A curvilinear snake arm robot with gripper-axis fibre-optic image processor feedback

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SUMMARY

A curvilinear robot constructed from a number of modular flexible sections of fixed length and diameter but independently controlled radius and direction of curvature has been equipped with an optical fibre image guide transmitting images from between the gripper jaws to the remote TV camera of Microvision-100, a microcomputer controlled real-time DMA-based vision system that is easily trained to recognise the shape, position and orientation of components. The gripper position and orientation is controlled by feedback from the vision system, the action taken depending on component recognition and inspection for defects. Redundant degrees of freedom enable the curvilinear robot to avoid obstacles and work in confined spaces.

1. INTRODUCTION

Robot control and inspection by fixed TV cameras[1] imposes severe limits on the positions and orientations for the fields of view. For maximum flexibility a robot vision system should include a field of view along the gripper central axis but this is not easy to achieve with conventional robots, grippers and TV cameras. Although a small, solid state CCD area image sensor could possibly be mounted between the gripper jaws of many existing robots it is difficult to find space for the lens and for the closely associated electronic circuits. A possible solution to this problem is to employ optical fibre image guides which have a typical diameter of less than 1 cm, including the lens. Any type of TV camera can then be mounted in a convenient and protected position up to several metres from the gripper. A colour camera provides the additional advantage over monochrome of being able to distinguish between components and features on the basis of spectral information.

Image guides are expensive and delicate components that are easily damaged by tension or by bending with a radius of curvature less than the recommended minimum. Finding a suitable safe route for an image guide presents a problem for conventional robots since there is usually no protected path through the centre of the robot, gripper or other end effector and mounting the image guide beside a rotating gripper is inconvenient. Our approach to these problems has been to design from first principles a robot and gripper with a continuous hollow central core through which the image guide can be threaded and which protects it from abrasion, trapping and bending with less than the minimum radius of curvature. The new curvilinear robot evolved for this purpose thus acts as a protective guide for the image guide and as a flexible load carrying manipulator capable of reaching difficult places, such as the inside surfaces of hollow vessels through small access ports, that would be quite inaccessible to robots with polar, revolute or cartesian co-ordinates etc. Absolute positioning accuracy of the curvilinear robot is significantly improved by vision feedback and positioning of the gripper relative to an object anywhere in the field of view is largely determined by the 256×256 pixel matrix of the Microvision-100 robot vision system that has been developed to process the image guide TV camera video signal and to recognise component shape, position and orientation. Microvision-100 has some of the characteristics of an earlier vision system[2] but far greater processing flexibility and resolution. In a few tens of milliseconds it inspects and recognises components in random positions and orientations within the field of the axial gripper vision system and provides feedback signals to guide the gripper to an appropriate position and orientation.

