# Robots: sense & sensibility

## Part 3 of Mark Witkowski's robotics series tackles the problem of equipping a machine with the five senses

MAN and the higher animals are often said to have five senses: sight, hearing, touch, taste and smell. These are concentrated about the head in the eyes, ears, skin, mouth and nose. Information that comes from these organs allows us, and all living creatures, to react positively in an uncertain environment.

On the other hand, it is common practice in industrial robotics to modify the world so that it conforms to the requirements of the machine so little or no sensory information is needed. When the robot is used for welding or paint-spraying, this scheme works well, since much skill in these tasks is in maintaining a sufficient degree of consistency and repeatability in the quality of the work.

When robots are used for tasks where it is not possible to predetermine the environment totally, the control algorithm of the machine must be continually modified to take into account these variations.

Production-line assembly of units from their component parts is a typical example. Small items must be picked up, often from random piles of similar objects, oriented and placed in the correct position on the workpiece. Because it is difficult to ensure that each component arrives at the workstation in a predictable way, the robot has not yet been widely used in assembly tasks, which generally remains the province of unskilled human labour.

The next generation of industrial robots will be equipped with a great many more sensing devices which will make them useful for tasks other than a limited range of fixed-sequence operations. They will increasingly be able to act correctly in a wide range of unpredictable environments — doing the right thing at the right time.

A machine must possess 'human-like' sensory faculties in order to qualify as a robot. They are an essential link between the world and a computer program that emulates intelligence. Until recently, the trend in robotics has been to describe sensors only in relation to a specific robot or robot task. In many cases a robot will only have one or two sensor inputs, but as robotics matures this will change.

Larcombe (1979) has looked at the sensor requirements for a mobile industrial robot and Wang and Will (1978) describe a range of sensors for a fixed-base manipulator system.

Robots must currently use different sensors from those that people use. We place considerable reliance on sight, which is currently too computationally expensive to be used to a great extent in current robot practice. Plenty of research is being done on robot vision, though, which I shall examine later in the series.

Hearing, smell and taste are also not of much value in robotics, although one might reconsider if a robot intended to be a chef. Touch — tactile and proximity sensing — have an important role to play; this review of some of the current ideas will concentrate on this and 'proprioceptive' sensing.

Proprioception is a genuine and undisputed 'sixth' sense we have — that concerned with monitoring the internal state of our bodies. It monitors hunger, body temperature, muscle extension and force and joint position. Similar information about a robot is required by a robot-controlling algorithm.

### Fine-tuned sensors

Robot sensors may either be general, to allow the machine to cope with many tasks, or they may be specific to one task only, and must be changed when the robot moves on to another job. The advantage of the latter method is that sensors can be carefully tuned to the situation they are to detect. Furthermore they can be made to give a clear, preferably binary, output that unambiguously triggers the next sequence or robot behaviour with a minimum of computational expense or complexity.

The advantage of general sensors lies in their flexibility since each new job requires only reprogramming for a different combination of existing sensor hardware.

Information they provide, in addition to the minimum actually required, can then also be used to monitor and warn of malfunctions that the simple sensor would miss. These gains are offset by the extra expense, number of things to fail and a huge increase in the skill required in programming the robot.

In some applications, the general sensor scheme is essential. For instance: robots used for artificial intelligence research, or those used in remote manipulation telechiric control must have it, particularly if there is no direct visual contact between man and machine. Improved sensors will allow robots to tackle more complex tasks at greater speeds with less modification to their environment and with greater safety for those people that have to work in close proximity to them.

All mobile vehicle robots and manipulators require sensing to some degree. The minimum would be a mechanically precise pick-and-place manipulator that only requires a single interlock with the machine that feeds it parts.

Sensors that warn of impending collision are among the most important on a mobile robot vehicle. In all but the most tightly controlled environments this is essential since most useful robots are large, heavy and fast enough to make them potentially dangerous; 'if it hits it, it will break it' is a sensible maxim.

Proximity and touch sensors can be divided into three distinct groups: those that work over a long range, say greater than six inches; those that function closer than six inches yet involve no actual physical contact; and those that work by actual contact.

