ROBOTS

rams from cams

The "power suit" that allows a frail human being to lift tons of dead weight and leap moderate-sized buildings in a single bound has been a science-fiction dream for years . . . until now!

THOMAS EASTON

“... here is how it works . . . a mass of pressure receptors . . . You push . . . the suit feels it, amplifies it, pushes with you to take the pres-sure off the receptors that gave the order to push.

"The suit has feedback which causes it to match any motion you make, exactly—but with great force.

"Controlled force . . . force con-trolled without your having to think about it. You jump, that heavy suit jumps, but higher than you can jump in your skin.

"... that is the beauty of a pow-ered suit: you don't have to think about it. You don't have to drive it, fly it, conn it, operate it; you just wear it and it takes orders directly from your muscles and does for you what your muscles are trying to do."*

Sound familiar? It should. Especially to readers of science fiction. It's Heinlein's forecast—often fol-lowed by other writers—of a self-pro-pelled, feedback-controlled, armored suit, such a thing as an infantryman needs when the exigencies of war require him to carry more than his back can hold and perform maneuvers his muscles cannot.

By the time of Heinlein's story, however, wars may not be fought by men in the field, with or without powered combat suits that follow their wearers' movements as closely as a suit of clothes.

Figure 1. Handyman—a two-armed master-slave manipulator used for handling radioactive equipment and materials. This photograph shows the operator in close proximity to the slave, which is whirling the hula-hoop. In actual operating conditions, a con-crete barrier separates the master sta-tion and the slave, their only con-nection being an electrical control.

Even today the engineers are working on devices similar in principle to that suit, and their progress is such that by 1980 a man may well be able to step into such a machine. Furthermore, these same devices, together with certain developments in theoretical biology and information sciences, may be the forerunners of the first true robots, machines able to move about on legs with no more than occasional super-visory instructions from remote con-trollers. They may not have intelligence, but they will be autonomous in away that no machine has ever been, for reflexes such as those found in cats and dogs may provide appropriate responses to many of the circumstances that may confront or befall them.

This article is intended to outline and motivate one possible path for the development of robots. The path is not inevitable, nor is it unique, but it seems to me a very likely possi-bility and—on the principle that the engineers could do worse than to imitate Mother Nature—very possi-bly the easiest way to build the first robots. More details on some of the information used here, and good dis-cussions of some of the problems in-volved in designing intelligent and locomotor machines, may be found in M. L. Silbar's article, "In Quest of a Humanlike Robot" (Analog, No-vember 1971), and in L. L. Sutro and W. L. Kilmer's article, "MR Robot" (Analog, May 1970). But hopefully, the data and arguments presented here will provide a general under-standing of the possibilities.

Heinlein's suit is science fiction—but not quite. Modern technology hasn't yet produced anything quite like it, but it is coming close. Wal-dos—clumsy things with little or no real feedback—have been with us for years, but they are not suitably de-signed for incorporation into such a suit, much less into robots. There are more sophisticated, more recent ap-proaches using feedback—not on the data from pressure receptors, for that kind of control data provides too many separate pieces of information for efficient processing and decision making by the cybernetic system of the unit—but on the data from recep-tors which measure changes in the angles of the joints of the operator's limbs. Such data are more useful be-cause they are more immediately as-sociated with a movement, they re-flect its form more precisely, fewer receptors are required, and the re-sponse of the unit is nearly synchro-nous with intention.

Heinlein can be faulted only on the limits of his vision, for though he forecast the movement-following suit, he neglected to see the obvious and necessary corollary that allows the engineers to go him one better: not only are they designing machines very similar to his combat suit, but they are using in their design the concept of force feedback (FFB). Re-sistances, loads, and obstacles which may impinge on the mechanical ef-fectors of their systems are sensed and returned to the operator so that he can feel what the machine is doing as if it were his own body. FFB amounts to an extension of the operator's kinesthetic senses (not touch) into the man-machine combi-nation known to the engineers as the Cybernetic Anthropomorphous Ma-chine (CAM).

