Communication is problem in programmed control

Part four of Mark Witkowski's series concerns itself with the programmed control of industrial-style robots and problems of the communication of ideas from the user to the machine.

HOWEVER BRILLIANTLY designed and constructed, and whatever sensory provision is made on a robot device, its usefulness, usability and performance is ultimately dependent on the control algorithms used. Not that one would want to spend a year writing code — assume that robots are all computer-controlled which is, of course, untrue — to compensate for an unstable mechanism, or trying to guess that the world is doing because the robot is insufficiently instrumented. Generally a good robot is made usable by virtue of its programming, a lesser one may be saved.

Deterministic approach

In some cases, the software is so central to an idea that the robot is not built at all, just simulated on a computer graphics terminal. Programming of robots tends to fall into two categories, first the deterministic approach, in which the robot is programmed with specific actions known to perform a given task. New ways are always sought to program robots with the minimum of effort for the maximum effect and some have met with success.

When direct teach mode instruction becomes too cumbersome, programming languages are developed to describe the problem and its solution. As there is an incredible mass of detail in the most trivial of everyday tasks, these languages are being developed continually and re-structured to cope. This first category is the province of the industrial robot and industrially-orientated robot research.

The second software category falls within the bounds of artificial intelligence research, where the emphasis is on robot problem solving, and where instead of being instructed in minute detail, only a broad outline or the final goal need be specified, possibly in a natural language. Artificial intelligence techniques are being incorporated slowly into robot programming languages as the tasks the robots are required to perform become more complex and the current intuitive methods are found to be inadequate.

Currently, unfortunately, each robot and manipulator tends to have its own teach technique or programming language. There has been little conformity and standardisation, with no universally-accepted language. Unlike different types of computer which, even though they have distinct order-codes, have standardised user languages, manipulators are still sufficiently diverse in design to defeat the compiler writer.

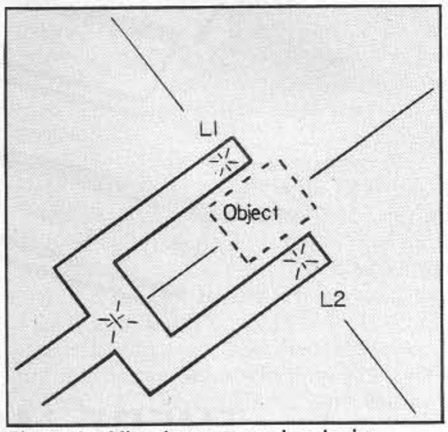


Figure 1a. Visual programming device.

However, numerically-controlled machine tools have been programmed in APT for years — ITT research institute, 1967 — different numerically-controlled machines are catered for by post-processing a universally applicable intermediate codeform from a single compiler into the specific control signals required.