Long-range sensing will be of use in obstacle avoidance and route planning. Medium-range should allow sufficient time for the vehicle or manipulator to slow down and could be used to guide the robot or arm until contact is made. The last group of sensors will indicate the extent and area of contact and possibly the amount of force being applied, either by the robot on an object, or by the object on the robot.

Ultrasonic rangefinding is a popular method

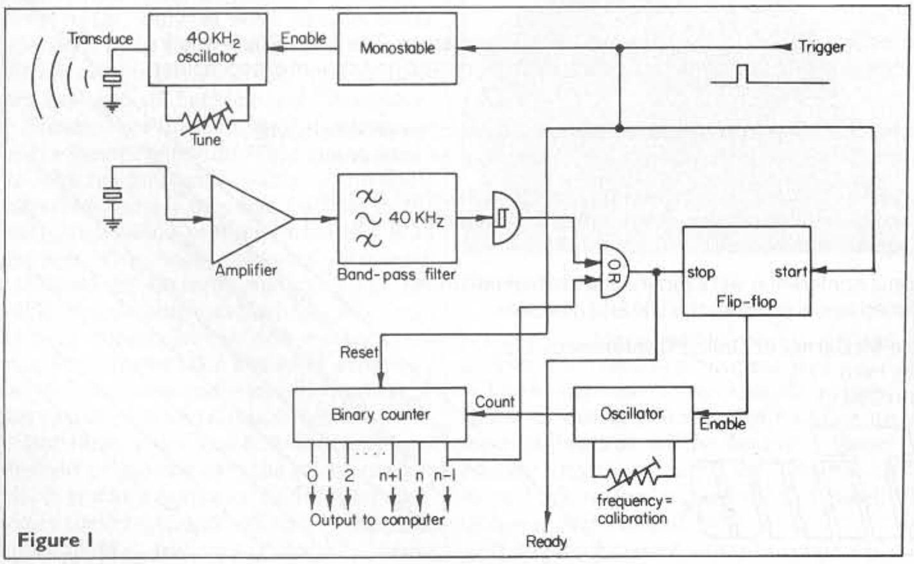


**Figure I**

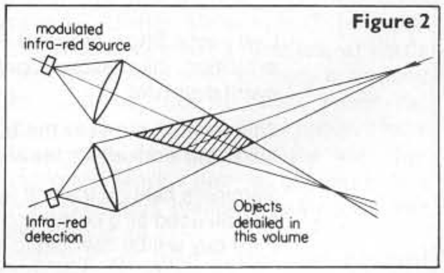


**Figure 2**

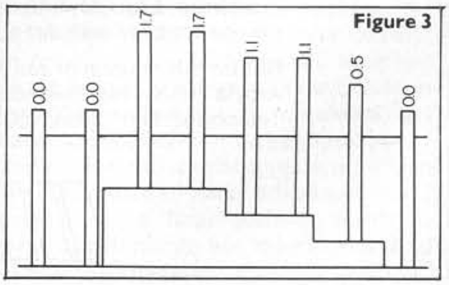


**Figure 3**

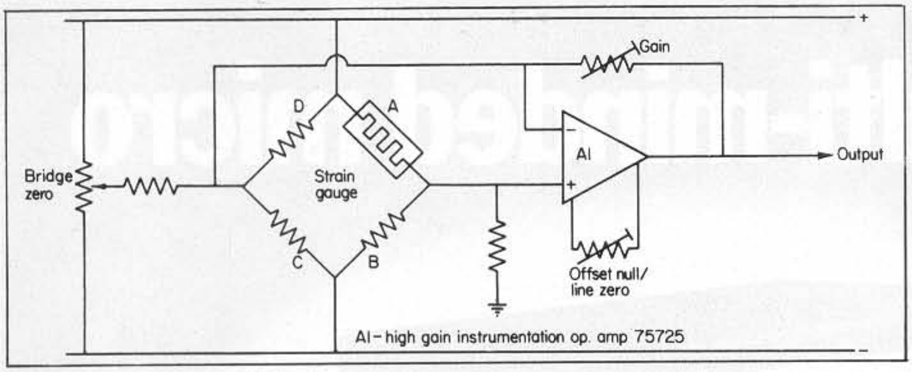
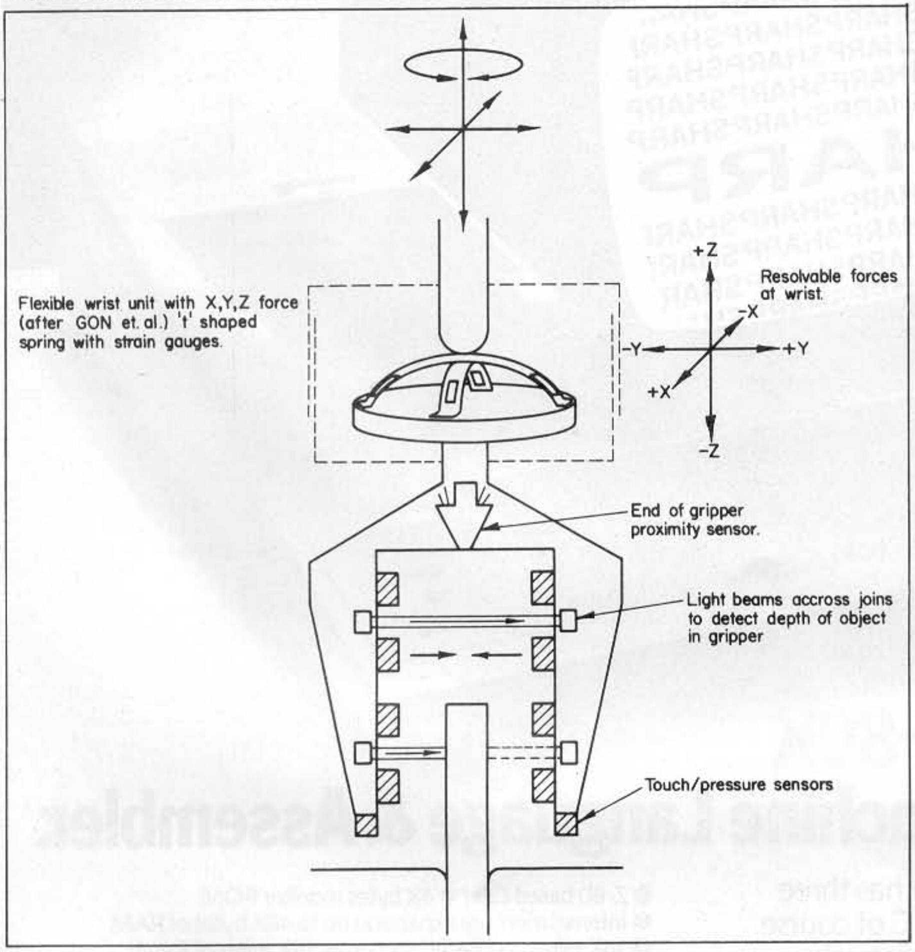


**Figure 4 (above); figure 5 (below)**



of long-distance object detection. It has been used on several robot vehicles to provide obstacle avoidance and on manipulators to give 'range-imaging' (eg Loofbourrow's 'MIKE'). A brief burst of ultrasound ( > 20KHz) is transmitted from a crystal or piezoelectric transducer and any echo caused by the sound being reflected from an object is timed to indicate a distance. (The speed of sound in air is about 300 metres per second).

**Figure 1** shows a block diagram of an ultrasonic ranging system. When the monostable is triggered, it enables the transmitter oscillator for a number of cycles (typically 10 at 40KHz). This signal powers the transmitting transducer.

The same signal also sets a flip-flop which starts a second oscillator that feeds into a n-stage binary counter which has been reset to zero by the trigger pulse. This second oscillator continues to count until the echo returns.

When the pulse is detected by the receiver transducer, it is amplified, bandpass-filtered to remove unwanted signals and used to halt the counting oscillator by re-resetting the flip-flop. The binary result at the outputs of the counter is directly proportional to the distance to the object that caused the echo. Calibration is effected by altering the frequency of the second oscillator.

If there is no echo, the transition of the n + 1th bit is used to halt the second oscillator; this bit remains set while the data is read, indicating a null result. National Semiconductor manufacture a single-chip device that incorporates the transmitter and receiver sections and includes a switch so that only one transducer is required, the LM1812 (see manufacturer's information).