Before going on, however, to show how CAMs may be turned into ro-bots, we should briefly consider three such machines as illustrations of the CAM concept: Handyman, Hardiman, and the walking truck. They are not all at equal stages of devel-opment: Handyman is on the mar-ket, but the others have not yet reached the prototype stage. So far we don't have even a simple version of the combat suit available, but that; and more, is on the way.

Figure 2. Hardiman—an exoskeletal manipulator to augment man's strength, made possible through hu-man sensing control.

Figure 3.(below) Left arm of Hardiman. Dur-ing testing the operator successfully lifted the single arm's design load of 750 pounds. It performed well in the six major areas of concern—individual joint stability, joints-in-series stabil-ity, kinematic interactions, mechani-cal interferences, ability of the oper-ator to control the system, and ease of operation—and "confirmed" the engi-neers' "confidence in the design and analysis of servo joints in series."

Handyman, shown proving its dexterity in Figure 1, was designed for the handling of radioactive mate-rials; only FFB brings it well out of the realm of mere waldos. The operator, on the left in the figure, wears a harness which measures the motions of each arm and transmits appropri-ate signals by cable to the servos of the manipulator on the right, while the forces encountered by the ma-nipulator in its task are in turn mea-sured and reflected to the operator via small servos in the harness as FFB. The coupling is so direct and detailed that the operator does not have to think about operating the machine. He simply concentrates on the manipulation task itself, observ-ing the actions of the mechanical arms and hands as if they were his own, much like Heinlein's space trooper but with more accurate and stable control.

The closest approach of modern technology to Heinlein's conception is to be seen in General Electric's Hardiman, a walking manipulator that is attached to its operator like an exoskeleton (Figure 2). It is intended for use in bomb loading, underwater construction, and many tasks in-volving the handling of heavy mate-rials. Hardiman is planned to have a load-handling capacity of 1500 pounds with FFB reducing the load felt by the operator to 60 pounds by insertion of a scaling factor into the feedback circuits. Such use of man's natural kinesthetic senses for fine control will make delicate tasks, such as picking up an egg or opening a door, much easier for the operator to perform. Without it, the muffling ef-fect of the machinery and the ex-treme power available make it all too likely that the operator will ap-ply too much force or apply it in the wrong direction, thus cracking the egg or ripping the door off its hinges.

The same problems would necessar-ily apply to a robot: kinesthetic feed-back is essential for the fine adjust-ments necessary to delicate tasks.

The various motions of the oper-ator's limbs are measured by sensors attached to the joints of a light mas-ter skeleton fastened to him, and ap-propriate control signals are then ap-plied to the 26 force-reflecting servos of the more massive and powered slave skeleton which does the actual work. Completion of the Hardiman prototype was planned for the spring of 1968, but by July 1970 only one arm, able to carry its own weight and lift its design load of 750 pounds (Figure 3), had been built and tested. This arm, however, did prove the usefulness of the design and show that GE's plans are realistic. Hardi-man will be built and then only ar-mor will be needed to provide the world with a near-equivalent of Heinlein's combat suit.

The same kind of movement-fol-lowing control is being considered for, and used in the design of, walk-ing trucks, where the legs of the truck are the slave component and the operator may be supported in a harness that permits him to control the truck by "walking" on all fours. FFB permits the operator to feel ir-regularities in the ground and adjust the gait accordingly. Figure 4 shows the present conception of such trucks. They will be able to go where wheeled vehicles cannot and may be used in exploration, transport of goods and personnel to inaccessible locations, and, perhaps, as sophis-ticated prostheses for multiple am-putees.

What is a CAM? It is a combina-tion of man and machine, the two in-terconnected by feedback in such a way that the operator needs no spe-cial skills other than those he needs to operate his own body. Particular tasks may require special skills, but operation of the machine does not: it follows the movements of the oper-ator's body and his intentions and may be considered an extension of his body. Special sensors and special effectors, duplicating in function those of his body, let him reach, grasp, strain, lift, walk, run, and twirl hula-hoops as if he were naked to the wind.