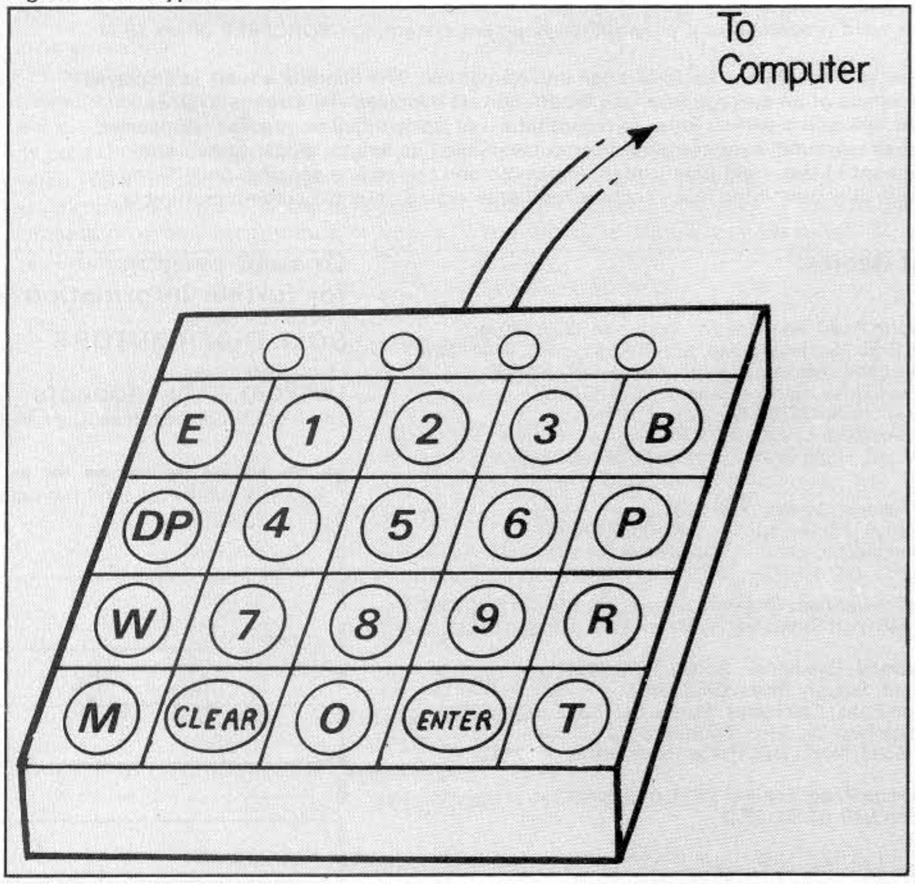
Simplest method

By far the most straightforward method of programming an industrial robot is to manhandle it through the desired sequence of actions. Continuous path robots, as used in paint spraying or welding, are effectively programmed by a skilled human operator leading the arm's spray/welding head through a complete spray or welding job with the actuator power turned-off. The joint position sensor values are recorded at frequent intervals, either in computer memory, or on tape. When the job is completed to the operator's satisfaction the power can be re-applied and the robot will repeat the operator's actions exactly when the stored data is re-played.

Assuming that one has taken the precaution of placing a new workpiece in precisely the position and orientation of the original, the robot will do as good a job as the man did.

With pick-and-place-type robots, the arm is moved to a series of significant positions in the sequence of actions with a joystick control. Although there are many possible designs for this type of control

Figure 1c. V/I keypad.



unit, in principle there will be a switch for each of the degrees of freedom, and a teach button. In a typical application, the arm may be required to move to a component feeder, grasp an item, move to a press and deposit it in place, move out of the way, pick-up the piece after stamping, deposit it in an outgoing hopper and finally return to the feeder to collect the next blank.

This process will involve many discrete steps and the manipulator is moved to each using the multi-switch control. When it is aligned perfectly at each point in the cycle the teach button is pressed, and the joint positions recorded. This is repeated for each significant point, and there may be many before the cycle is re-played to check the sequence.

Specialisations

As the main control unit will compute a straight-line trajectory between the points during playback, it is essential for the user to define sufficient intermediate points to avoid obstacles — none of the actions made between teach points is stored.

There are a number of possible specialisations to this mode of robot instruction by teaching. Figure 1a shows a Visual Programming Device (VPD) used to program the University of Rhode Island (URI) five-degree-of-freedom arm which is shown in figure 1b — Birk and Kelly, 1976, and Kelly and Silvestro, 1977. A computer-compatible TV camera views the base upon which the objects the robot will manipulate are placed. When the VPD is placed on the base, it is possible to calculate the co-ordinates and orientation of the two lights, L1 and L2, from the TV image. The VPD is placed round the object to be grasped and the 'P' button pressed on the keypad — figure 1c. During the playback phase, this will have the combined effect of moving to, orientating with, grasping and lifting the selected object. 'R' has the effect moving to, lowering and releasing the object at that specified VPD position. Other commands include 'B', Begin, and define the 'home' position. 'T', move Through a point specified by the VPD, 'E', End, and move back to the home position. 'Wnnn', Wait for NN.N seconds, allowing operator intervention. Recorded or memorised points are available, TMn, RMn and PMn for Through, Release at the Pick up at the co-ordinates stored in Memory location n. This is a particularly useful feature as it is difficult to re-position the VPD repeatably by hand.