Higher frequences of ultrasound allow a higher resolution because of the shorter wavelength and can be used in narrower beams offering greater selectivity. Longer wavelengths are less attenuated by air and are effective over longer distances. The 270KHz system described by Wang and Will has a seven degree cone on both transmitter and receiver, which gives sufficient resolution to allow contour maps to be generated with the system.

Several refinements to this technique are possible: phased arrays, analysis of the complex waveform returned by several objects or objects that are not flat. The latter has been used as an acoustic aid for the blind known as 'seeing with ears' (Kay 1979 and Boys *et al* 1979). Unfortunately the pattern-recognition problems when trying to analyse these signals by computer will doubtless prove to be no easier than analysing picture information.

## Ultrasound ranging

Ultrasound merits further research — one should not forget how effectively bats use sound. In many species it has totally replaced sight, with no apparent loss of ability.

Simple ultrasound ranging devices do have their disadvantages. They can be prone to acoustic interference, though filtering the received signal helps; they are not very selective, though broad coverage may be desired. Some surfaces absorb ultrasound, while all flat surfaces act as acoustic mirrors and specular reflection is a major cause of huge surfaces being missed.

As with radar, the returned signal falls off in power with a fourth law with distance, so sensitive receiver amplifiers can be swamped by echoes from nearby objects. It should also be remembered that many domestic animals and pets, such as rodents, cats and dogs can hear these sounds and they could be discomfited by high-intensity ultrasound.

Time-of-flight range finders using light or radio waves are not used much in robotics as the flight time is in the order of nanoseconds per foot. However, optical triangulation techniques are used for rangefinging and a chip is manufactured that performs a correlation on two images, producing a minimal signal when the two are superimposed. The triangulation reflector is scanned back and forth and the signal is used to servo the focus lens of a camera. This system has been incorporated in the recently announced Sankyo ES.44XL VAF ciné camera (see manufacturer's information).

## Doppler microwaves

Doppler microwave modules could find application in long distance robot sensing. Although they provide no useful range information, they are highly sensitive to movement, both of the vehicle on which they are mounted and objects in the environment. Here again, the signal would be confused and difficult to interpret, but they may have value as a safety sensor when people must work in close proximity to a robot.

Proximity sensing — indications of external objects less than 12 inches away — offers several possibilities for sensor design. Several designs are based on optical methods. In principle light, either infra-red or visible, is focussed on a point in space some inches away from the robot surface (Pond 1979). Any light returned from that point is focussed on a photosensor. While there is no object at that point, the light returned will be negligible; when an object is at the exact point of focus, the returned signal will be at its maximum **(figure two).**

This system is very selective but certain surfaces will reflect the light poorly and transparent objects pose a particular problem. Furthermore, this type of senor is sensitive to other sources of light that may be of much greater intensity than the transmitter. It is

*continued on page 89*

*continued from page 87*

usual to modulate the outgoing beam and to ensure that the receiver is only actuated by light modulated in that way, either using bandpass filters or by employing a tone-decoding phase-locked loop such as the NE567 device.

Texas Instruments produce an infra-red led/phototransistor pair mounted in the same housing and angled to give maximum optical coupling when an object reflects the light at a distance of 0.2in — the TIL139. **Photograph one** shows a similar device. (The 14-pin dil indicates the size).

This device may well be of special interest to Micromouse builders as it would be ideal for detecting the red-painted tops of the run walls. By using the signals from several of these, the mouse could be steered and could also locate branches in the maze. If you expect your mouse to be on television, the beam *must* be modulated, since their lighting is notorious for upsetting equipment.

## Proximity sensors

Proximity sensors are available that will detect most materials by capacitive or inductive changes as the sensor head is brought close to the object. Such devices are used in some standard industrial applications and so are available in commercial grade housings. This makes them suitably robust, though not always very cheap. They are not entirely suitable as general purpose sensors due to wide variations in response to different materials. Inductive types respond to most metals; capacitive types will also respond to non-metallic materials such as wood or PVC. Fluidic sensors are also used in commercial applications.