Besides this, the mechanical por-tion of a CAM is mechanically per-fect for use in robot design. It is a Perfectly articulated skeleton, complete with "muscles," designed to permit very close imitations of hu-man or animal movements—and the first true robot man builds will be designed to approximate man (or more likely a quadruped, for reasons of balance) very closely. The mecha-nism lacks only the control system provided by man in the CAM, a sys-tem of coordinated reflexes and deci-sions based on kinesthetic informa-tion, a system that provides a coordinated output, not a series of single, separate signals to each servo, but salvos of signals to specific groups of servos. In man, the corre-sponding groups of muscles are termed synergies; within one the effects of a movement on the rest of the 'body are cancelled so that bal-ance is not disturbed and muscles are recruited to aid those involved directly in a task. Might it not be possible to remove man from the CAM and replace him with circuitry able to generate the appropriate con-trol signals?

Figure 4. Artist's concept of the walk-ing truck or quadruped. The front and rear legs of the machine will be con-trolled, respectively, by the arms and legs of the operator in movements sim-ilar to those of a cross-country skier. The proposed speed, payload, and di-mensions are: approximately 5 miles per hour; 500 pounds; and 10 feet high, 12 feet long, and 3.5 feet wide.

Both Hardiman and the walking truck have effectively parallel master and slave skeletons, unlike Handy-man, where they are separate though connected by cable. It is currently being considered that it might be possible to separate them com-pletely, retaining only a radio link, so that the operator might wear the master skeleton in a safe and comfortable control center while the slave (or slaves) performs dangerous or difficult work under the sea, in or-bit, or on other planets, wherever it might be cheaper, easier, or safer to send only machinery.

The advantages are obvious, but the drawbacks are the same as those attending any other use of remote control: in particular, wherever there is a time lag, progress in the task must be slow. For instance, a walk-ing truck on the moon or Mars, if re-motely controlled through every de-tail of its tasks, might stumble with one foot into a crevasse and before the operator could withdraw that foot and move away from the haz-ard, the machine could be at the bot-tom, damaged, trapped, or certainly restricted in its future usefulness. The only solution, given this mode of control, is to move so slowly that accidents cannot occur within the time lag.

On-the-spot control, however, is just fine. Responses are immediate and emergencies cannot develop unattended. All that is needed—given that we would rather send a machine to Mars than a man and that the machine is of the CAM kind, versatile, independent of ter-rain and task, easy to control—is some way of providing on-the-spot control, perhaps by making the ma-chine autonomous in a sense, requir-ing only general supervisory instruc-tions from the remote controller. The whole point of this article is that this can be done.

However, before trying to show how it can be done, one preliminary question must be answered: what will be the form of the first robot? It is, I think, fair to assume that the sole task of the first one will be loco-motion, a well-defined problem of coordination whose solution will ease later attempts at building a more general robot.

Theoreticians have analyzed loco-motion and concluded that only a quadrupedal machine can show "static" stability: that is, if while moving, the locomotor machine is stopped dead in its tracks, only a quadruped will not lose its balance and fall when it is moving in the transverse crawl and the slow trans-verse walk. Only in these two gaits is a polygon of support—a figure drawn with the vertices matching the feet on the ground and enclosing the ver-tical projection of the machine's cen-ter of gravity—continuously maintained.

Other gaits show "dynamic" sta-bility: that is, a polygon of support is not continuously maintained, but the motion of the machine is such that before the machine can fall, a foot will contact the ground, the resultant thrust countering any dis-equilibrium. Since a bipedal ma-chine must nearly always rely on dy-namic stability, then for ease of control and the possibility of leaving the machine parked and waiting for use, the first such machine must have four or more legs. The walking truck is the most nearly available example of this and, because of its mechanical resemblance to quadrupedal mam-mals, a great deal may be learned about the control of the machine by studying the animal.