Well-suited

This form of programming is well-suited to the overhead gantry, five-degree-of-freedom manipulator used. A more general six-degree-of-freedom arm would need programming in three dimensions. Perhaps this could be done with stereo television cameras or a navigation-style position sensor.

The visual instruction scheme (V/I) is used in four stages. First the calibration phase. Two fiducial lights, to the left on the base-plate in figure 1b, are used to calibrate the camera co-ordinate-generating program. Recording the sequence of actions using the VPD and keypad is the next stage. Then the Edit/Verify mode is entered. With the aid of a single-step facility, all the points can be checked and changed if they are incorrect.

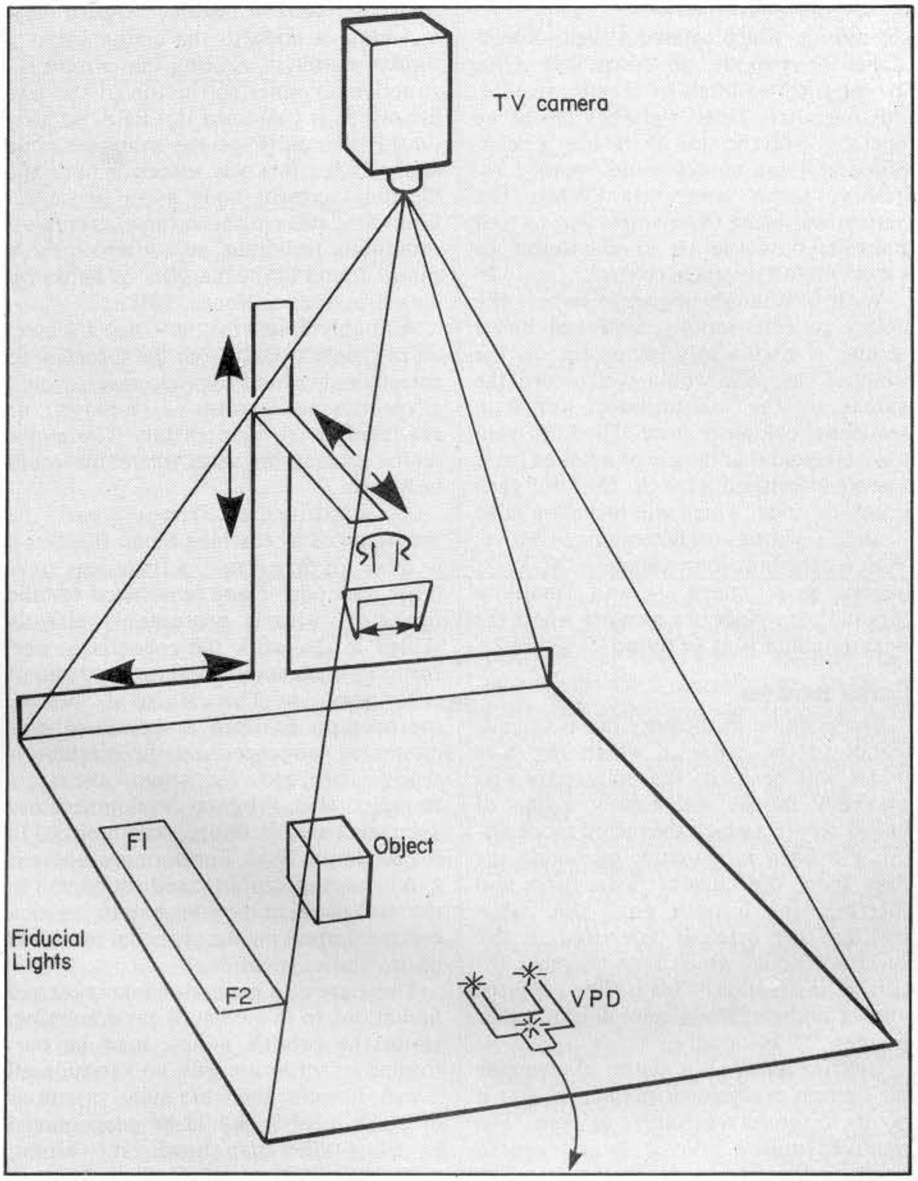


Figure 1b. URI V/I lay-out.