Zero-range — actual contact — sensors can be either binary or analogue. A microswitch is a cheap and readily obtainable touch sensor, that comes in a good range of sizes, types and actuating forces. **Photograph two** shows one of eight microswitches being used to provide all-round touch sensing on a small robot.

Each of the robot's four sides has a pair of switches joined together by a length of phosphor-bronze strip. The strip is loosely bolted to the switch lever so they can be operated independently, according to where the object touches the vehicle.

This arrangement detects most obstacles at floor level — anything that juts out above the level of the switches should be removed from the vehicle's environment. Notice how the ends of the connecting strip have been bent out; it works best that way.

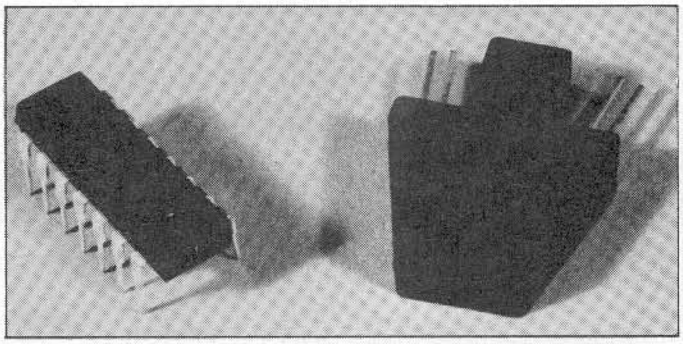
Tactile resolution can be increased by fitting more switches to the surface of the machine, or by fabricating a special-purpose matrix or strip of sensing devices. **Photograph three** shows a line of 16 experimental touch sensors.

## Tactile resolution

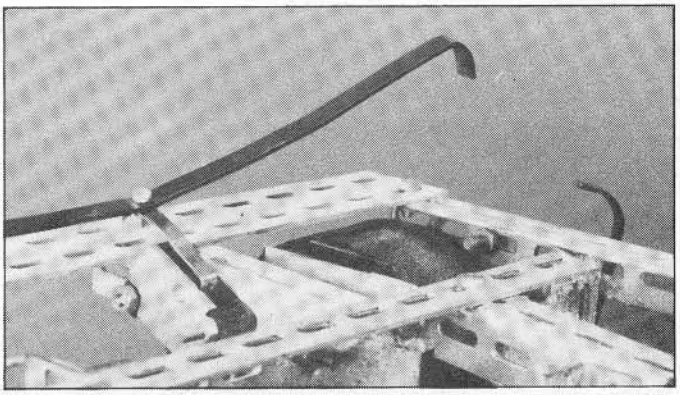
Carbonised conductive foam, as used to store CMOS devices, is mounted between two conducting surfaces made from printed circuit material. The conductivity of this material increases with the degree of compression. This change of resistance is easily converted to a voltage and fed to a microprocessor.

Several problems prevented the use of this system. The most serious was that the foam became unstable after it had been cycled many times. The material is also rather stiff, and while one segment worked well (for a time), when the vehicle was asked to compress many segments, the change in each individual segment was too small to give a useful signal. However, the idea may be revived for a larger, more powerful vehicle. Larcombe (1976) has also designed arrays of tactile sensors.

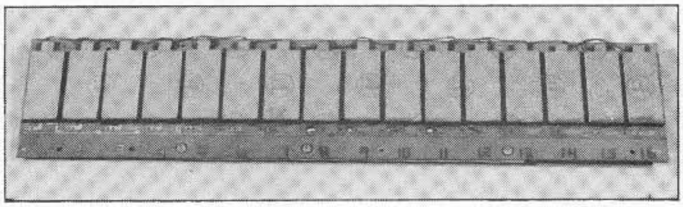
**Picture 1: Infra-red/led phototransistor pair (right) of special interest to Micromouse builders**



**Picture 2: One of eight microswitches used to provide all-round touch sensing on a small robot**



**Picture 3: Special-purpose strip of 16 experimental touch sensors**



Pugh, Heginbotham and Page (1977) describe a matrix contact sensor in which a plate is drilled with holes in which a number of ferrous rods may slide up and down. When the plate is lowered onto an object, the rods are pushed up through the plate to a depth proportional to the height of the object at that point. The displacement of each rod is measure by the depth it has entered a coil (**figure three**). A contour map of the object is thus rapidly formed.