2. CURVILINEAR ROBOT CONFIGURATION

2.1. The basic module

The basic modular section of the curvilinear robot shown in Figure 1 comprises an incompressible steel spring of bending length l_b fixed at both ends in steel tubes of length $2l_0$. Discs, denoted by d_{i-1} and d_i for the ith module, are centred on the tubes and have four large holes through which the robot actuating cables are free to move. In Figure 1 only the four actuating cables for disc d_i are shown in full, to avoid confusion, and each of the n moving discs d_1 to d_n, requires four cables, each of which has a breaking strength of 160 Kg. In addition to the large cable trunking holes each disc has eight small peripheral holes identified by the eight compass directions. Disc d_i is shown with four actuating cables of interdisc length l_n, l_s, l_e and l_w terminating in the n, s, e and w holes. When all four cables have the same length $(l_b + 2l_0)$ disc d_i is in the same plane and on the same axis as disc d_{i-1} as shown by the dash lines in Figure 1. If, however, l_s is shortened and l_n lengthened, whilst keeping $l_e = l_w$, disc d_i rotates clockwise, as the spring l_b bends, until the horizontal position denoted by the full line is reached. The image guide inside the spring also bends but the dimensions are chosen so that the radius of curvature r only reaches the smallest permitted value r_m
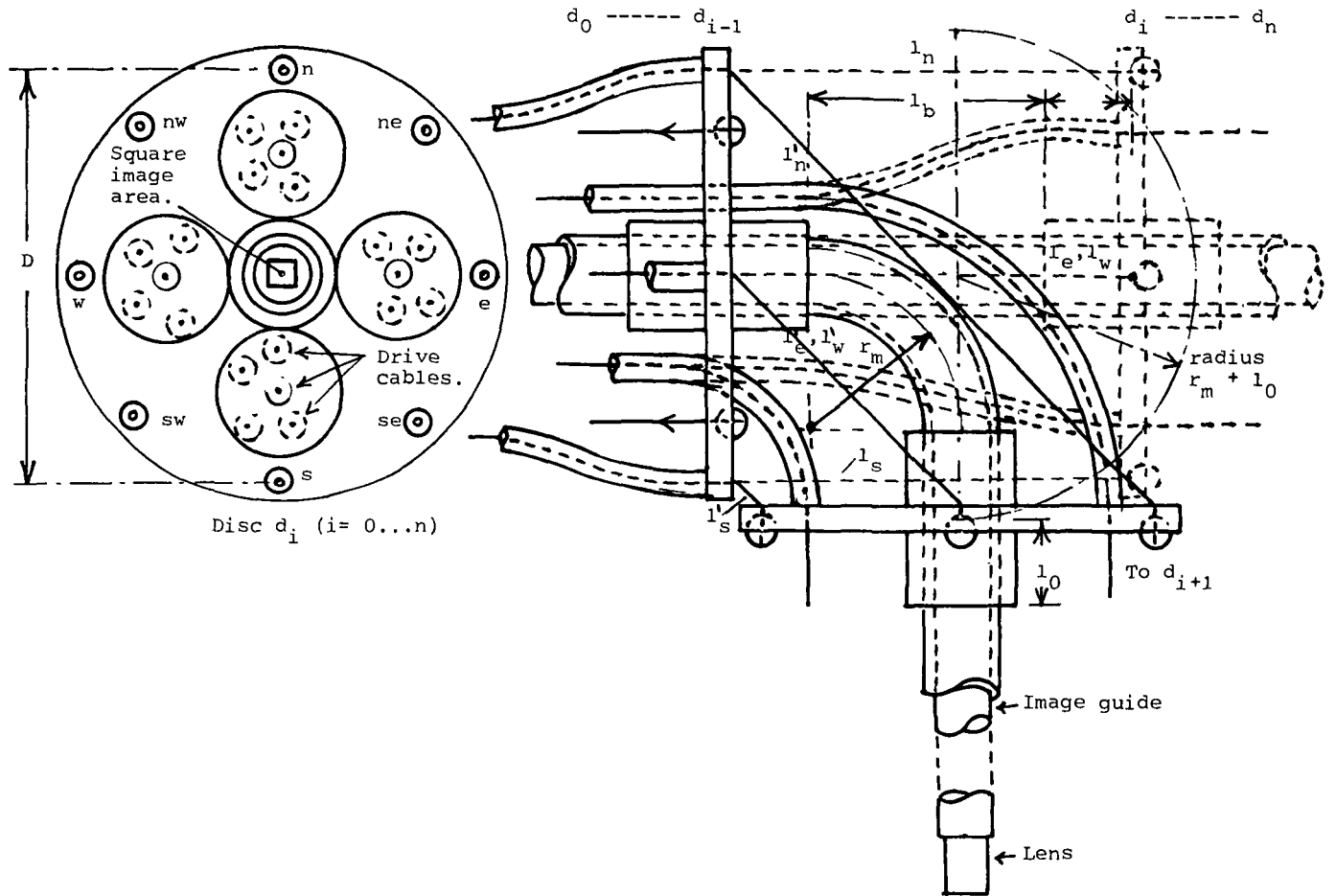
Fig. 1. Basic modular section of Curvilinear Robot with central axis image guide. The section is shown with minimum radius of curvature r_m (3 cms) in the plane of the figure and also (dash lines) with maximum radius of curvature ($r = \infty$). Drive cables for discs beyond d_{i+1} are omitted for clarity.

(3 cms) when l_s is a minimum and l_n a maximum as shown.

It will be seen that the module has circular symmetry so that if l_n is shortened and l_s lengthened the disc d_i rotates counterclockwise through any angle, up to the

Fig. 2. One of $2n$ cable drive modules.

maximum $\pi/2$. Similarly, with $l_n = l_s$ and $l_e \neq l_w$ rotations up to $\pm\pi/2$ in the e and w directions are obtained. Any degree of pan angle θ_p ($0 \leq \theta_p \leq 2\pi$) and tilt angle (bending) θ_t ($-\pi/2 \leq \theta_t \leq +\pi/2$) can be obtained in the same module by suitable choice of the four cable lengths. A tilt of $\theta_t = \pi/2$, measured as a deviation from the axis of disc d_{i-1}, in the north-east ($\theta_p = \pi/2$) direction, for example, can be obtained by reducing l_n and l_e by the same amounts and also increasing l_w and l_s equally. There are thus $2n$ degrees of freedom in n modules and these are controlled by $2n$ dc-motor driven capstans under microcomputer numerical control, as illustrated in Figure 2.