Misalignment can be corrected by altering one or more of the individual co-ordinate components. Points may be added, if, for instance, insufficient clearance was allowed around some obstacle or when some new sub-sequence has to be added. Points may be deleted if a path-length proves to be excessively long. When all is as it should be, the arm is put into playback mode and used.

When a manipulator is used as a disabled persons' aid, particular care has to be taken with the design and lay-out of the input mechanism. Todd (1979) describes a multi-mode input cluster with which tetraplegics may operate a manipulator in a number of different ways by head movements alone. He used a ring of 12 photocells suspended in front of a video monitor, which would operate the manipulator when a light beam projector attached to a pair of glasses frame shon on to one of the cells.

Tree structure

Information displayed on the monitor close to each of the photocells labelled their function. Certain cells would have the effect of changing the labels, and hence the effects the Z-80-based controlling microprocessor had on the manipulator. These changes were organised into a tree structure of different modes, including direct control, pre-programmed automatic picking-up and changing to a different input device.

In addition to the photocells, there was also a ring of 12 momentary push switches, arranged in the same manner as the photocells — so that the monitor labels were still useful — operated by a stick held in the mouth. There was also a joystick, operated by placing the lever in

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the mouth, which offered a multi-dimensional input mode, up/down, left/right, in/out and two levels of breath pressure. Furthermore, three switches could be operated with the side of the user's head. Some of these modes could be used together, some separately. While the patient was using the manipulator to feed himself, it would be unreasonable to expect mouth-operated control.

With any taught-sequence robot, the ability to edit, modify, add and delete actions is particularly important. In the simplest case one would just record the values of the manipulator joints in sequential computer store. The URI team has suggested that the use of a linked list is a more effective approach. Data for each point, or node, which will include a label — so it is named — a mnemonic — Move, Wait — the arm joint values — X, Y, Z, angles, grip, speed — and finally a 'pointer', the place in a memory where the next data unit is to be found — figure 2a.

Data nodes

The position in memory has no significance to the order in which the data nodes will be used, the edit/verify and playback modes will follow a line of linked pointers which the record mode set-up. Playback is a matter of taking the data from the current instruction and interpolating a path until the robot assumes the attitude specified in the successor node, which then becomes the current instruction. This is then repeated until a node with a special end-of-queue pointer "*" is found.

Deleting a node is a matter of changing the current predecessor pointer so that it points to the current successor node. The removed node's pointer is changed to point to the first node in the free list, which initially consists of all nodes, the action list is built-up during record mode by changing pointers from the free list to the action list. The special pointer that indicates the start of the free list FREE is then changed to point to the recently removed action node, figure 2b.

Adding a node to the action list is a similar matter of altering the current instruction's pointer to the top of the free list, which is contained in FREE, altering the FREE pointer to the next free node and pointing this new successor node the the old successor node as in figure 2c. Linked list storage allocation is a standard computing technique, about which more can be found in the majority of books on data structures — Knuth, 1968.

A doubly-linked list, in which a second set of pointers point from the successor to current and current to predecessors would allow the actions to be re-played or searched in reverse order. There are doubtless some instances where this would be helpful.

A majority of robots will be programmed by teaching them. It offers a number of important advantages over other methods. There is no need for the operator, who is presumably already skilled in the work the robot is to perform, to understand the intricate detail of robot operation. There is also no need for the operator to learn a specialised programming language, and the machine is ready for use as soon as it is commissioned. Program development and debugging are, therefore, accomplished in the minimum time. Furthermore, there is a minimum of sophisticated equipment in the work-area, at most keypad or joystick control, improving the potential reliability of the whole system.