Grids of tactile sensors are of particular importance on the inside of gripper jaws, as they indicate to the system when an object has been touched, and also that it is correctly oriented in the jaws. Ueda *et al* (1976) uses a similar idea, with only a single rod, to measure distance in robot welding tasks — a distance measuring triangulation sensor is also described in this paper.

Strain gauges, as shown in **photograph four,** provide a useful method for measuring stress and force applied to or by either a vehicle or manipulator. A strain gauge is a thin strip of resistive material, often a copper-nickel alloy, on a thin flexible plastic sheet backing, fabricated by accurate photo-etching techniques. The background of **photograph five** is a 0.1 inch grid.

Typical resistance of a strain gauge is 120 ohms; when the track is bent or distorted a resistance change occurs due to changes in the length of the track and the physical characteristics of the alloy. The gauge is bonded to the surface of the stressed member with an epoxy adhesive.

Resistance changes are small, so the gauge is normally incorporated in a Wheatstone Bridge and the resulting signal amplified by a high-gain operational amplifier circuit, as in **figure four.** Figure four shows the outline of a quarter bridge circuit. Changes in resistance in the gauge, A, cause changes in the differential voltage at the inverting and non-inverting inputs of the operational amplifier. Both the gain of the circuit and the zero point (with the gauge unstressed) can be altered to suit the application.

In a half bridge, A and B are now both gauges and C and D remain fixed resistors of the same value. This arrangement produces a greater signal, better signal-to-noise-ratio and temperature compensation than the quarter-bridge. A full bridge circuit, in which A, B, C and D are gauges, offers the best performance of all.

Strain gauges are manufactured in many configurations, linear (as in the photograph), for multi-dimensional stress (rosette gauge), for torque loading and diaphragm distortion (Jones 1977, or any book on transducer and instrumentation systems). Many gauges will be used in a multi-dimensional force sensing unit to give a simultaneous read-out of applied force in the X, Y and Z directions.

Several designs have been produced to work on manipulator joints, particularly the wrist. Goto, Inoyama and Takeyasu (1974) describe a cross ('+')-shaped coupling fabricated from sheet spring steel at the wrist with a strain gauge on each of the branches, which has been used for assembly tasks involving inserting pistons in cylinders machined to close tolerances (20 microns).

Wang and Will (1978) describe a modulator

*continued on page 91*

*continued from page 89*

system, one module for each degree of freedom giving essentially independent outputs. Such a system would lend itself well to use in the 'fingers' of grippers, to detect how much force is being applied to an object being squeezed. The Olivetti SIGMA assembly robot has a force-sensitive wrist in which displacement is measured against springs by position sensors (Salmon 1977).

The Charles Stark Draper laboratories hve done a good deal of research into the whole problem of mechanical assembly, using both multi-axis force sensors and compliance wrists (those with a certain amount of 'give'), particularly of close fitting parts (Nevins and Whitney 1979). **Figure five** shows a possible sensor configuration for a wrist and gripper on a manipulator.

The most important proprioceptive system on a manipulator arm is feedback showing the position or angle of each of the joints. In a computer-controlled arm this is essential. The final position of the gripper is calculated in relation to the working environment, and the movement of the joints is guided along planned routes to avoid known obstacles, including, in a multiple arm system, the other arms.

Many of the currently available point-to-point and continuous-path industrial robots are servo-controlled. Signals from their position sensors are recorded during the 'training' phase. During the playback phase, this recorded signal is compared with the current arm position and the error signal is used by the computer to drive the arm correctly (eg Aareskjold 1979).

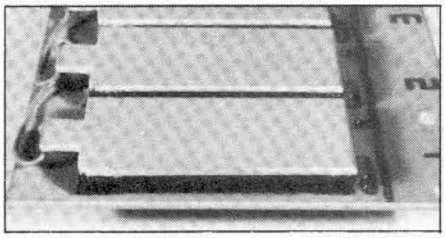
## Position encoders

Position encoders can be either analogue or digital, linear or rotational. Linear or rotary potentiometers produce a signal according to where a slider is on a resistive track — a voltage applied across the ends of this track give a voltage proportional to the position of the joint. Generally these have a lower precision and repeatability than digital types, but are cheaper. Their linearity is more important than actual resistance value.