2.2. Gripper positions and orientations

Following the general notation adopted by Renaud[3] for conventional robots, the centre of disc d_0 will be taken as the origin of the curvilinear robot and disc d_n is the final disc on which the end effector is mounted. If d_0 is mounted horizontally on the vertical Z_0 axis and there is only one section ($n = 1$) with two degrees of freedom the gripper centre point C can move over an approximate hemisphere with $0 \leq \theta_p \leq 2\pi$ and $-\pi \leq \theta_t \leq 0$ as shown in Figure 3a. The hemisphere is flattened in the $r = \infty$ position by an amount $2r_m - l_b = 2r_m(l - \pi/4)$ since $l_b = \pi/2r_m$. This effect can be seen more clearly in Figure 1 and complicates any general analysis. A useful idea of curvilinear robot flexibility can be obtained, however, for
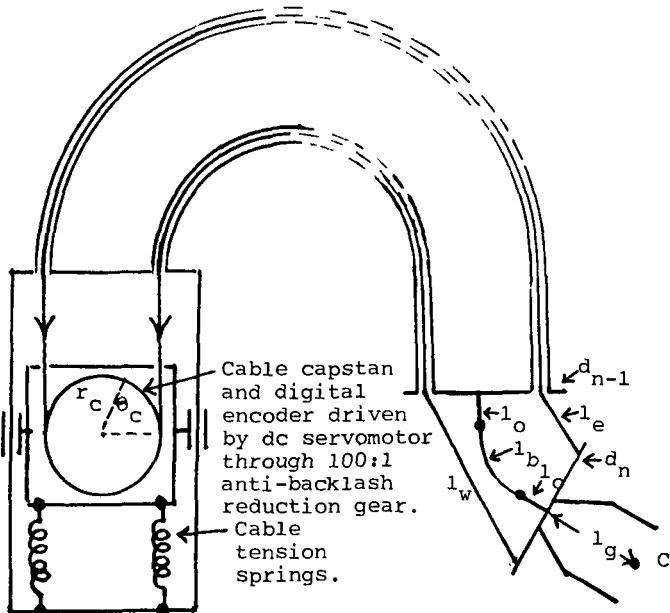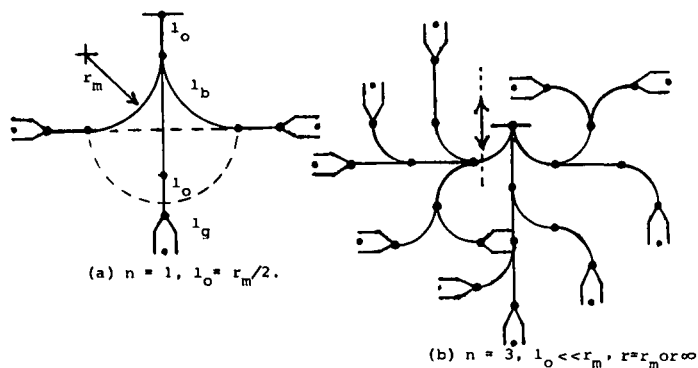
Fig. 3. Examples of curvilinear robot gripper positions and orientations for $n = 1$ (a) and $n = 3$ (b). All curves are shown in the plane of the figure for clarity but in general have any pan angle θ_{p_i} ($0 \leq \theta_{p_i} \leq 360$, $i = 1 \cdots n$) and any radius of curvature r ($r_m \leq r \leq \infty$).