There are also many disadvantages and limitations to this form of programming, while the robot's action may be performed *ad infinitum* with no variation all is well, however there are many situations in which a robot should be programmed by telling rather than showing it — Hohn, 1979, Holt, 1979.

Consider the task of picking eggs from a feeder, i.e., a fixed location, passing through some inspection processes, and finally transferring them to a carton — figure 3 — or that of picking the next item of a neatly-stacked pile, each of which is to be found at a position lower than the last.

One fairly bad solution would be to train the whole sequence explicitly. By training the fixed sequence, supply, P1, P2, P3, P4, branch, it could be saved as a macro. Then it would only be necessary to train each of the different branch paths and, after each, press the macro-expand control which substitutes automatically the stored path into the linked-list sequence action queue.

Real power

The real power a programming language gives a robot user is in relation to acting on sensory data. We didn't decide on how to describe the tests on those eggs, or how to dispose of bad ones. As soon as anything more than a few binary interlocks are considered the possible combinations of sensor tests explodes and finding some orderly way of handling the ensuing branch points, feedback loops and error recovery becomes essential.

Subroutine call or macro-expansion can, as with all computing, reduce programming effort considerably, as well as impart a much more modular, top down, control structure to the task solution, particularly where small modifications are required to a basic action sequence. Language makes the description of transformations to the already-programmed actions more powerful. It becomes possible to describe actions relative to some object or previous action, rather than absolute position, or to superimpose the motion of a conveyor belt on which the work-piece is moving.

In some circumstances, it may be desirable to rotate, expand or contract the sequence, or reflect it to give a mirror image. Consider the left- and right- hand sides of car assembly. Where absolute positioning is required, manual control of the action sequence may be insufficiently accurate or repeatable. Print statements in the language are used to provide a written log of robot activity, display messages and sound alarms when operator assistance is

Figure 2a. A linked list.

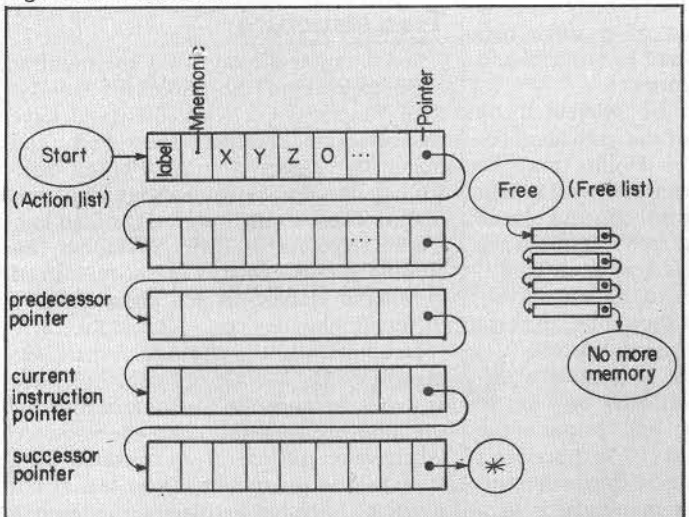
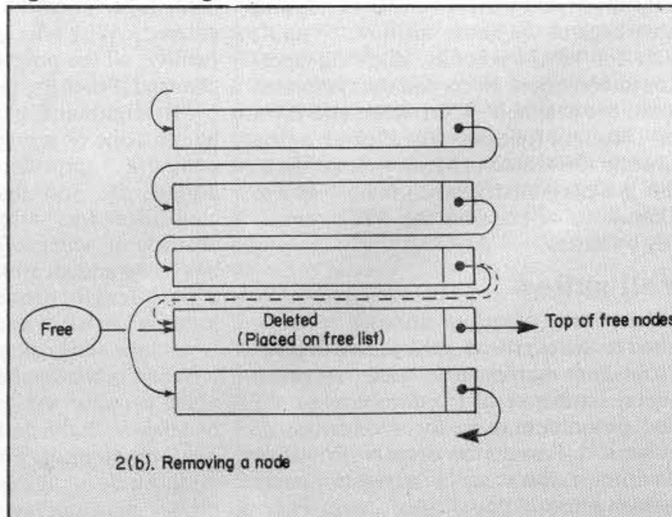


