ROBOTS ~ THE FACTS

Dr Peter Sydenham, ETI Special Correspondent presents the factual side of Robots and analyses the many seperate factors needed in all Robots.

ROBOT DEVELOPMENT from the Middle Ages onward is simultaneous with the rise of man's ability to devise and build complex mechanical machines which grew once men realised that considerably more advancement was possible by employing experiment with theory. (The result of such men as Roger Bacon of the 13th century.)

The bulk of mechanical ingenuity and skill was expressed in clock-making of great sophistication. The very famous 1354 Strasbourg clock depicted the St. Peter denial of Jesus, a main feature being a cock that moved, stretched and crowed.

These skills were occasionally employed to make devices other than clocks. Jacques de Vaucanson, around 1750, constructed a well-documented duck automation toy. It stretched, took grain from the hand, swallowed and, seemingly digested its food, leaving deposits behind. It consisted of hundreds of moving parts.

Robot development also has its beginnings in the form of calculating machines, such as the Pascal and Leibnitz instruments of the 17th century, and the later Babbage engines of the 19th century which included stored program and digital number processing.

We tend to think of the Babbage calculating engines as complete in what is exhibited today in the London Science Museum. In reality, however, they required an energy source of several kilowatts to drive them. A small steam-engine was to have been used by Babbage.

The first electrical digital computer, by Zuse in the late 1930s, used relays to perform logic. The first valve installation was in the middle 40s and it was much too large in size and too small in capacity to provide brain-power for a mobile robot device. Today things are much more favourable. We return to the feasible robots of near modern times at the end.

What Forms a Robot?

In the first half of the 17th century Descartes suggested that the physiological animal can be thought of as no more than a vastly complex machine. Intolerance of ideas, especially those that had religious implications, was extreme in those times and no doubt Descartes only spoke and wrote a little of his concept. Pascal, for example, was dangerously close to being the subject of a witch hunt after people saw his simple (to us!) add-and-subtract calculator — after all, it could do the tasks attributed then to a god.

The idea that animals are merely machines is known as the reductionist or mechanistic philosophy. As we cannot prove, by any means whatsoever, that there is more to man than man can ultimately devise, we cannot, at present, resolve the issue. Nevertheless, there is much about animal systems that is reducible to plain engineering. It is these known facts that suggest that many jobs that were considered as man-suitable in the past could well be done by machines instead. The justification is, to use a well-known quotation, "to make human use of human beings": If an automaton can do the same tediously repetitive task as is done now by a bored and dehumanised human operator, then there is a case to make use of it. This is the story of man's industrialisation, especially since the 18th century.

The human animal is a fine example of a general-purpose, mobile, self-repairing, self-reproducing machine, one that can adapt to new tasks and new environments as need arises. It is not perfect for all jobs, but does provide a fine basis for modelling robots of work, even though the materials and strategies used are different in practice.

Animals can be thought of as hardware systems, consisting of several kinds of sub-systems put together, to form the whole system. The complete system is capable of many modes of behaviour. A diagrammatic representation is given in Fig. 2. Let us look at the building blocks first.

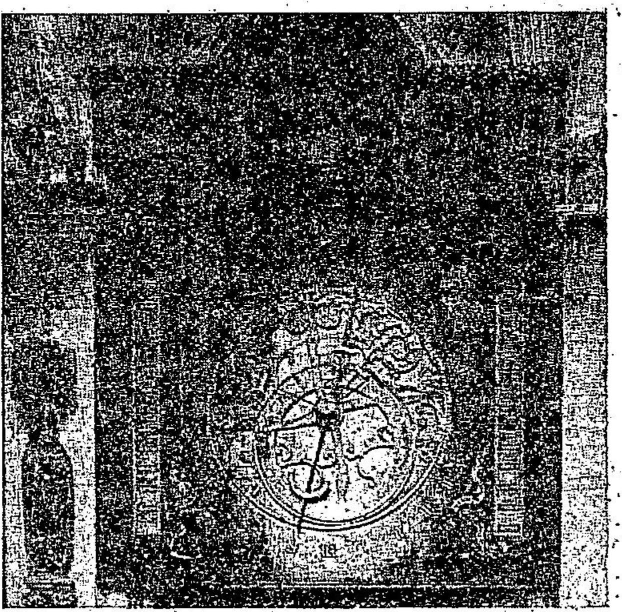

Fig. 1. Clocks, like this one made in 1512 in Munster, Germany, incorporated great mechanical craft. They provided need for mechanical skills used in robot devices.

Structural framework — This is the mechanical part holding everything together. Bones, skin, tissues in the animal can be equated to metal, wood or plastic frames of machines. The framework is developed to satisfy, as a compromise, requirements of lightness, rigidity, appropriate articulation, protection for vital parts, and correct location of one part with respect to another. Note that robot machines do not use the same materials that are found in animal systems. To date it has been more profitable to use quite different substances because man knows too little about the production of regenerative, self-repairing materials used by nature.

Actuators — On to the frames are added converters that change the available energy form into mechanical work. On animals these are the muscles; on robots they are usually electric, hydraulic or pneumatic motors. Again, although muscle-like devices have been made, robot actuators use different principles of conversion and different energy sources from animals. Actuators cause limbs to move, hands to hold, and the whole to translate where needed.

Sensors — Automata that, for instance, play music, are preprogrammed. Regardless of external influences, once set going, they will attempt to keep playing despite changes to their environment. Robots can be much more sophisticated for they possess sensors, or receptors, that observe what is happening around and to the robot. Sensors provide signals that, after data processing, tell the actuators how and when to work in a way that modifies an otherwise hardwired kind of performance.

It seems that many animal senses work on the basis of having a multitude of on-off digital sensors built into each sensing device, the combined, parallel, signal output being a measure of a sensor signal strength. Robot sensors rarely work this way for we are unable to handle so many parallel channels as nature uses. Robots usually incorporate analogue output sensors — the so-called linear signal in integrated circuit jargon. To detect the seat of a fire, an automatic robot fire extinguisher will use a proportional signal infra-red detector homing the robot towards the position of maximum signal output. In some cases man-made robots do use digital output sensors but not so commonly as analogue ones. An example might be a digital shaft encoder sensor mounted to measure an arm's angular position.

We cannot measure every variable that arises in the material world. Even so, literally thousands upon thousands of sensors have been devised so the robot designer of modern times can go a long way with what exists already, especially if one sticks to industrially marketed units in order to keep costs low.

Data Processing Centre — Signals from sensors are routed to DP centres. The brain is the central unit of humans. Not all animals have only one brain. Some early prehistoric animals are believed to have had two brain centres. Signal pre-processing goes on in animals before a stimulus reaches the brain. This can also be the case in robots. Robots can have local brain-power plus a central unit. We cannot make much of a comparison between DP of robots and animals, for we still have only a meagre idea of how the physiological brain operates. Insight that we do have is enough to say that robot brains will be quite different in physical structure from animal brains. We tend to opt for non-redundant data processing methods using a limited number of binary locations. The brain appears to make use of massive redundancy and enormous bit storage capaciy (10^{20} is an estimate).

Terms

Robot — In Gothic it is akin to a word meaning "inheritance", in German to "work". An old Slavic word that is equivalent is "rabota" and in Czech and Polish "robota" means servitude or forced labour. Professor George's book (see list) says it is "a machine devised to function in place of a living agent".

Robotics — Gaining rapid acceptance, this term describes the discipline that designs and creates robot device structures and sub-assemblies. The following word is reserved for its system organisation.

Cybernetics — Study of multiple feedback loop, self-governing systems, usually of great complexity, as are found in living organisms and advanced man-made control systems.

Automation — Any device that has apparently spontaneous action. (Plural is Automata.)

Humanoid — Robot form of man.

Android — Automaton of man-like form.

Homunculus — Inferior robot form of man.

Prosthesis — Man-made, human body replacement parts.

Ecoskeleton — Robot frame that fits around human to give power to limbs.

Golem — Man-made creature not having man-like form.

Mobile — Robot device having mobility.

Manipulator — Handling device.

Telechiric — Derived from Greek for "distant hand".

Communication Links — Sensors feed signals to actuators via DP centres. The links we know and use in automatic machines are electric wires, optical fibres, air and oil tubes. Nature, however, uses the nerve links in which pulse signals are regenerated in mysterious ways by electrochemical methods. We can make use of Nature's concepts but not her hardware methods.

Energy Supply — Animals derive energy converting foodstuffs into energy by chemical means in muscular tissue. Robots cannot do it this way, but make use of the sources known to man at this time. Electricity can be generated by converting fuel to electric current. In mobiles a usual source of energy is electricity from storage cells. Restricted mobility and fixed robots can obtain power by an umbilical supply cable. Hydraulic and pneumatic systems derive energy from their compressor unit — the lines act as energy transmission links to the converter unit.

Robots that perform work will be somewhat inefficient for all energy systems will have losses. The human system consumes around 100W at a rest condition (of which most is lost as heat) and can provide about three times this power as work for limited periods. This would, by implication, suggest that a robot doing the full tasks of a man needs a 400W supply capability.

The man machine looks quite puny: 400W is not exactly powerful. Robots are not so limited: For a start, a man begins to tire after a few hours at 200W output — a machine equivalent can go on tirelessly. Robot manipulators can provide whatever power level is desired. They are made to lift huge loads. An example is a framework that a man fits into, giving him arms that follow his own with greatly increased load capability.

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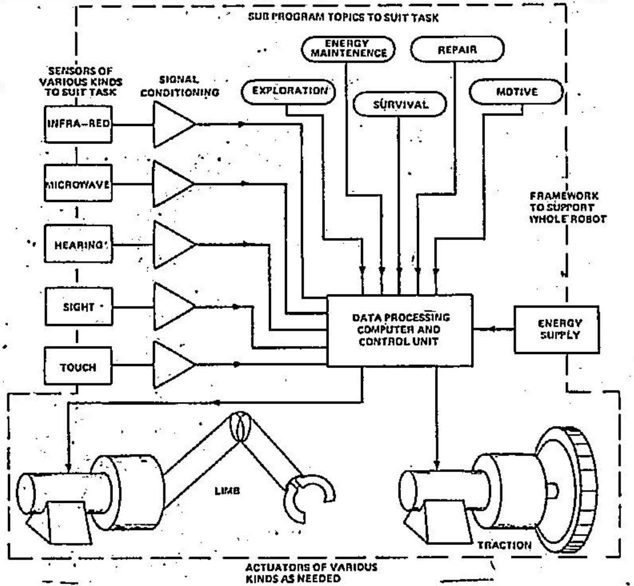

Fig. 2. Robot systems are made up from sensors, actuators, and data processing power operating together to satisfy a number of operational modes.