larger n values by assuming each module to be either bent by the maximum amount with $r = r_m$ or kept straight with $r = \infty$. For sufficiently large n this would enable the robot to find routes through a three dimensional "city block" type of maze. With this rough assumption the robot consists entirely of 90° elbow joints of radius $l_0 + r_m$ or straight sections of length $2l_0 + l_b = 2l_0 + (\pi/2)r_m$ (see Figure 1). We can also distinguish two extreme cases for which $l_0 \ll r_m$ and $l_0 \gg r_m$. In the latter case the curvilinear robot resembles a revolute robot but with the new property that each short bending section of length l_b, between long straight sections of length $2l_0$, has two combined notations θ_p and θ_t, as in the ball joint of a camera tripod. Some examples of these configurations are given in Figure 3b for $l_0 \ll r_m$, $r = r_m$ or ∞ and $n = 3$. By adding a vertical degree of freedom to the first disc d_0 the gripper orientation at any x, y co-ordinates can be reproduced at any z value within the vertical range.
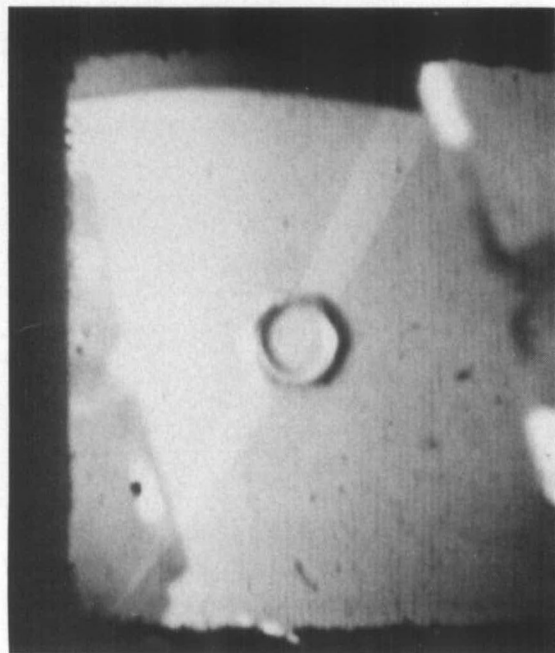

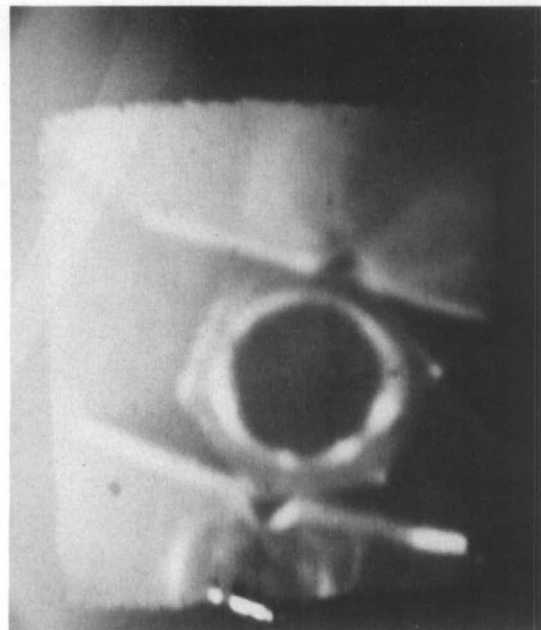Fig. 4. TV monitor picture showing a nut at some distance from the gripper jaws.

Fig. 5. The nut in Figure 4 between the gripper jaws which have been rotated to facilitate the gripping action.

2.3. Gripper design

The gripper had to be designed to accommodate a central hollow tube for the image guide and lens. Parallel jaws are driven by two dc motors through two 60:1 reduction gears on opposite sides of the tube and the two motors are kept in step by a toothed belt and pulleys. Gripping force is controlled by motor current but for greater accuracy force sensors could be incorporated. The gripper jaws have orthogonal V grooves, two of which can be seen gripping a nut on the central image guide monitor picture in Figure 5. The gripper can rotate through more than 360° and is capable of lifting 1 Kg, the car connecting rod shown in Figure 18a and b weighing 0.75 Kg.
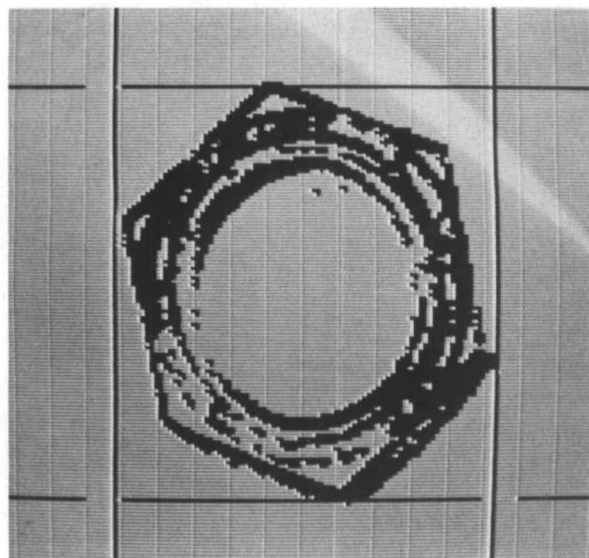