Figure 2b. Removing a node.



called for. There are many instances where the design criteria for a good robot control language are similar to those of any other type of computer language. They must allow the user to specify every aspect of the task to be performed, without being too cumbersome. Robot languages for manipulators may either describe the task in terms of robot motions or the position and transformations of the work pieces.

WAVE from the Stanford artificial intelligence laboratories — Paul, 1977 — is an example of an industrially-orientated manipulator control language. It is written as a sequence of one-line instructions, and is worth closer examination. In WAVE, an object is described by the position the manipulator must be in to grasp it. There are six items required to specify the position and they are assigned to a variable name thus:

TRANS variablename 30,20,10,0,90,0

assigns a particular position (X = 30, Y = 20, Z = 10) in co-ordinate space to the gripper with a unique orientation. The Scheinman arm at Stanford has six degrees of freedom and the latter three parameters to TRANS specify the angle of attack of the gripper completely in relation to fixed reference orientations.

Instructions

MOVE variablename

would then cause the manipulator to move from its current position and, assume the co-ordinates and orientation specified in a previous TRANS instruction, which in itself caused no action. MOVE is an absolute instruction, motions relative to the current position can be made with:

CHANGE vector1,scalar,vector2,angle,time

which moves the arm a distance specified by scalar in the direction given in vector 1, also rotating it by angle about vector 2, at an optional speed.

VECT variablename x,y,z

is used to specify a vector with x,y and z components, and can equally be used to give a direction or a force heading and value. The gripper is opened and closed with:

OPEN 5

open the gripper to five inches and:

CLOSE 1

close the gripper, the jaws will close until either physical resistance or a specified force is met by appropriate sensors. If they close more than the parameter allows, less than one inch, a well-defined error condition is generated, usually meaning that the object to be grasped was not in the expected position.

CENTER 1

centres the hand about an object using touch sensors on the insides of the fingers, without moving it. CLOSE and CENTER use sensory data inherently, whereas MOVE and CHANGE do not.

The STOP instruction may be used to abort a movement when a certain, expected, pre-condition is met. So the code:

```
VECT DOWN 0,0, —1
VECT HIT 0,0, —30
STOP HIT,NIL
CHANGE DOWN, 10,NIL,0,0
```

moves the arm down a maximum of 10 inches in the Z direction only, vector DOWN times a scale factor of 10, but this stops if a force vector of 30 oz. is encountered in the minus Z direction, upwards. The co-ordinates of the obstacle that caused the arm to halt are saved in FLOOR, they may be used later by:

RESTORE FLOOR

this save and restore feature is particularly important in remembering where objects already manipulated are — rather than where they ought to be.

There are several forms of program control:

JUMP label

clearly transfers control to code at "label:". Iterative actions are controlled by the loop instruction:

SOJG loopvalue, label

which decrements the contents of the variable loopvalue and, if it is still positive, jumps to label. Loopvalue is initialised with the instruction:

ASSIGN loopvalue, n

for n times round the loop, these loops can either be used to repeat a total sequence of actions or make final position adjustment iterations using sensory data.

Error handling is by the SKIPE n instruction, skip over the next instruction if error condition 'n' is encountered. There are many possible predictable error conditions — gripper closes beyond expected amount, failed to STOP, object encountered where none should be. Alternatively, SKIPN skips the next instruction if an error is not trapped. This form of error handler is all very well, as long as the programmer is aware of what is likely to happen so provision can be made.