Motivational Mode — In-built must be some means that ensures that the robot constantly goes about the business for which it was created. This mode is temporarily given lower priority when circumstances dictate. As a simple example, a mobile designed to cut the grass of a lawn may need to divert its attention from grass cutting toward a battery recharge. After charge it must return to its duty.

Survival Mode — The programming basics must incorporate means to put the robot into behaviour modes that reduce and, hopefully, eliminate damage to the robot. The lawn cutter above must recognise that the concrete edging or stray stone must not be brought into contact with its blades. The survival mode must also extend to preventing the robot doing damage to its environment.

Energy Maintenance Mode — As well as the obvious need for the robot to ensure that it has power enough available for instantaneous load, it should also be able to prepare an energy budget of near future need. If it is a battery-fed mobile, it may well find itself out of energy enough to get back to the recharge point.

Exploratory Mode — Robots can have greater than one purpose. Such purposes may not exist all of the time and all in one place. When no purposeful sensor signals are received, actuators should be set by a sub-programme to cause the robot to go and look for a task. In animals this is seen as inquisitiveness. Without it humans are referred to as lazy and unmotivated, as would appear a robot.

Maintenance and Self-repair — The good robot is one that does not deteriorate in performance. This is not a reality, however, for although wear rates of mechanical implements can be reduced by better design and more expenditure, it usually can only be done at greatly increased cost. It is to be expected that robots, at least for many years yet, will require maintenance like greasing, bearing replacement and sliding surface repair.

The first thing the robot will need to do in this mode is to diagnose its own troubles, deciding what repair action is to be taken. Then it must organise some way to replace parts. This mode is probably more idealistic than real for most robots at present, but the software programmer and robot designer should, at least, give some consideration to this need.

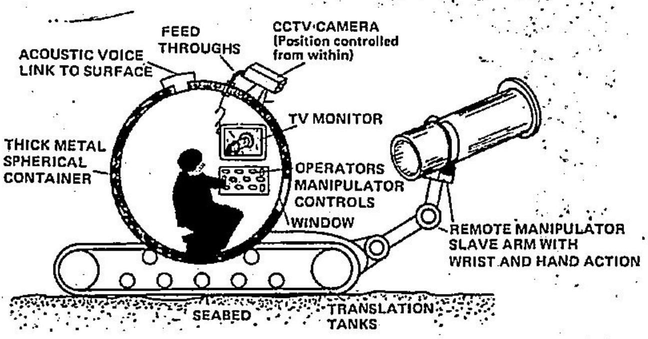

Fig. 3. Underwater a robot manipulator provides an operator with an effective ecoskin and increased ability to do work.

Robots and People

In 1942 Isaac Asimov put into words three laws of robotics that have become famous in this field. They refer to the relationship between robots and people that designers should bear in mind for obvious reasons. The laws are:

(1) A robot may not injure a human being or, through inaction, allow a human being to come to harm.
(2) A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.
(3) A robot must protect its own existence as long as such protection does not conflict with the First and Second Laws.

Asimov never intended the laws to be the one and only guide to robot designers — far from it, they were the result of science-fiction writing. They are not foolproof and do not extend to all situations, but do remind us of some basic ideals to consider in programming a robot's behaviour pattern.

Programming the Robot

A fully determined robot performance, that is, one that will obey instructions that are all preset before it begins to work, is little better than a special-purpose machine. It cannot do other than what is expected by its programmer. This basic level of performance is required of many robots, but is not the complete capability. It might be preset by a punched-tape or magnetic tape in the same way as many domestic knitting machines work. Most manipulator robots get these instructions via an initial man-operated run using special controls that allow the operator to run the manipulator through the required manipulative routine. Once done it becomes a stored programme routine.

Far better, if possible, is to servo the output required according to inputs of error. For example, to put a pin in a hole is better done by viewing the error between the pin and hole reducing the error to zero rather than presetting an arm to put a pin where the hole is expected to be.

The latter open-loop method assumes that all relative positions of limbs of the robot are held within the final tolerances needed to put the pin into the hole — which

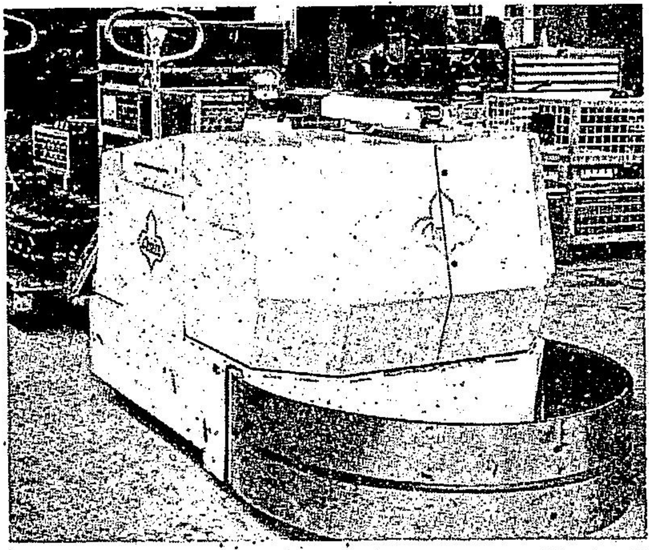

Fig. 4. The Ameise Teletrak driverless tractor train guides itself to follow a guide-wire set into the floor. One day it may be economic to provide the robot with navigational ability that compares with that of humans.

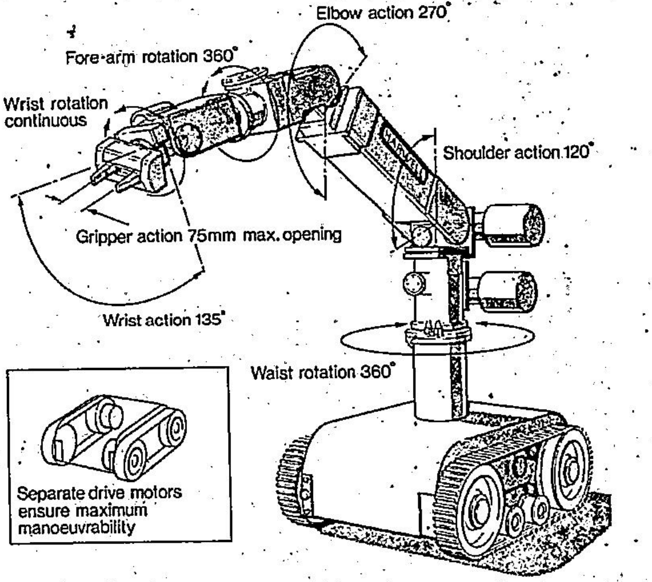

Fig. 5. ROMAN, a recent Harwell mobile, is made for use in hazardous industrial situations. It is electrically powered using cable control.

are extremely tight limits in many cases. The former method makes use of feedback and it is a feature of servo systems that actuation components inside the loop can be reasonably inferior in quality. This is a most important system concept — think of the problem of finding a place on a map by dead reckoning from a set of distances and bearings, as opposed to improving one's situation as you go by recognition of error still existing.

Recent Robots

Many authors on robotics include mention of a wide variety of inter-disciplinary automatic devices. This broadens the subject enormously and is a quite reasonable thing to do for robots can take any form. For reasons of space, we restrict ourselves here to mobiles and manipulators.

It is said that the term "robot" gained public acceptance as the result of a 1923 play by Karel Capek. It was at that time in history that ideas about automation began to flourish in earnest because of the favourable technological atmosphere. Electronic amplification was just available, mass production of consumer goods was established; sophisticated industrial control was emergent at a seat-of-the-pants level (theoretical considerations came later in the late 1940s).

Electrical computation began in the late 1930s, resulting in the first working vacuum tube system in the 1940s. Computer research no doubt stimulated interest in artificial intelligence, AI for short. Things were really happening by the 1950s. Studies of adaptive control, self-organising systems, AI and a new discipline called cybernetics were developing rapidly — research workers became very optimistic that machines would soon be able to design better machines. But they found over the successive years that it was not so easy!

Cybernetics was the term popularised by Norbert Wiener in 1957 for the discipline covering self-governing systems of all kind, seeing them basically as all the same thing, regardless of application. The term is derived from the Greek language and means the art of steersmanship. It is of interest to include the fact that Ampere had previously used the term to describe the science of government.

Theory of automata became an established pursuit a little later. Pattern recognition was another related area that became fashionable to work on. By the early 1970s the realisation that these ideas would not blossom so quickly, if ever, to give regenerative machines and robots replacing men in all their faculties, was accepted. Such goals are now seen to be much further away.

Today the past efforts of many people in the above fields have been tidied up, extended, ignored and much has been weeded out as irrelevant or false, leaving today's robot designers with a very useful and full theoretical and practical background to work from.

Mechanical design aspects of robots have advanced through work in prosthesis, in nuclear materials handling, in a relatively few academic engineering departments and within a small number of industrial groups.

Data processing for robotics concentrated on seeing what could be learnt from biological systems — maybe this was not so fruitful considering that designers have to work with different materials than nature uses. Then came the mini computer, almost small enough to build into a reasonable size robot device. Costs at first were prohibitive. Computing power and speed were very limited for operating robots at the motional speeds and precisions needed. Today we now have the quite cheap microprocessor, where the larger part of its sale price is for the market promotion, mechanical packaging and application notes.

Before Time

Advanced ideas usually meet opposition in a society. Bruno was burnt at the stake in the 1500s for suggesting astronomical theory was wrong. Pascal nearly went the same way for making his adding machine. Even Ohm had his simple law of the 1830s opposed by men of learning. The road car was held up in development for over 60 years by the need to walk in front of a vehicle with a red flag. Fear, preservation of the status quo, misplaced motives, politics and the natural and more healthy need for cautious acceptance usually emerge before a new concept finds acceptance.