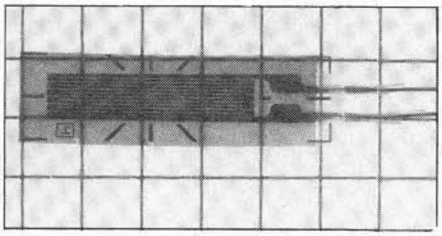
Digital encoders, in which a binary code is read optically from a disc or strip using a light/photocell pair are common. The binary code may either be straight binary, in which case certain transition errors are possible, or a Gray code in which only one bit changes at a time. Eight to ten bit codes are not uncommon and are generally adequate for robot use (about 0.3 to 1 degree resolution in 360). Special techniques in which interbit distances are resolved can give resolutions equivalent to 20 bits. Many of these techniques and systems are described in Woolvet (1977).

With constrained manipulator joints, errors are usually non-cumulative — there is always a reference position on each joint, often defined by an end-of-travel sensor, indicating the limit to mechanical movement. When a control program has to track the position of a mobile vehicle, the problem is far worse. On small machines stepping motors may be used, and integration of the number of steps made (eg Ralph Hollis's NEWT).

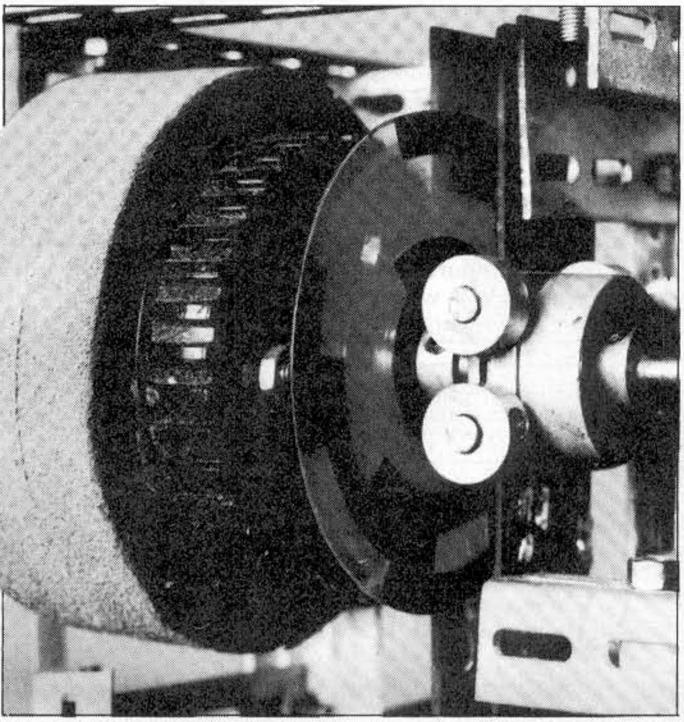
On larger vehicles, less easily-controlled drive systems are used. The distance the vehicle travels may be monitored by odometry — integrating the cumulative rotations of the wheels, and then calculating the current co-ordinates of the vehicle. A similar process is known to sailors as 'dead reckoning'.



**Picture 4 (left): Strain gauge**



**Picture 5 (right): Close-up of photo-etched plastics sheet backing**



**Picture 6: Gray-coded disc used to measure wheel rotation**

As this system requires continuous updating, it is computationally expensive, and prone to cumulative errors. Tyres can change diameter due to wear or differing inflations and wheels can slip on a poor surface, or if subjected to excessive accelerations. Inertial navigation systems avoid these problems but only at prohibitive cost. **Photograph six** shows a Gray-coded disc used to measure wheel rotation on a small robot.

A learning micromouse will almost certainly use a system of this nature. Wheel rotation would be translated into an X-Y coordinate system. A combination of TIL139 type proximity sensors and microswitch touch sensors, possibly with wire 'whiskers' attached (as with Hobby Electronic's HEBOT), will tell the software when a 'T', 'L' or '+' junction or blind alley has been encountered. The current co-ordinates would be stored and used for route planning later.