WAVE allows a complete program to be built-up in 'macro' modules, each of which may be tested in isolation, starting with some clearly-defined condition and exiting in an equally clear state for the next module, or on giving an error message. The 'WAIT error message' command halts the system, prints the "error message" and waits for operator intervention. Because of the uncertainties inherent in all real-world manipulations, WAVE offers a number of facilities.

SEARCH X,Y,0.1

sets-up a box search in the x and y planes, starting in the x direction, with increments of 0.1 in figure 4. This pattern of initial guess followed by a sensor driven search, or some variation, is a standard technique in robot assembly programming.

Assembly operations

In a number of assembly operations, close fitting parts can be better mated with some of the degrees of freedom released, such that they are only balanced against gravity and acceleration forces. They will then comply to external imposed forces to prevent jamming:

FREE 2,X,Y

gives translational compliance in the x and y directions.

SPIN 1,Z

gives rotational compliance.

FORCE vector

maintain the given force in the direction of the vector. To further ease the problems associated with close assembly:

WOBBLE 0.1

superimposes a 0.1in. sinusoidal perturbation on the hands' movement. These compliance and oscillatory modifiers are designed to reduce the incidence of close-fitting parts seizing together if force is applied at some angle not exactly perpendicular to the line of best fit.

The amount of processing required to convert these instructions into a form suitable to drive the arms motions is not trivial.

In this case the actual drive parameters are planned, using a model of the arms physical dimensions, possible motions and dynamic considerations in a time-shared

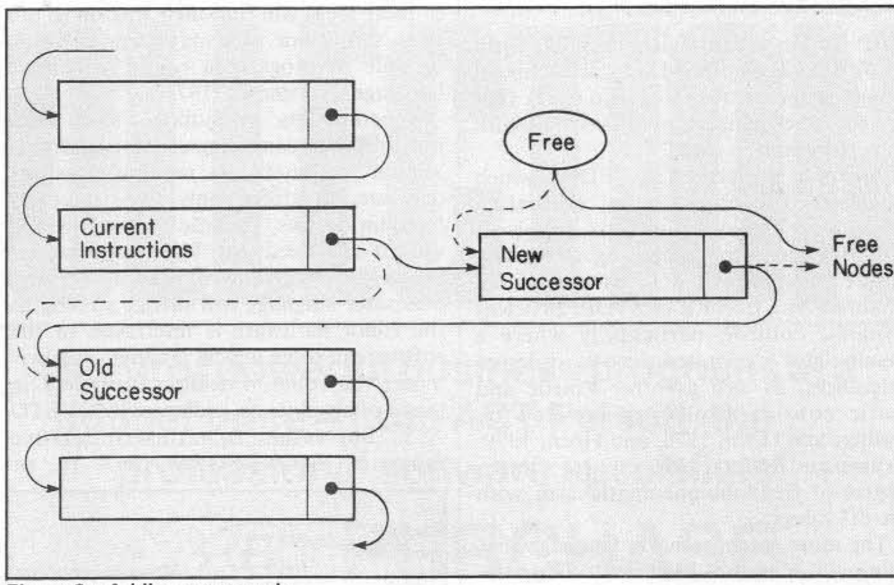


Figure 2c. Adding a new node.

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PDP 10. The assembly-language-like form of WAVE is translated into arm control object program. Planning also check that the requested action is not impossible with the configuration used.

The plan is executed in a PDP 6 which interprets the object code, evaluating trajectories and acting as a six-degree-of-freedom servo, re-computing as needed where pre-planned actions have been modified by CENTER or STOP. Efficient dynamic control, particularly where a manipulator is operated close to its design tolerances, as well as other kinetic and static considerations are covered by Raibert and Horn, 1978, and Horn, 1979. Drazan and Jeffery, 1976, control a three-degree-of-freedom pneumatic arm with on/off valves.

The more recent trend in languages for manipulator control has been to bring the syntax more in line with current Algol-like programming languages. BEGIN .... END block structure, IF ... THEN ... conditionals, WHILE .... DO ... and REPEAT ... UNTIL ... control structures — Paul and Nof, 1979.