So it has been with robots. Science fiction writers paint both gloomy and happy scenarios with robots. We tend to remember only the former. Robots are merely

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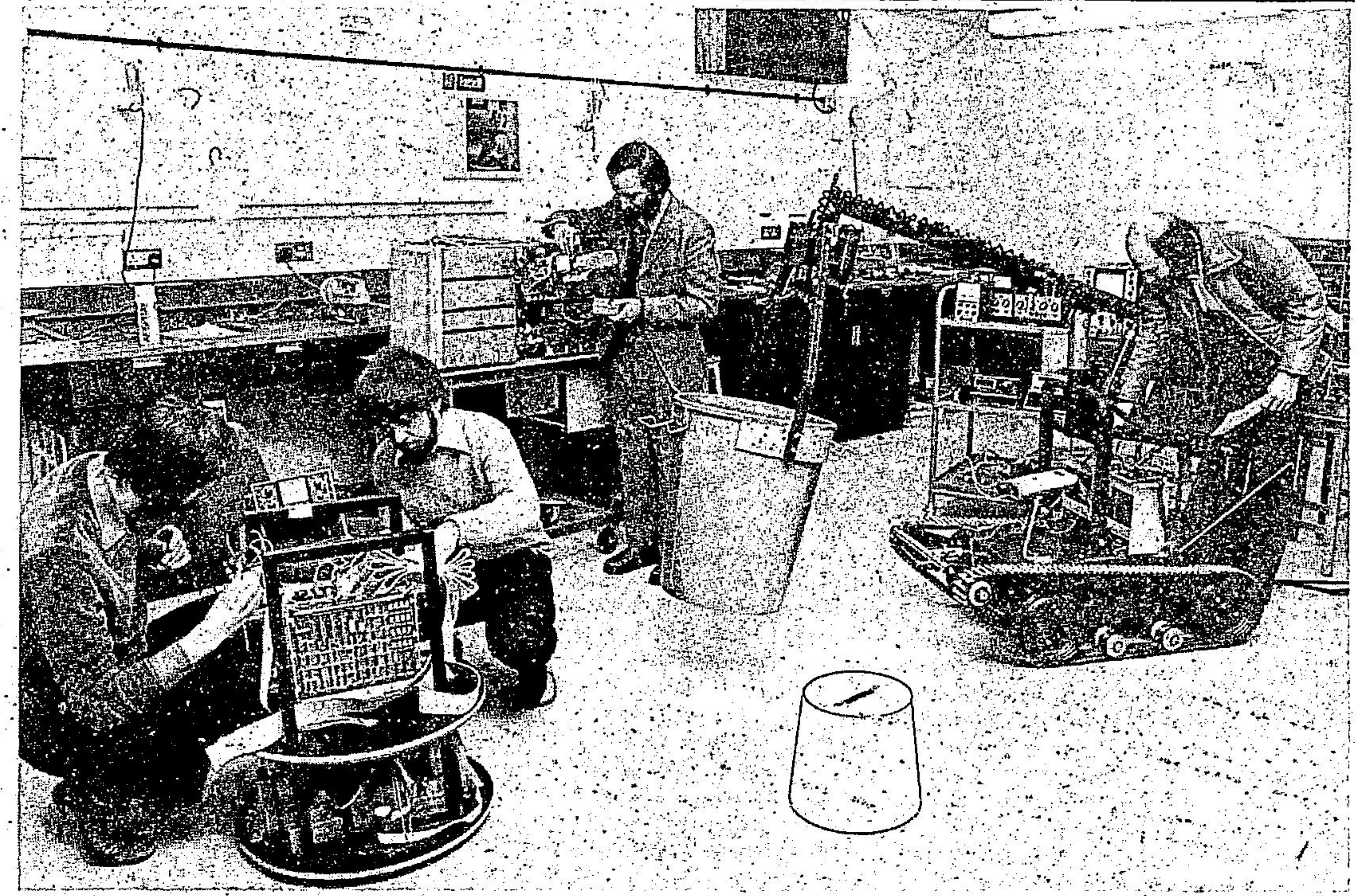


Fig. 6. Four projects of the Warwick University Robot Laboratory. That on the left uses an inboard microprocessor. At the rear is a hand-like short arm manipulator. The tracked vehicle is originally sold as the army bomb-disposal unit — it acts as a ready made vehicle to conduct research on. (Keystone Press Agency)

machines of greater capability and versatility than man has made to date. As with all of man's technology, he has to learn to use them appropriately. We should not fear the robot but look deeply into its value to us.

Returning to earth from the levels of philosophy, it is quite certain that the robots we build over the next decade will not challenge our existence. We know too little at this time to build them with such powers. There are, however, numerous requirements where robot devices can replace men performing tasks too hazardous for men to do. Machines are the extension of man on earth and no force is likely to stop man's use of tools which has been part of his culture from the very beginning.

University Research

Robots of the future will make use of techniques discovered and developed in research groups working on artificial intelligence, robotics, computing science, electronics, plus many more areas.

The Science Research Council of Britain supports robot research. The main laboratory of the Robot group at Warwick University is shown in Fig 6. In the same room is the computer terminal to which the four projects shown are hooked-up to give them significant data processing ability. Around the walls are placed acoustic transducers used in positioning work.

A group at Edinburgh University work on putting artificial intelligence into robot devices. They have built a servo-controlled, computer-based, handling system.

A prime purpose of University research is to seek better ways to achieve goals. Theirs is not really a task of building devices that are totally engineered. For this reason one seldom sees a finished robot but more units in stages of change.

Never before has the field of robotics been so ready for development. Simple robots with quite sophisticated brainpower are in the price range of the non-professional. Amateurs can now enter the field knowing that the capability of their effort made now will be improved as efficient and powerful strategies are transferred to the general public domain at low cost via mass-produced integrated circuitry and software packages. A good comparison is seen by remembering that visual display units that write words were wonders of the time ten years ago. Now the equipment is reasonably standardized, far more advanced and within the price range and building capabilities of many teenagers.

Organisations

British Robot Association
Secretary, Dr. M. Larcombe, Robot Laboratory, Department of Computer Science, University of Warwick, Coventry, U.K. (A professional body with leading manufacturing companies as members.)

Robot Institute of America
20501 Ford Road, Dearborn, Michigan 48128, U.S.A. (This professional U.S. body has recently inaugurated a medal — the RIA Joseph G. Engleberger Award — for individual outstanding contributions to the science and practice of robotics.)

ETI

ROBOTS~ BRAIN POWER

Dr Mike Larcombe investigates the logic that makes a Robot think it thinks!

ROBOTS DO NOT HAVE BRAINS. 'Wet logic' technology — brains to you — is many orders more complex than the world's most complex machine (which is probably the International Telephone system, not any supercomputer). Robots are however extremely bright — for machines. They are much smarter than computers — which suffer from the so-called GIGO syndrome (Garbage In, Garbage Out). Unlike the dumb computer they answer back — ask a smart robot to walk through the wall and you will get the robot equivalent of a flea in the ear. Give them a reasonable task and they will carry it out — give an impossible task and they will either a) refuse to do it, b) try to do it for a while and then give up, c) have a seizure (badly designed robots only — as we do not yet really know what makes a good design, this means most of them).

Through A Robot's Eyes . . .

It is easy to be patronising while watching a robot at work — especially as their vision is either poor or non-existent. A few minutes attempting to perform the same task using the same robot body under remote control and using the robot's own sensors soon convinces the human that the robot itself is best qualified to control its body. Without direct visual feedback remote control becomes exceedingly difficult — when dealing with feedback from non-human sensors such as sonar or doppler radar, virtually impossible. In its own sensory environment the robot is a master of control. In our laboratory at Warwick where robots use sonar their behaviour in the dark is much superior to that of their designers.

No undisclosed miracle of technology lies hidden within the robot's carapace — no 'positronic brain' is required. Most of the more advanced robots contain — or are controlled by — computer, and frequently by multiple computers. With the advent of reasonably powerful micro-computers with 16 bits or more to chew the computer power can now be contained within the robot body. The smaller 8-bit micro-processors tend to wheeze and groan under the processing load required for even a small robot. The really high IQ robots still tend to cling to the apron strings of a big computer but it is only a matter of five years or so before they can cut loose.

Now if you had been paying attention you would have noticed that in the first paragraph I was somewhat disparaging about computers. Yet computers control robots — how come the robot is smarter? Well the robot is a lot more than just computer — it has sensors and actuators and perhaps a boxful of specialist processing functions such as motor acceleration-deceleration control or positional servo systems. A small robot will have more input-output channels than many of the larger time-sharing computers. The robot's necessary data handling load may well exceed 10 Megabits/second — much too fast for a micro-processor by itself. Fortunately much of this load is trivial — such as limit switch logic — and is easily handled by special logic, but nevertheless it must be handled. The road to automatic control is littered with sad and pathetic figures who thought all they had to do was connect the wires into a computer, and it would do it all, 10 Megabits/second requires a great deal of computer and a great deal of money!

Flexibility

A robot program is unlike an ordinary computer program such as a payroll program. A payroll program is a set of sequential steps moving data, making decisions and ultimately stopping. A robot program is attempting to weigh up a continuously changing 'situation' and assess what to do in that situation — much as an analog computer is continuously monitoring both its inputs and its internal state. It is no good having a robot which does not realise it is about to — or has — run into a wall because the program has not got to the wall bumping bit yet. (I am supposed to be a bit asbent-minded myself, but this is carrying 'thinking about something else' to extremes.)

