though, that this mechanism was also invented in England.[5] The big, nearly vertical cylinders lift the excavator. The smaller, nearly horizontal cylinders effect the striding movement.

In our project of 1940 we also considered hydraulic drive. In fact, we hardly considered anything else. Fig. 8 shows a selection of leg mechanisms we studied: No. 6 is kinematically identical with the Russian excavator mechanism shown in Fig. 7.

We chose to go ahead with the rather complicated No. 2. This was attractive in being a kind of inverted wheel, in which a segment of rim rolls backwards and forwards under rails on the machine's chassis and the axle at the ankle joint moves intermittently along the ground. Fig. 9 shows it all in a partly engineered state. Above the foot is a pair of stepping cylinders which lift it up and force it down. The rolling thigh joint with its integral circular rim is driven by pairs of striding cylinders on each side of the joint. At the bottom right-hand corner the foot is fitted with overshoes to adapt it to soft ground.

The source of power was to have been a row of 1000 hp diesel engines driving centrifugal pumps to supply hydraulic

[Courtesy: General Electric Research and Development Centre]

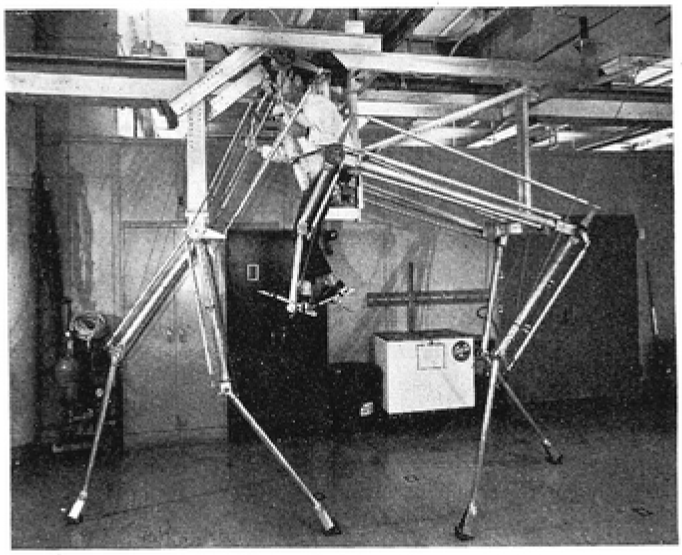


Fig. 12. Feasibility study for a four legged truck resembles Fig. 10

fluid to the leg cylinders. On reflection it does seem that these sketch drawings were almost impertinent in their optimism. The gap between them and a real, developed, walking machine is about as wide as the gap between here and the moon.

Feedback

A key decision in walking machine design is the answer to the question: should each foot go through a fixed, predetermined path in the same way as the element of a caterpillar track or the rim of a wheel; that is to say, should we have had a machine which walked just as inanimately as a track crawls or a wheel rolls? We never had much doubt that the answer was no.

The feet should all be individually controlled to walk intelligently, as required by the environment and purpose. And, man being a four-limbed animal, the four legs of the walking machine could be individually directed by the four limbs of the driver.

At that time we had had long experience of the hydraulic relays or servo-mechanisms used in steam turbine governing. It seemed obvious that the movements of the driver's hands and feet should be magnified with the aid of such relays to dictate the movements of the feet of the walking machine. An easy refinement of the same idea was to arrange for the forces acting on the feet of the machine to be scaled down and fed back to the operating handles and pedals, much as in present-day power-assisted car controls. The idea was that, eventually, the driver's neuro-muscular system should completely identify with the whole machine.

It is interesting that in America, starting from the remote-handling equipment used in radio-active material handling, the same line of development has been pursued. The name they give it is 'Cybernetic Anthropomorphous Machine' or CAM for short.

Having thought out the broad principles, we felt the need to convince, not only ourselves but the authorities, of the soundness of this idea of human control for a four-legged walking machine. Fig. 10 shows a model built to demonstrate four-legged walking by remote control and nothing more; a solid diagram, rather than a piece of engineering, but at least it had four legs which could both stride and step. Each of these legs was associated with two flexible control cables made of expanding curtain rod and piano wire. One cable controlled vertical stepping movements of a leg end or foot, while the other controlled the horizontal or striding movements.

There were, therefore, eight cables in all, leading to a lever arrangement on a control structure, looking rather like a hatstand. An operator sat at the hatstand with his feet on two hind-leg pedals and his hands holding two fore-leg handles.

After a good deal of toil, we could make the model walk about the floor and climb gingerly over a pile of books. We had much more trouble with friction in the flexible control cables than in learning the reflexes and we felt that the 'cybernetic anthropomorphous' principle was fairly well established.

That nearly completes the story. If our proposal seems far-fetched it might be compared with that in Fig. 11 which shows a 1962 idea for a two-legged walking machine put forward by the International General Electric Company.[6] This is a CAM and could not possibly work if it were not. A dummy in the driver's compartment represents the operator who walks the machine with his legs.

Mr A. C. Hutchinson *was educated at the Royal Naval College, Osborne, Bedford School and the Queen's Engineering Works of W. H. Allen and Co. Ltd. While doing a four-year Allen Engineering Studentship, he obtained an external degree of London University. In 1927 he joined the Steam Turbine Design Department at Allens, rising to become Chief Steam Turbine Designer in 1948. In 1954 he moved to the management side of the Company and is now Technical Adviser to the Group Managing Director of W. H. Allen, Sons and Co. Ltd. Mr Hutchinson was Chairman of the Eastern Branch in 1962/3.*

Postscript

In the five years since the above was written, tracked and multi-wheeled vehicles of various kinds have continued to dominate off-the-road locomotion. The American General Motors Corp. has been particularly active in their development.

Walking machines are still being considered, however, though for military purposes in very soft or very irregular ground, rather than for moon transport. Fig. 12 shows a feasibility model for a four-legged walking truck constructed by the International GEC for the US Army Land Locomotion Laboratory: it has appreciable resemblances to the model in Fig. 10.

Finally, it may be worth noting that the invention of walking machines is not new. There is a very detailed British patent[7] for one, dated 1814.

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