Stanford's later language AL, a successor to WAVE, also has an Algol-like structure and introduces new ideas into this problem area — Finkel et al., 1974. Al, and the MIT language LAMA — Lorano-Perez 1979 — and others — Ambler and Popplestone, 1974, are all concerned, to varying extents, with describing assembly tasks by the objects which are to be manipulated, rather than the actions actually required to perform the task.

It would be by far preferable to state the problem in English, or some subset, than describe actions. In all cases this will dramatically increase the analysis and planning stages to produce the executable plan. Consider the effects of inserting the primative instruction:

INSERT (OBJECT,HOLE)

on both computational and knowledge database requirements.

With all the advantages of programming languages, it would be elegant to also incorporate the directness of the teach mode. Gini and Gine, 1978, report on the POINTY system in which the manipulator is used to point at objects and generate data structures automatically about that item in AL. Eventually the best of these ideas will find their way on to the work-shop floor. One may even, one day, be able to program a robot in natural language — Bernorio, 1977.

Programming of mobile robots does not need the same degree of transformational arithmetic as manipulators, as they are, in effect, only two-degree-of-freedom devices. Because of this, there is almost no need for highly-specialised languages to control them — any computer language will suffice so long as the robot hardware is interfaced to the software in some logical manner. Furthermore, the robot is seldom instructed in terms of absolute co-ordinates, MOVETO X,Y; but rather in terms of relative motions, MOVEFORWARD 10 or GOLEFT UNTIL SENSOR3 > X.

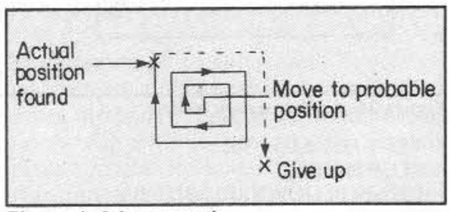


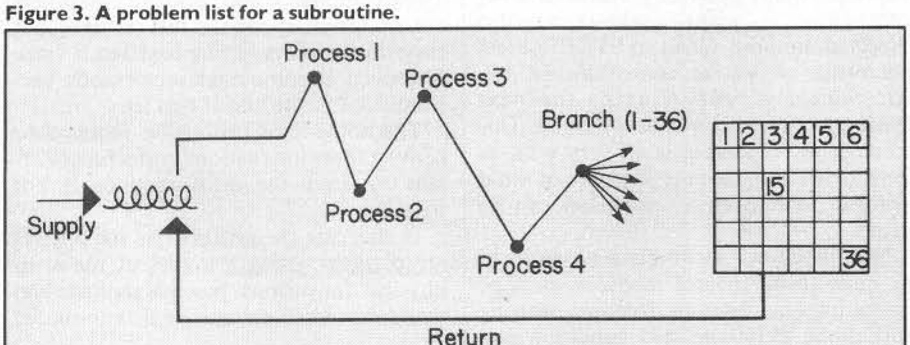
Figure 4. A box search.

Even when the algorithm functions in absolute co-ordinate space the transformation to relative motion, even if must be planned, is straightforward. The programming language LOGO has been used to teach children about various concepts in mathematics and computing using small, two-wheeled, turtles which, with a pen attached to their undersides can be programmed to draw pictures on the floor, according to programs the children write — Papert, 1971a and 1971b, and Papert and Solomon, 1971.

Less computation

As there is far less computation involved in determining the vehicle's actual path, these languages can be interpreted. Input text is scanned directly to perform the actions, whereas WAVE had to pass through a planning stage. The advantages of easy testing, editing, rapid turnaround and good diagnostics usually more than outweigh the time overheads imposed by interpretation. While the school children will see only the simpler aspects of LOGO, a full implementation of the language can be used for complex A.I. programming — bundy et al., 1978.

Figure 3. A problem list for a subroutine.



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