Further distinctions between the payroll programs and the robot programs may be made. The payroll computer does not require any knowledge of the nature of space and time — indeed it has no 'knowledge' of what it is doing. In fact it is a classic GIGO program — input 'BLOGGS, F PAY RATE — 97.5' and poor old Fred, gets a negative pay packet and is unlikely to be

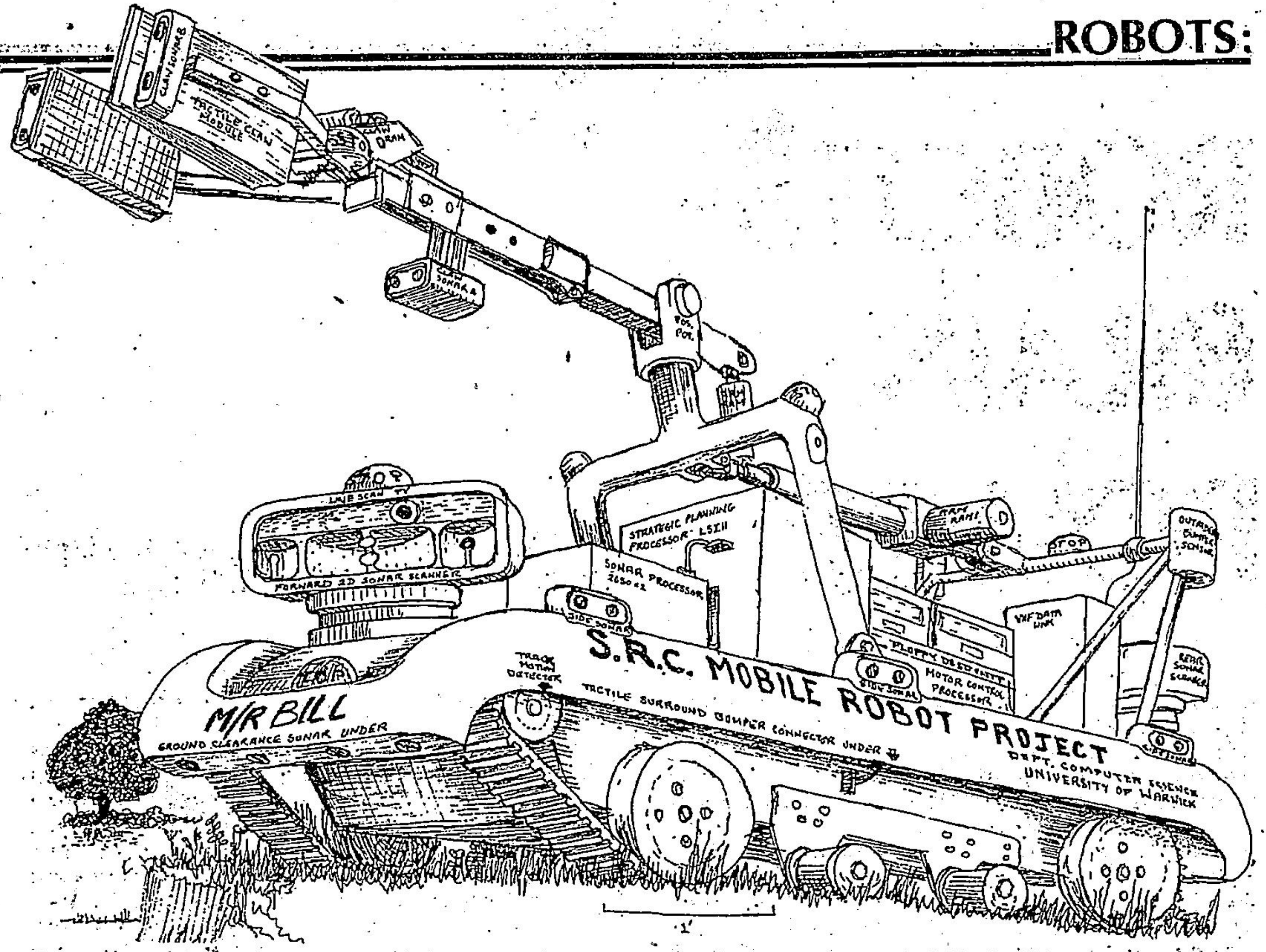


Fig. 1. Sketch of a possible research project under consideration at Warwick University, Robot Laboratory. All the various sensors have been proven individually, if they get enough money they want to prove them collectively:

mollified by the apparent tax rebate and returned National Insurance contribution. The program does not know about the positive nature of pay — much less the negative attitude of Fred.

Central to many robot programs is a set of stored information which is generally called the world model. The complexity of this model is chosen to give the robot some knowledge of the real world without giving useless information. It is no use informing a robot that trees and grass are green if it uses infra-red vision — whereas the information that grass is on the ground and trees stick out of it is useful.

The robot program need no longer take sensor or command data at face value. It compares incoming data with world model data for 'reasonableness'. If a well appears to be moving (program checks sonar range to expected wall with world model distance between computed position and wall position and finds continuous variation) the program can quickly check with other fixtures to see whether it is sliding about itself or an unknown flat intruder is present or the wall is actually moving (the latter two cases may not be distinguishable). If an external command to move forward occurs the program can first check with the world model to ensure that no obstruction is to be expected and then check during the movement that an unexpected obstruction does not exist.

The unexpected obstruction leads us into a really intriguing area of robot technology. Having found a palpably real 'thing' and perhaps having discovered a few useful facts about it (does it move if pushed? does it move by itself? is it round? how wide is it? can it be circumnavigated? does it emit ultrasound? does it emit light? etc., etc.) these facts may then be entered into the world model by the robot itself. This may seem a small step, but for robot-kind it is a giant wheel-turn. The robot's behaviour is governed by comparing the incoming data with the stored world model data, but the robot itself is modifying this data — therefore the robot is modifying its future behaviour. This is at the very least a form of learning — that is to say, it is to some extent unpredictable.

Free Will

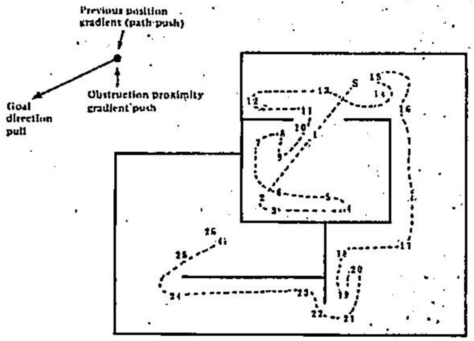
The robot is not deterministically programmed. There is an old saying about computers to the effect that the program is only as good as the programmer. In the case of robots this is no longer true in its original sense since two programmers are at work. In addition to the human programmer the totality of the robot's environment acts as a 'programmer'. Since the mechanics of the world are imprecise this second programmer never repeats is program exactly.

This indeterministic nature becomes clear when during a robot operation something surprising occurs and I am asked what is it doing. I usually have to say I do not know since the only way to find out for sure is to get the robot to explain in some way or to stop it and inspect its memory. Either way can take some time. There is a well known robot simulation program (illustrated) which deals with manipulations of stacks of geometric solids such as cubes and pyramids — the interest being that while you can stack cubes upon cubes and pyramids on cubes you cannot stack anything on a pyramid. This program has the advantage for the layman of communicating via a computer terminal in a reasonable facsimile of English. Having completed some long sequence of moves to stack a small blue cube on a big red cube (involving clearing everything on top of both cubes out of the way) the computer pauses and the programmer asks it: "Why did you move the green pyramid off the blue cube?': the computer answers 'To reach the blue cube.' The programmer probes further: 'Why did you move the yellow cube off the red cube?': the computer answers 'So that the blue cube may be placed on the red cube.' The programmer in great inquisitorial enthusiasm asks 'Why did you place the blue cube on the red cube?'. With the reserve only computers can muster, it replies 'Because you told me to.' This 'back-tracking' is relatively easy in a simulation program and the computer used was very large. However, in a small mobile robot program space is at a premium and exotic 'chatty' communication impossible. The same space premium forbids the storage of *all* events — it is necessary to build in methods of selectively removing surplus data — a forgetory if you like. This is akin to the short term memory system we appear to use: important stuff is kept and the junk is forgotten. This selective 'purging' may remove the data required for back-tracking and it may be impossible to determine why the robot behaved as it did in a particular situation.

The robot may be given a bag of problem-solving tricks for using in conjunction with its memory one of these may, for example allow it to solve the problems of getting about a maze-like environment as quickly as possible by 'mentally' finding the route before actually covering it (Fig. 2). There may be other specific strategems for manipulation and so on. At the moment of writing however, the robot is not really capable of learning new tricks for itself. This may require an extension of the world model concept to cover more of the dynamic and sequential aspects of task learning.

Here, Boy . . .

Robots are not yet capable of the full range of intelligence we expect even from an animal. They cannot learn new tricks, yet they can solve goal-seeking problems which would baffle a dog and can communicate in English with some degree of understanding. Clearly they do not fit into our usual categories for intelligence: The term 'machine intelligence' should be considered for the moment as standing apart from our normal spectrum of intelligence. When we know where to put it in that spectrum we will have learned much more about intelligence itself. Experiments with robots and in the field of Artificial Intelligence will help to elucidate this age-old puzzle of thinking. I suspect that just as in movement the robot is more likely to use wheels than legs it will use something dissimilar in structure to the brain for its 'thinking.' What is important is that as we understand the dynamic principles which govern both wheel and leg we also find the principles that govern both machine and biological intelligence. **ETI**



1 MAKES BEELINE FOR GOAL
2 WALL PROXIMITY DEFLECTS PATH
3 NEXT WALL PROXIMITY DEFLECTS PATH
4 PREVIOUS POSITION GRADIENT FALLS OFF AND OBSTRUCTION PROXIMITY & GOAL CAUSE TURNBACK
5 PATH AVOIDS PREVIOUS PATH
6 INERTIAL EFFECT OF PREVIOUS POSITION GRADIENT CARRIES IT ACROSS PREVIOUS PATH
7 CORNER CAUSES ROBOT TO TURN AGAIN
8 GOAL DIRECTION PULLING-PATH AT 7 PUSHING
9 TOO MUCH PREVIOUS PATH REPULSION ROBOT EXITS
10 AVOIDING WALL AND PREVIOUS PATH
11 GOAL PULL TURNS ROBOT
12 CORNER CAUSES FOLDBACK
13 THE DOORWAY 1 10 11 TOO FULL OF PREVIOUS POSITION REPULSION— INERTIA EFFECT CAUSES PATH CROSSING
14 15 16 DITHER CAUSED BY RAPID CHANGES IN RELATIVE IMPORTANCE OF GOAL PULL AND PATH OR OBSTRUCTION PUSH
17 CLEAR RUN DOWN WALL DIRECTED BY GOAL PULL AND OBSTRUCTION PUSH
18 19 20 FOLDBACK RESOLVED—PATH PUSH AND GOAL DIRECTION SORT IT OUT
21 22 DOORWAY NEGOTIATED BY GOAL PULL AND OBSTRUCTION PUSH
23 24 WALL FOLLOWING—INERTIAL EFFECT OF PATH PUSH OVERCOMES CHANGE IN GOAL DIRECTION
25 CLEAR HOME RUN
26 TWO JOULES OF DRAUGHT DC AND A PACKET OF CRISPS PLEASE!