Fig. 6. Microvision-100 locates the position of the nut relative to the gripper axis by enclosing the binary edge image in a rectangle.
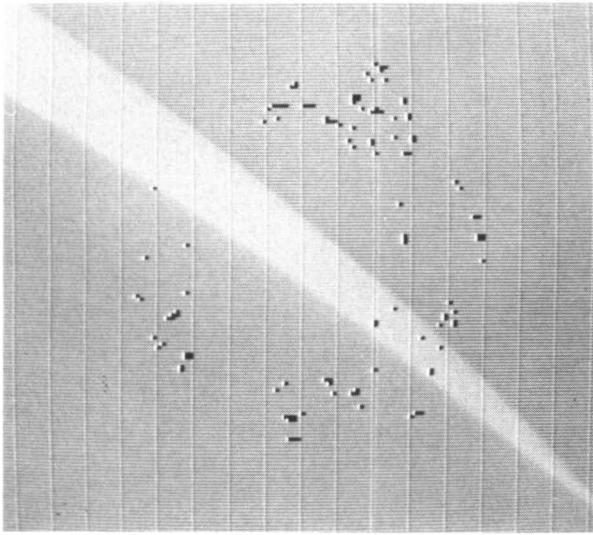
Fig. 7. The image is compared with a stored template and small differences due to quantization noise are shown.
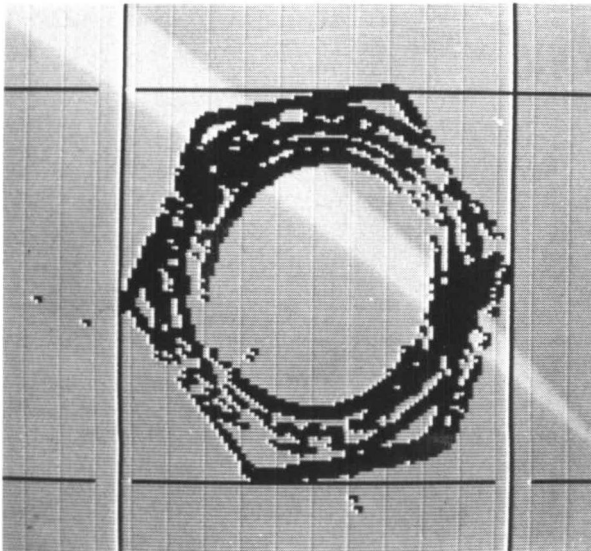

Fig. 8. The nut is rotated relative to a reference orientation for the stored template to produce large differences (Figure 9) that disappear at the correct gripper orientation as in Figure 7.
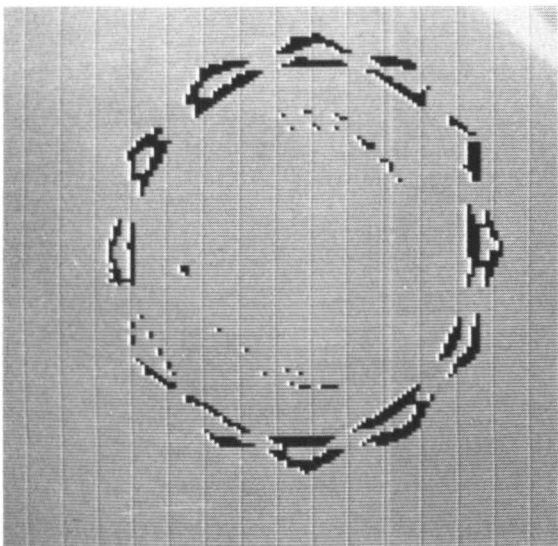

Fig. 9

3. VISION INTERFACE AND PREPROCESSOR

The image guide terminates at the TV camera C-mount adaptor and the video waveform is digitized by a high speed six bit ADC. The six gray level bits are processed by a byte parallel pipeline processor that computes the magnitude of the image gradient at each pixel in real scan time. If the gradient magnitude at a pixel exceeds a threshold the pixel becomes a binary 1 but is otherwise zero. This operation is very sensitive to surface imperfections such as scratches and can be used to detect surface defects on components that should have a smooth finish. In other applications, however, rough surface texture is irrelevant (e.g. in castings) and only the shape, position and orientation of the component has to be recognised.