But given the form, how is the ma-chine to be controlled? Continuous specification of limb or joint position won't do, for that would require too much computation and the machine would have little or no computer ca-pacity remaining for other tasks, pro-vided that it could carry a large enough computer for control at all. The best way may well be to copy the control methods found in nature. I don't mean that we must duplicate a nervous system such as may be found in a cat or dog, but that we could duplicate its function in a cer-tain broad sense. Nor do I mean that a general purpose computer be "taught" to duplicate the function of a nervous system. I do mean that some of the structuro-functional re-lations of the parts of the central ner-vous system may be duplicated in the wiring of a robot so that the con-trol methods are innate; just as a computer computes by adding one and one by reason of its wiring, this robot would control its movements in biological ways.

To determine these biological con-trol methods, two immediately obvi-ous aspects of locomotor behavior must be noticed: (1) volitional move-ments, which are smooth and labile in their expression, vary to fit the moment and its task, and adjust to correct for irregularities in the envi-ronmental conditions, and (2) the re-flexes, which are stereotyped, stiff, and elicited only by particular kines-thetic and other stimuli.

A reflex (not a conditioned reflex) is a "wired-in" response, such as the familiar knee-jerk reflex, of one or more muscles to a particular stimu-lus. It is an innate relationship between effectors and sensors. Its form may be modified by such factors as location of the stimulus, what the animal is doing, and other reflexes.

Furthermore, the reflexes, when they are viewed all together and compared with volitional movement, seem to overlap it much as words do language. Reflexes are not volitional movements, just as words are not language, but volitional movements may be broken up into fragments that, very closely resemble the re-flexes, just as language may be bro-ken into words. And it is a con-sequence of the "Theory of Tasks" currently being developed by Dr. Pe-ter H. Greene of the University of Chicago Departments of Theoretical Biology and Information Sciences that reflexes are indeed the com-ponents from which may be built volitional movements. It should thus be possible to take the reflexes ob-servable in nature, copy them in cir-cuitry, install them in a CAM, and organize them into the movements which we wish a robot to be able to use.

A robot, or walking truck, equipped with such reflexes would not be the intelligent machine of science fiction; it would be instead a Reflex Autonomous Machine (a RAM) able—once instructed where, how fast, and when to move—to travel without being blocked or de-stroyed by the permanent features of the terrain on which it moves.

Unlike Disney's Audio-Ani-matronic dinosaurs and Lincolns, a RAM is not a pre-programmed ma-chine or puppet; it is an adaptive machine, able to respond appropri-ately to some of the exigencies of its environment, equipped with biologi-cal reflexes which presumably allow it to operate effectively in all those environments that have contributed to the evolution of those reflexes, but unable to learn from experience unless that were to be built into it. If, as seems likely, it is equipped with the perceptual and command systems studied by Sutro and Kilmer, it will become a true robot, verging on what one might take for intelligence and able to do much more than merely walk.

As described here, a RAM is a ve-hicle for transport or observation, but it need not remain so: Hardiman too is a skeleton and man too walks and works on a basis of reflexes. Hardiman too could he equipped with reflexes to let it walk alone and do more than walk, for hands will be necessary for many tasks, but a hu-manoid RAM will probably be pre-ceded by a centauroid one, a Hardi-man torso mounted on a walking truck and operating partly on a basis of invented reflexes to coordinate six limbs rather than the more usual four. The skeletons, or CAMS, are our givens and the control methods are attractive, but we have yet to combine them. If and when we do, robots—RAMs from CAMs—will join the tools man uses for work and exploration, freeing not only his life from danger but his mind and time from waste.

*R. A. Heinlein, Starship Troopers, pp. 82, 83, Berkley Medallion edition, 1968, copyright 1959 by R. A. Heinlein. Quoted by permission of G. P. Putnam's Sons.

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