Fig. 2. An example of what can happen when you tell a robot to travel from Start to Goal.

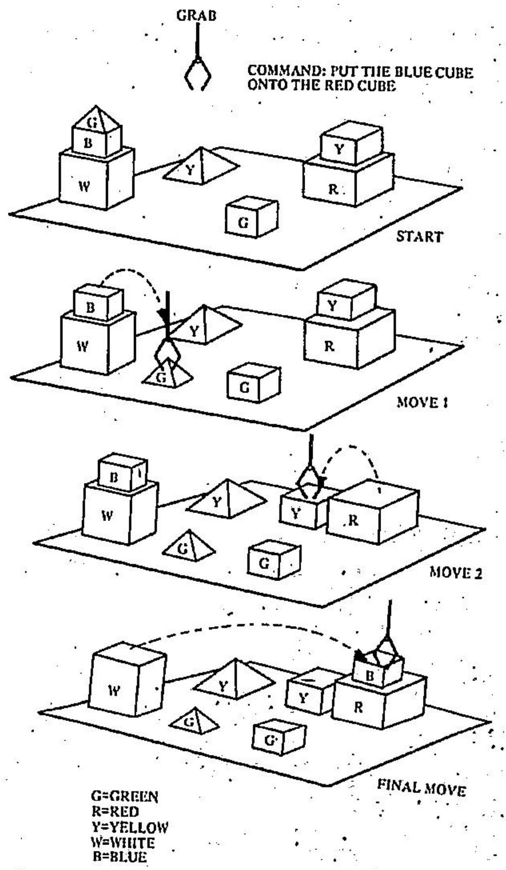


Fig. 3. The way a robot moves blocks around can lead to blunt replies from the computer:

ROBOTS~ BUILDING GUIDE

Dr Michael Larcombe of the Robot Laboratory, University of Warwick and ETI Special Correspondent Dr Peter Sydenham give a background into building your own robot.

PROBABLY THE MOST IMPORTANT thing to realise is that successful robots do not grow as can an electronic circuit development. Mechanical structures and components are vastly more time- and money-consuming to alter as changes are seen to be needed. Because of this the deficiencies of mechanical elements incorporated into a robot tend to be retained. Add a few of these shortcomings together and the device will not perform as expected.

Thus planning is vitally important from the word go. Many decisions must be made before money or time is committed to specific hardware. The ability to imagine and synthesise the finished product before it is built is the skill that humans have over the robot — so use it well.

Getting Under Way

The imaginative process of design is greatly aided by the use of diagrams, sketches, plans and written results. A tidy report file must be kept going from the start of the project.

After deciding what functions the robot is to fulfil, the next step is to develop a master system diagram of the whole, detailing the various sub-systems and their interaction with other sub-systems. Figure 1 is an example. Wherever practicable, try to develop the overall system as one built from basic system units that can be developed and tested as separate units in isolation.

Keep the master schematic block diagram updated each time major changes are incorporated. For each block, or group of blocks, there should be further diagrams showing more detail of the construction and circuitry. Even the simplest robots can soon become too complex to record as a whole. An orderly hierarchy of records is needed.

When the stage of realisation of adequately basic schematic diagrams is reached, the design can then progress to the creation of the blocks, designing each sub-unit to suit the specifications decided earlier. At this juncture (and later) several earlier decisions may turn out to be inadequate so, once the final change is agreed upon, go back and modify the master system and other blocks as is necessary.

It is always preferable to design the sub-units so that they can be tested easily. It helps build confidence in the design as they can be pre-tested before final assembly of the whole. It also makes good sense to be able to isolate a unit easily when a fault occurs that must be traced. Pre-testing gives useful test results for later comparison. Assembly should also be designed to allow all major subcomponents to be removed easily for maintenance and repair. There is nothing so frustrating as a fault occuring right down inside the structure where layer upon layer of mechanics and electronics must be removed to get to it. Make use of hinged panels, plug-in circuit boards, easily bolt-on drive and sensor assemblies with removable circuit connections. For one-off prototypes there is good sense in building in far more flexibility of assembly and disassembly than could be tolerated in a mass-produced, well-tested design. Where possible, build the working unit as a second one, retaining all developmental work for possible later comparison.

Always attempt to design sub-units so that they do not interact with other sub-units. For example, a manipulator arm must be sufficiently stiff in bending and torsion to retain its shape when loaded. If it bends, the position of the hand could differ from that indicated by position sensors which, in turn, will try to correct out an error that was not there by the ideal design standards. If the power supply droops when a load comes on to an actuator, this may alter the supply voltage to circuitry, altering the performance of other components. Where interaction results it may alter the fully-assembled units' performance in ways that are not easily discovered at the testing stage of the sub-units.

As sub-units are created their circuit drawings must be laid out neatly with all component values marked. Good mechanical sketches should be made. It is all too easy to forget that a few months later, after working on other aspects of the robot, one does not remember the detail tackled previously.

Choice of Components

As the sub-systems harden in design so will the specifications of the elements needed. They will generally be of optical, mechanical or electronic nature. At some stage each specific component must be located, if procurable, or made, if not. Circumstances will largely decide the choice. Optimally one chooses the best available unit, but in reality such factors as cost, availability, life and replaceability will force the designer to make compromises. The cheapest may suffice. Usually, but not always, the more expensive mechanical component is the best to use. Mass-produced components from construction kits and popular toys, such as aero models and model trains, are good value. Bicycles, domestic appliances and motor car parts are another source of quality low-cost assemblies. Specialised electromechanical construction kits, such as Meccano, Fisher-Technic, FAC and Presto, are easy to employ, but they can be expensive to get started with. They also can lack the rigidity of structure often needed.

One thing to avoid is the use of complex components (such as motors) that you possess already but which cannot be replaced or repaired easily.

Choice of alternatives is less important with electronics as most solid-state devices now have many roughly equivalent alternatives, but, even so, steer well clear of using devices that are not currently marketed at low cost on an extensive basis with double or more sourcing.

Structural Frames

The robot's functions are made possible through actuators and sensors causing the whole and the limbs to move as desired in a dynamic sense. The structures holding the limbs and the limbs themselves must be adequately stiff — that is, they must not deflect or twist more than is allowable under load. There is no such thing as a totally stiff structure, for no material known to man is inelastic. A basic aim of structural design for a robot is to provide an inelastic structure having minimum mass. This rule especially applies at the extremities of rotating arm-like structures where rotational inertia increases more rapidly than linear elastic deflection as the distance from the centre of rotation increases.

Elasticity of a structure can introduce many unwanted interactive couplings — weak gear train mounts may allow the gears to unmesh as the frame twists with increasing load. Smaller misalignments will usually introduce increased frictional losses.

The principle of triangulation enables rigid light structures to be built. It says that each segment of a panel or beam required to be stiff in the plane of its flatness is made from triangles of connected limbs. Open squares and rectangles must be made into triangles by the addition of a central cross member. Linear rigidity is relatively eacy to achieve; torsional rigidity is much harder to obtain for that mode of flexure requires stiffness at 45° to the linear axis.

Stiff and Floppy Members

Solid thin sheets obey the triangle rule and are always theoretically stiffer than a sheet which is lightened with holes or made from elemental bars. However, the solid, thin 2D members are rarely better than the same weight of the material re-arranged as a 3D member which will possess torsional rigidity as well.

Structures can be made incredibly stiff and light if the maker is prepared to put enough work and cunning into their design.

Triangulated structures work on the principle that members are either in direct axial torsion or compression. If in tension they can be as thin as their strength requirements allow, but if in compression a long thin member will buckle and fail well before it collapses through lack of compressive strength. Compression members are, therefore, kept as short as possible and have stiffness to increase their buckling strength. Tubes and angles are commonly used. (Think of early aircraft structures using struts and wires.)

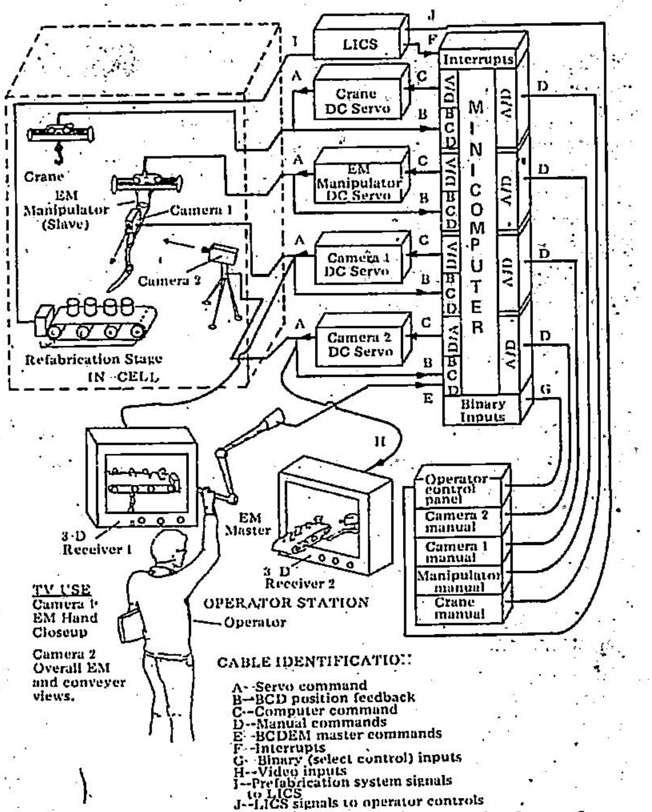


Fig. 1. Systems diagrams, like this of a manipulator for a high-temperature gas-cooled reactor in the U.S., must be kept up to date as development proceeds. Keep subsystems as seperate entities as much as possible.