One solution is to use odometry or dead reckoning as the basis for a total navigation system, but to back it up with information from other sensors. Sonars will detect fixed obstacles, whose position is known; light or radio beacons can provide directional bearings, allowing triangulation. The computer system must therefore generate and maintain a map of its surroundings, a useful extension of the maze-running algorithms that micromouse work will produce.

Aviation provides many interesting examples of navigation by the use of external signal sources. Radio navigation aids, such as Loran 'C', the Decca system, Omega and GEE (from the last world war) involve two or more ground stations that simultaneously transmit pulses.

Signals received from these transmitters will have a phase relationship due to the propogation delays from the transmitters. If they arrive at the same time, the receiver is on a line equidistant from the two stations. Time differences between the two signals define the receiver to be on a hyperbola between the two. By using a third transmitter, the point of intersection between the two hyperbola fixes the receiver's position.

Generally, the delays using radio waves would be too short and acoustic systems would suffer badly from reflections and other unwanted signals. If the system were reversed, such that the vehicle transmitted and several ground stations received, relaying the information back the system would stand a better chance. Cohen's 'drawing' robot, for example, has four ultrasonic receivers at the corners of the robot area (0.2in resolution in 16ft).

For robots that use mainframes and mini-computers as part of a ground station, this poses no problem, as timing information can be sent with all the other information flowing between robot and computer. Transponder systems in which the vehicle transmits a coded signal which is retransmitted from only one of many possible ground stations (time of flight proportional to distance) are also a possibility (*Navigation systems,* Byatt 1980).

All sensory information from these transducers, and a huge range of other possible designs, some or all of which may be appropriate to a particular design of robot, must then be fed into the computer system. Interfacing binary sensors, such as the microswitch touch sensor, digital shaft encoders and sonars to a microprocessor is straightforward. Parallel interface devices, such as the MC6820, are readily obtainable and easy to use, with full

*continued on page 124*

*continued from page 91*

interrupt capability.

Sensors can either be scanned (typically between 10 and 80 times a second), return a value on request or cause an interrupt when they change state. On the whole, the scanning system offers many advantages. The computer is always fed with up-to-date information, the scanning routine can monitor for predefined situations and the computational overheads are predictable.

The output of analogue sensors, such as strain gauges, potentiometers and proximity sensors will have to undergo an analogue-to-digital conversion. The two main techniques, ramp and successive approximation, were covered in *Computabits* (1978).

Typically, a robot sensor will be converted into an eight-, 10- or 12-bit number. The accuracy of digitisation will be governed by the resolution, dynamic range and linearity of the transducers.

## Limits to resolution

Resolution is the smallest step that can be distinguished from the next. In many transducers this is virtually infinite, but it may be limited by noise in amplifiers. Dynamic range is the operational range of the transducer, giving too small a signal at one end to the point where it saturates or breaks at the other.

A strain gauge has a dynamic range of about 1000:1, so that if the transducer is designed to respond to a minimum force of one gram, the maximum useful output will occur when one kilogram is applied. The dynamic range of the A:D converter should at least match that of the transducer.

Non-linearity, in a device such as a potentiometer, limits the confidence with which the signal may be used (high-precision potentiometers have linearities between 1 and 0.1% (manufacturer's information, Penny and Giles Potentiometers Ltd). Dynamic ranges can be extended or compressed over partially useful ranges with logarithmic or exponential post-processing amplifiers.

Several single-chip A:D converter systems exist. The National Semiconductor ADC0816 is an eight-bit converter that incorporates a 16-channel analogue multipler that can be used to scan sensors with little extra logic (manufacturer's information/data books). The multiplexer is fabricated from CMOS switches.

The CD4069 is a 16-channel multiplexer, without the converter. The ADC1210/1211 chip is a 12-bit converter (without multiplexer). Many different converters, in a range of speeds, resolutions and prices are on the market. Typical conversion times are two to 10 microseconds per bit.

Now we have looked at the types and styles of robots that are made, and the sort of data we can expect from the environment through the robot's sensors, I shall deal in the next part of this series with software and computer programming systems for both industrial and experimental robot control.

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