Structural Choice

The choice of materials is not always easy, for light strong materials, such as aluminium alloys, are not easy to join by the amateur — rivets or bolts must be used, as welding and soldering are not possible without special equipment. Avoid pure aluminium for structures — it is too soft. Aluminium does not need a protective coating but looks better if it has one.

Steel is more easily joined by welding and hand-soldering or brazing, but, although having the greatest stiffness of common metals, it is one of the heaviest. It corrodes easily — plating or painting is a must for all steel parts of a well-made robot. It is a mistake to think steel parts can always be painted after the robot is finished — there are usually too many wires and components attached to do a good job afterwards. So paint or plate as you proceed *before* assembly.

Plastics are a relatively new element of structural design. Very respectable jobs can be made using modern adhesives and plastic formulations. The catch is that they are comparatively flexible and heat-sensitive. As they get hotter, they may sag, will certainly get more elastic and, worse still, may deteriorate completely in the long term. Great care must be exercised about the choice of plastics used.

Wooden materials have their place, but always opt for waterproof qualities that are well seasoned or treated to retain shape.

Modern glues, such as instant-epoxy kinds and filler-based epoxy resins, are often an ideal choice for fastening members. But, again, care is needed in their use. If in doubt, conduct tests on test specimens before embarking on the real job. The simplicity of glues often leads one to make quick joints that are impossible to open when the unit requires disassembly. The easy path is not always the best in the long run.

An important point often overlooked is that the robot frameworks may be subjected to excessive loads and forces during the testing and development stage. Transportation of the whole, or merely picking it up or having limbs moved by external forces such as prying children's hands, can often break assemblies that are well within their design limits of need. If this is the case, try to incorporate safety features, such as clutch drives, that will slip for excessive load.

Motoring

Most DC motors used are cylindrical in nature and use permanent magnets to supply the field needed. They will have a relatively small number of commutator segments and are best run at quite high speeds. For slow speed shafts a gearbox is needed to reduce the motor speed and increase the drive torque available. High ratio gearboxes, however, introduce backlash and friction problems that reduce the effectiveness of tight servos. Avoid high-ratio gear trains and any other kind of drive with slop in it. Worm drives can also present problems as they cannot be driven by the output shaft. The better systems use anti-backlash gear wheels, but these are expensive. High gear-up ratios amplify the rotational load inertia seen by the motor, so keep high-speed loads light if good response is needed. Fastest energy exchange occurs when the load inertia seen by the motor equals its own value — similar to the energy transfer law for electrics.

The printed armature, radial shape, motor is well suited to robot work as it has many commutator segments, great overdrive capability for use in transients and excellent low-speed performance. Gears are often unnecessary with servos built of these. Inexpensive versions are available (car fans, for example), but they usually lack a second output shaft or an inbuilt tacho. Versions with inbuilt tachos are really satisfying to use but are priced for professional robot designs.

Simple DC motors from toys are rarely adequate for long. They are not designed to last. The extra cost of better motors will be found worthwhile.

Remote Control

Control from a position away from the robot can be had most easily by using a wire link in the case of fixed manipulator machines and limited movement mobiles. Wires are certainly the cheapest and most reliable link, but in the case of mobiles and some special applications, non-contact telemetry is needed to and from the robot.

Radio control would be the obvious choice as many marketed systems are available at reasonable prices. Model aeroplane control, and more recently model car and boat controls, are easily adapted to form command links. As most robots work at power levels greater than the actuators used in model planes, it will be necessary to add power amplifier stages (relays for simple on-off control, linear amps for proportional controllers) at some convenient output point of the telemetry system.

Acoustic senders working at around 30 KHz can be used for systems needing detection from any direction of robot orientation. Optical beams are restricted as links to situations where the beam remains aligned with the robot receptor.

See Me, Feel Me . . .

The basic senses of human beings are touch, sight, hearing, smell, taste. These provide many ideas for robot sensors. Other senses exist, such as ultrasound, radio waves, infra-red and ultra-violet radiation, that are not given to humans.

When finalising a sensor stage ensure that its output signal level, impedance and frequency response suit the stage, or stages, it must drive. Most sensor outputs need amplification, and it usually makes best cost sense to use an integrated linear circuit to obtain the gain. IC stages generally have low output impedance and set voltage swing limits. Typical values will be ± 10V with a zero bus for linear devices (higher are available but are more expensive), zero bus with +5V for TTL logic and a wide range of choice for CMOS logic. There are few standards so it is not possible to categorically define signal levels. Choice of levels is, however, worth serious study before the design goes too far, as the fewer the bus voltages used the better. They must also match the chosen supply source. Try to avoid the need to create numerous bus voltages from basic supply rails — zener and series regulator units waste power.

The cost of low resolution analogue to digital and digital to analogue converters (low resolution will usually be adequate in robots) is now such that the output form of the basic sensor can easily be converted to the other signal form if it is more appropriate.

Space permits only a brief account of a few typical sensors used in robot devices.

Touch Me . . .

Simple touch sensing is easily done with a light arm or feeler that operates either a microswitch for on-off control or a linear or rotary potentiometer for proportional control. Whereas virtually instantaneous signal changes can be created in electronic circuits, the same is not true of mechanical systems. A touch-bar moved as warning that the robot must stop immediately should be able to deflect sufficiently as the unit comes to rest. Either make the bar flexible or give it a spring joint where it can bend elastically. The amount of deflection needed depends upon braking effort, speed of robot and its mass. As a guide, a 20kg unit moving at walking pace and being braked by a reversed connection 100W motor may require as much as 50-100 cm of overtravel, depending upon the frictional force existing between its wheels and the surface it is on (decided by coefficient of friction, weight on the wheel and braking force on the wheel axle).

Tactile sensing, such as is needed to control the clamping force of a closing hand, requires proportional measurement of closure force.

A rubber or plastic tube filled with air makes a good protective buffer. Addition of a pressure-sensitive switch into an outlet enables the buffer to cut power supplies or reverse the velocity drive. Obviously, imagination and innovation can produce many more touch sensors.

See Me

Human sight is sensitive to only a very narrow band of the available electromagnetic radiation spectrum. Robot 'sight' can extend much further to make use of infra-red and radio frequencies as well as those in the visible region. Certain infra-red sensors can detect the thermal radiation of room temperature bodies and resolve them

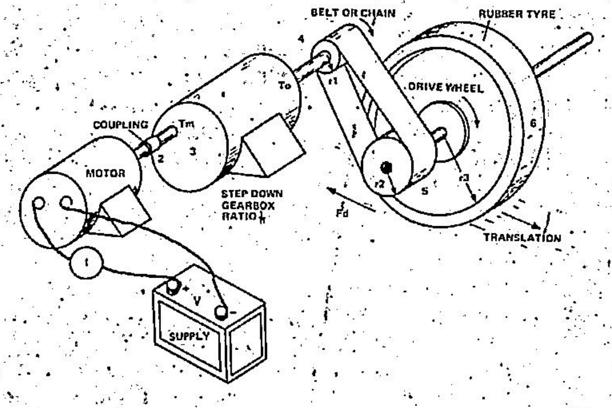


Table 2: Calculations for a hypothetical drive system

At 1 Power input = V.I = W

At 2 Power from motor = W. motor efficiency = W. Torque at output shaft Tm from data sheets

At 3 Coupling may lose up to 5% of energy transfer, but not torque unless slip occurs

At 4 Torque at gearbox output To = Tm × n

Shaft speed $= \frac{\text{Input shaft speed}}{n}$

Power available = Power at input × Gearbox efficiency.

At 5 Torque at wheel shaft = gearbox output torque $\frac{r_2}{r_1}$

Wheel speed = gearbox output shaft speed. $\frac{r_1}{r_2}$

Power to move robot = power out of gearbox × efficiency of belt or cahin drive

At 6 Force at wheel perimeter

$$\frac{\text{shaft torque}}{r_3} = F_D$$

Power available is as at 5 unless bearings lossy

Speed of robot translation = wheel speed $\times 2\pi r_3 \times$ slippage allowance

Force of translation = F_D × coeff of friction × load vertically on wheel

against backgrounds at a different temperature. If at the same temperature as the background, however, the object can go undetected. This effect, called 'washout,' exemplifies just one of the many kinds of sight problems that robots need to tackle. Most worthwhile seeing conditions resolve to those of pattern recognition once the 'visual' picture is transduced by appropriate sensors into electrical signals. In robots the higher order seeing problems to be tackled require extensive data processing facility. The microprocessor now promises to provide the kind of power needed at realistic prices for amateur robot projects.

The easiest to invent and build is the photodetector that responds to an increased intensity source using the DC level change as the sensed signal. This kind of sensor is suitable to move the robot toward or away from bright lights or to increase or decrease its activity as the ambient light level changes. It is of little value in applications where the robot has to seek out a certain 'marked' place or beacon or follow a moving light marker.

In these cases, the source light can be coded by amplitude modulating it to at least 10% depth at some convenient frequency which is not a multiple of mains frequency (or it may well fall in love with all fluorescent and incandescent mains-fed lights).

Similar principles work for infra-red and microwave and also for acoustic methods. Seeing is usually taken to mean line-of-sight working only. Strategies may have to be programmed to ensure the robot obtains a line of sight long enough for it to learn of the direction to move to. (A sample and hold store of position is a must for such applications.) Modulated systems, although generally unresponsive to moderate ambient background illumination, will usually be affected by severe ambient levels, for these may saturate the circuitry. In such cases the output produced should be a fail-safe kind. (Many a robot has been camera-shy when powerful flood lights are turned on for the public debut on television or film.)

Hear Me . . .

Sound waves behave in much the same way as electromagnetic waves, but with one big exception — they travel much slower. For this reason acoustic senses and senders are a popular choice for robot sense of position and for detecting presence. Their use is mostly based on the radar principle of sending a pulse (or continuous wave) and monitoring the time (or phase) delay of its return. Acoustic radars give good positional sensitivity at room and workshop size ranges. Use of ultrasonic (above the 20 kHz limit of human hearing) frequencies help avoid signal-to-npise ratio problems in acoustically noisy environments. Beware, however, of ultrasonic sources produced by machinery.

An array of inexpensive piezo-electric crystal receivers mounted in a pattern across the breadth and width of the robot frame can, after some signal processing, detect the location of a single source. Two units mounted on a tracking robot antenna can be used as a binaural position sensor. A single send-cum-receive unit mounted on the robot is capable of locating obstacles for a survival mode of robot operation.

Smell Me, Taste Me . . .

Of the human senses these two have barely been developed in hardware form. Both are related to the presence of chemicals and therefore the methods of chemical analytical instrumentation are relevant. However, few analysers exist that are cheap enough for the hobbyist pocket. Certain measurements, such as CO_2, CO and O_2 detection, can be achieved cheaply by sensing a simple effect of these gases on the temperature of a heated resistance (CO_2, CO) or via the voltage generated by a special cell (O_2). Smoke is more easily sensed as an attenuator of light than by the presence of its chemicals. An analyser capable of detecting smells such as rotten fruit, individual people, or the finest perfumes requires the use of a mass spectrum analyser or other sophisticated methods costing huge amounts of ▶

money and weighing many kilograms. In short, smell and taste are not very profitable senses to use as yet. An exception is robots already made commercially that seek out the centre of fires for extinguishing purposes.

Acting Out a Role

Sensors produce the input signals tell the robot what is happening. To get the robot to act on such commands these signals are processed and used to drive power output devices, called actuators. These convert, in the main, the power source energy into mechanical work. Actuators for robots usually require electrical signal (analogue or digital) inputs providing linear or rotary motion via wheels, gears, belts, tracks and what have you to do work.

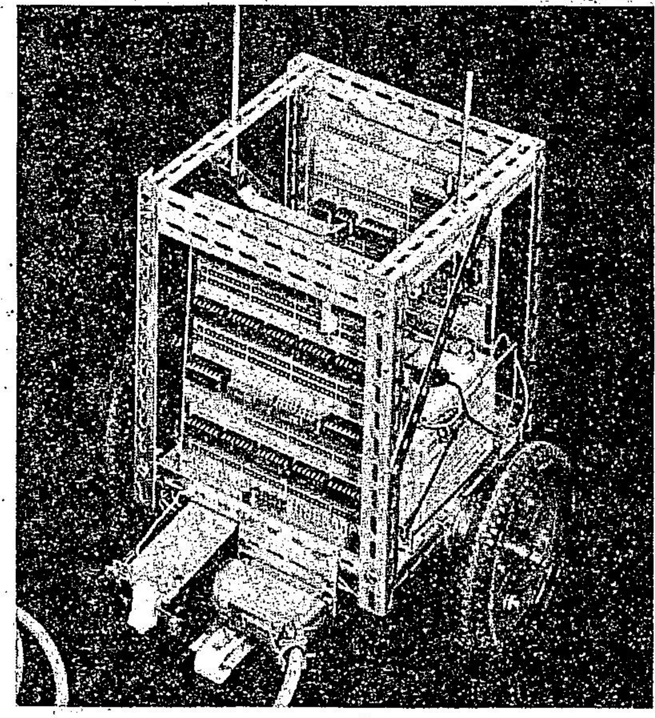
Robots require motions that give speeds and positions. Basic motions needed, depending upon use, are continuous linear motion (wheels driven by motors, cables would up by motors, rack and pinion), short-stroke linear motion (solenoids, restricted length rack and pinion), unlimited rotary motion (direct motor output, geared up or down motor motion), and limited angle rotation (rotary solenoids called torquers, pinion and wheel or rack). Chains, belts, pulley and flat flexible strips are elements used to provide various kinds of motion, including converting rotary motion to linear and vice-versa. The commonest and cheapest actuators are solenoids and motors. Where controlled variable torque is needed, DC systems are usually used.

Wheels are predominantly used to move mobiles. Walking is a spectacular method, but is far more difficult to design. Wheeled systems must be able to steer easily — car-like methods require intricate movements to escape a blind corner. Rapid response drives will require as much of the robot's weight on driven wheels as is possible. All wheels supporting weight but not being driven reduce the tractive effort available. The coefficient of friction of drive surfaces must be chosen to suit each application, or else excessive wheel spin will occur.

Open and Closed Loop

At this point it is worth devoting some time to the concept of closed-loop actuator systems, for all worthwhile robots use these. The reason is as follows: Consider a small motor coupled to drive a robot via wheels through a step-down gearbox. To get the robot moving requires more initial power than when it is running under steady load because friction of the static drive is greater than when running. Thus, as soon as it begins to move, the input must be reduced or else it tears away. Also, when the robot comes to a rise, the input voltage setting must be increased to give more power. This kind of controller is called an open-loop case. The real aim is usually to have the robot run at any given time at a steady known speed, over the range from zero to full speed, for all conditions of load.

This is done in a closed-loop system by sensing the actual speed of the motor (in electrical terms, by generating a voltage with a separate generator called a tacho coupled to the motor shaft) and comparing this value with that which represents the desired speed. The difference, called the error signal, is used to increase (or decrease) the motor current so as to bring the speed up (or down) to the correct value, where the generator output equals the reference level. Motor speed will, within available power limits, be held closely at that set by the input reference voltage level, despite changes in load. If the motor current can be reversed by the circuitry, a command for zero speed (zero reference voltage) given at, say, full speed, will attempt to reverse the motor giving quite impressive braking. As the speed approaches zero due to the braking, the error falls to zero and the motor comes to rest.



Good servos can provide tight control with rapid response to new commands. Their slight disadvantages are a need for a more sophisticated (but well worthwhile) system that costs a little more if the right motor is chosen, the chance of instability if it is too highly tuned and the possibility of having too responsive an action that may shear parts and slop liquids (but at least this is easily slugged or smoothed by appropriate integration of the error signal within the control loop). Overall, however, the performance of a closed-loop servo is vastly superior to the open-loop equivalent.

Position Servo-Systems

Position controls also should be closed-loop in operation. Here the actuator that brings about a positional change is fed an error signal generated from a position-sensitive sensor. An arm elbow joint, for example, would have a potentiometer rotating at its pivot axis. The voltage produced by the potentiometer is compared with the given reference signal providing the error to drive the actuator accordingly. This servo will ensure that the arm goes to the angle desired by the input reference voltage value, regardless of load (within limits of maximum load capability). If the arm overshoots the correct position, the error reverses bringing it back by reversing the actuator. Servos can be adjusted to approach the final value in a quick fashion with overshoots, or slowly without overshoot.

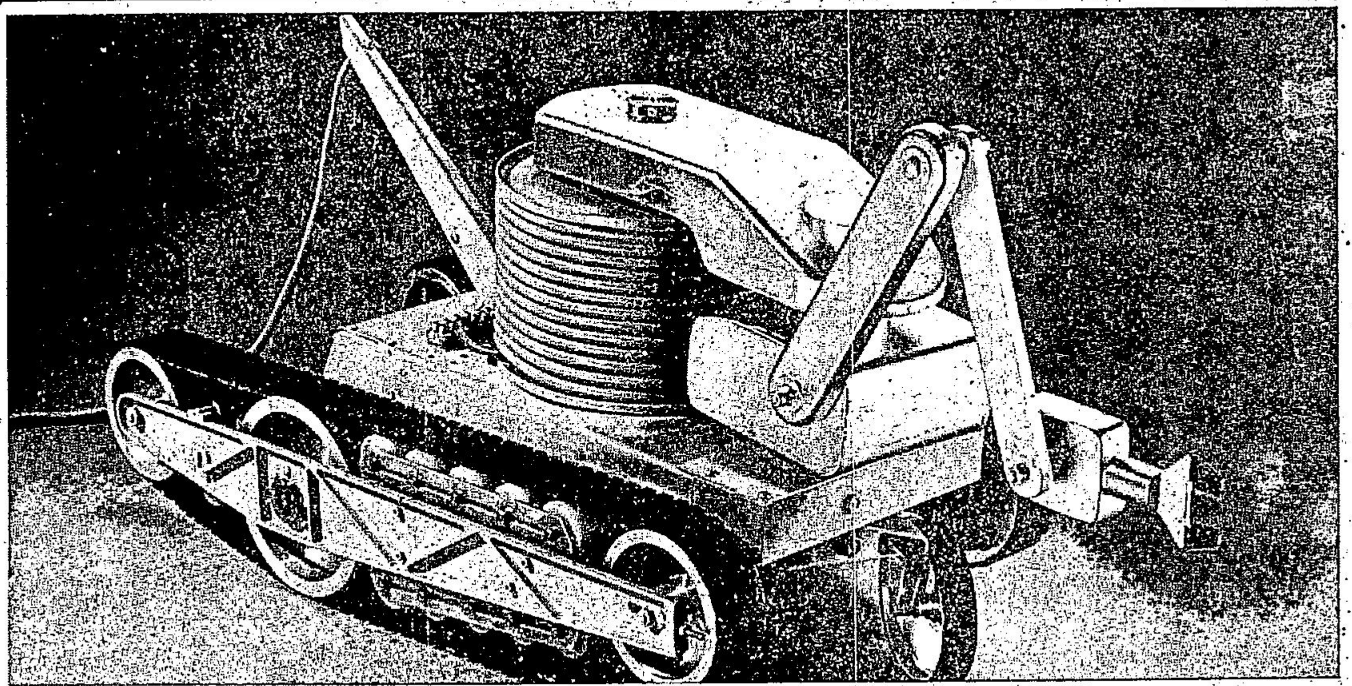


Fig. 2. (left). HORACE, a Warwick University Robot Laboratory mobile, is simple to make and uses commercial parts. Robots like this are well within the scope of amateurs. Note, the ease of access to parts.

Fig. 3. This working model of RIVET explores an ingenious method of transport. It can go over obstacles twice its own height

Position servos benefit by the use of a tachogenerator driven by actuator. The tacho signal is used to feed a rate of error reduction signal into the closed loop, making it move faster when wildly wrong in position and slower when nearly at the correct place, thereby giving it a chance to stop at the right place. This mechanism is known as damping.

As the gain around the servo loop is increased, the response gets tighter, smartening up. However, a point is eventually reached when the loop will begin to oscillate, first giving small dither around the correct place and then as the gain is further increased, rising to massive oscillations. Reducing the gain is the easiest way to combat this but not the cleverest. Compensation is the technical name used for the process of adding an integration and/or derivative of the error signal to the error so as to obtain higher gain with reasonable stability. The tacho of a position-servo does just that. Explanation of this is beyond this account, but is well treated in many books on linear control systems. The above explanation is somewhat simplistic but adequate as a basis. In reality the velocity servo described will run at slightly lower speeds than called up, as an error must exist to generate the torque needed to hold the speed.

Final Testing and Maintenance

The development of the robot should proceed in an orderly manner, each sub-unit being pretested and made as acceptable as thought necessary before final assembly begins. As each unit is added to the final whole, checks should be run to see that it still works as it should. See that the other units still work properly, as unexpected interaction is common in robot development. It is much easier to test for this as you go from stage to stage than to try and find which unit alters what at the end. As defects are detected — bugs always occur — rectify them before moving on. There is a natural tendency to rush on to the apparent end, only to be disappointed because it does not work properly. In other words, be patient; it is worth it.

Once the whole robot is "all systems go", the next stage is to conduct some field-trials. Put it through its paces doing the tasks it was intended to, but in situations where damage is minimized if the behaviour is not as expected.

Monitor the initial hours of work carefully looking for overheating of electronic and mechanical components, and listening for odd mechanical noises that indicate too much slop or friction. These may lead to premature failure if left unmodified. Limbs and other members that appear weak are more easily strengthened before they break than after! Smoothness of operational sound is a good indicator of satisfactory mechanical design.

Unlike electronic circuits that, once made, are initially maintenance-free except for faults, dynamic mechanical systems require regular attention. Lubricate bearings, slides, cables and pivots regularly, but do not overdo the oil or grease. Dry graphite may be better than oil in some applications. Areas of wear will need adjustment with use. Build this into the design to begin with, where possible, as retrofit is always harder.

Too often ignored is the final documentation. When the project is seen as complete, go back to the master diagram and files on the whole system and sub-system modules and update them to the latest stage. If you feel the robot will be used regularly over several years, or if it was built for the use of someone else, it is imperative that the documentation is readable, neat and complete enough to be a good guide to someone else at a time after its details have been forgotten by its builder.

Creating a robot is fascinating and rewarding. How well it operates is a matter of your design sense plus ability to execute the design in a professional manner. We hope the above, albeit brief, introduction will help, and wish all robot constructors rewarding, successful projects. **ETI**

ROBOTS~ THE REAL THRING!

Specials Editor Jim Perry travelled to Queen Mary College, London, to interview one of the pioneers of Robotics — Professor M. W. Thring.

Could you give ETI readers a short autobiography?

Well, I started life as a combustion expert, concerned with the combustion of coal and other fuels, also furnace design.

Then I became Professor of Fuel Technology and Chemical Engineering at Sheffield University, about twenty years ago. I began to get interested in robots; well, I was, strictly speaking, interested in robots as a small boy! I used to design them when I was quite young — but of course in those days there was no electronics, so they were all mechanical. Complex devices so that vibration into an ear released triggers and things.

Then I came back to it again at Sheffield. I was very concerned with the very real problem of highly trained men having to spend a large part of their lives doing work that did not use their intellectual training to the full. Especially in the case of the housewife, so I tried to design a domestic robot. I thought about it for many years and it has had one or two good applications. The most important of which was the fact that I developed a stair-climbing wheelchair for cripples. This was because I realised that a domestic robot would have to climb stairs!

The more I thought about the idea of a domestic robot, the more I decided to go in a different direction, for two reasons — one is that I'm very, very impressed by the incredible skill of the trained human hand / eye / body combination, which takes ten to twenty years to train and then can do sophisticated things. These capabilities are far away from anything we could do with a computer or artificial intelligence. This was a problem too difficult to hope to solve in my lifetime.

Secondly I have become more and more concerned with the unemployment problem. The principle object of robots, at present, is to throw people out of work by replacing them with robots.

I realised that the most important thing I could aim for in my life would be to try and get a method of mining solid coal without men underground.

This being a dangerous task and you having experience in coal technology?

Yes, up to four-fifths of the coal deposits are beyond the reach of conventional mining techniques.

So this led you to specialise in Telechirics?

Yes, Telechirics — or 'hands at distance' — was a solution that already existed. Although the primary development had been for nuclear work, also in space work and more recently undersea.

I would say that Telechirics is in the same position that computers were in about 20 years ago. Ultimately they could be of greater value to humanity than computers have been.

What other uses for Telechiric machines can you envisage?

One other use will be for microscopic work. Where you would have hands one tenth the size of a mans, with a magnification system, so that the operator would see and feel an object ten times larger than it was.

Another very important application will be in the field of surgery. Not only could you have the magnification, you could also have the patient in a sterile room.

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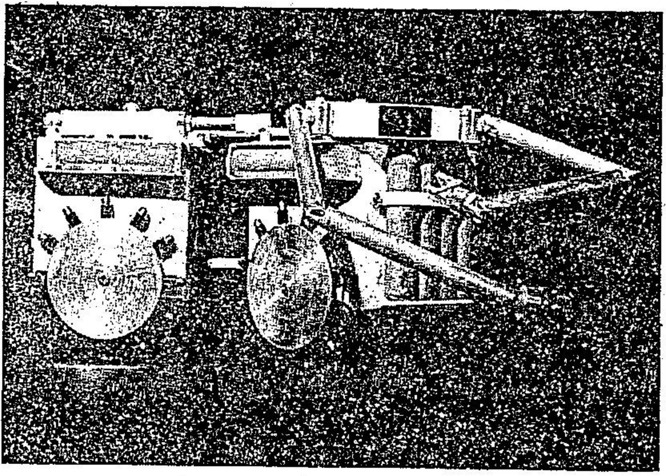

Fig. 1. A model of one of Professor Thring's robot coalminers.

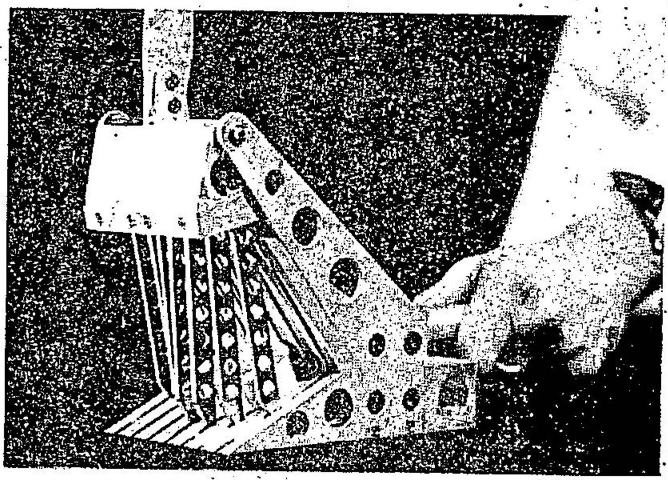

Fig. 2. Prototype mechanical hand for use with robots.

The techniques used in Telechiric machines have applications in the broader field of Robotics, how advanced is the mechanical side?

A great deal of work has been done on this, although I would say not enough yet. The biggest problem is that hydraulic systems are probably the best way of replacing human muscles — but on the other hand the control system must be electronic. We need much more work on the interface between them.

Where is research and development being done?

In Telechirics there is not nearly enough research, in fact there is practically no research in this country at all, at the moment. There is a great deal in France and America with some being done in Japan — most of this research is being done in connection with nuclear work.

What is the main advantage of Telechiric machines over Robotic machines?

Robots and automated machines breakdown, and they always breakdown in unexpected ways. Telechiric machines have the advantage that a human operator is there, at the other end, and can take appropriate corrective action.

How would you define the various Robotic and Telechiric machines?

I define all kinds of humaniod machine under three categories. First of all artificial limbs, including exoskeletons which can give great strength, where the human is in a one to one relationship with the machine.

The second group is Robotics, where there is a computer as the fundamental brain of the system. The computer carries out programs written by humans. A limitation is that we can never put the emotional brain of a human into a computer, also it will be very difficult to get the visual/mechanical relationship as good as a human's.

Perhaps most important, Robots will not be able to cope with the unexpected. Human beings have a remarkable ability to improvise in unexpected circumstances. I do not think that you will ever be able to put this into a computer and therefore into a Robot.

The third group is Telechirics, there may well be a large element of Robotics connected with the Telechiric machine. For example you may give it a small computer, so that when the man on the surface tells it to go in a certain direction — it will for example count obstacles and possibly even avoid them.

Do you think we will ever be able to use materials similar to the body in construction of machines?

As for as constructional materials are concerned, we have available engineering materials — which are much stronger and capable of exerting much greater forces than the human system.

The human system has some things that we will probably never be able to build. A muscle can carry out chemical reactions in every single cell of it, to produce work without heat — which the engineer can not do.

But it is the brain of the human that is way ahead of anything we can ever do — by brain I mean both intellectual and emotional brain.

What do you consider the best example of Telechirics or Robotics?

Well there are many, many what I call 'senseless robots' in use all over the place, the first example was the Unimate. There is a great deal of work on 'sensed Robots', in fact it has been going on for 20 years. I don't know of a 'sensed' Robot that is doing a complete job.

As far as Telechirics are concerned I think the one developed by General Electric in America, and the one which was started by various people in America and now is being developed in Paris are the most advanced.

What do you think about amateurs experimenting in Telechirics and Robotics?

I've seen several people who have done remarkable things in this way at home. It is a very fascinating hobby. But it is a bit like say, designing your own computer and making it at home. You cannot really compete with the large organisations because of the rather sophisticated engineering needed. As a hobby for fun yes, but I do not see it as a real solution to the problem.

Thank you for your time, Professor Thring, it has been a most interesting talk.