3.1. Recognition and inspection algorithms

The points of significant image intensity gradient are found in the first frame of 20 ms and the MV-100 monitor displays the 256×256 pixel resultant processed
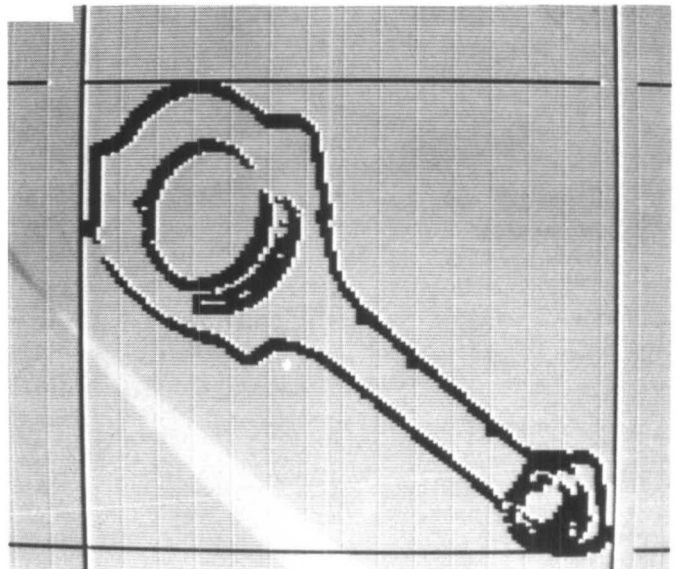

Fig. 10. Binary edge image of a car connecting rod and the enclosing rectangle.
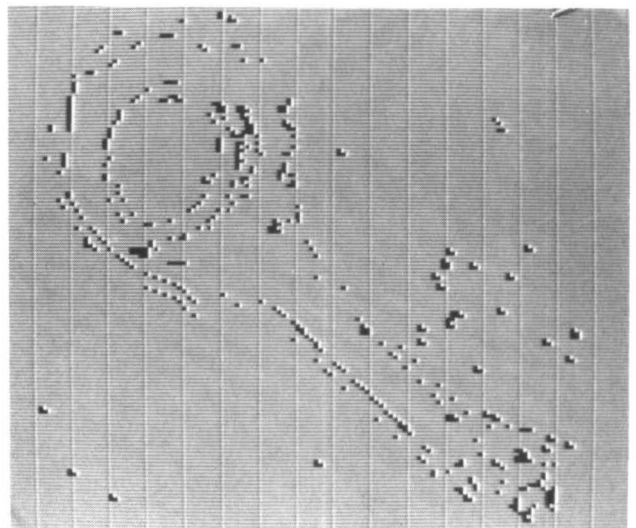

Fig. 11. Recognition of the connecting rod at the correct reference orientation and distance is indicated by a low count at the exclusive-or comparator stage.
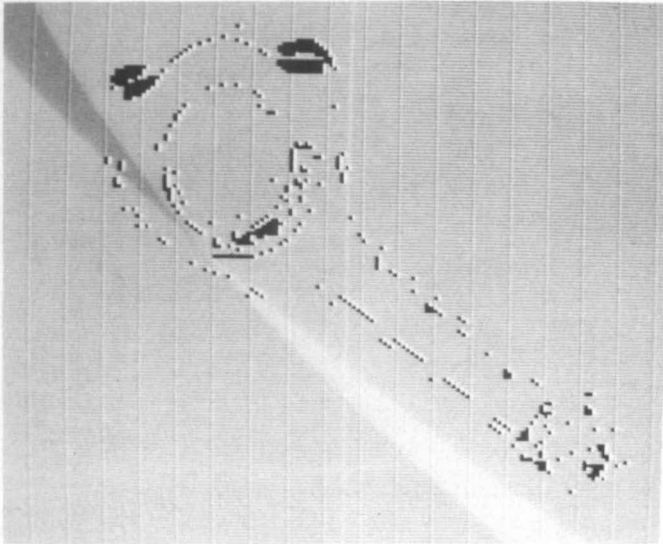
Fig. 12. The same system provides inspection for missing bolts which appear as black pixel areas.

Fig. 14. A connecting rod with half the large bearing missing produces the very large template mismatch of Figure 15.

image. Typical examples, produced by the small nut seen between the gripper jaws in Figures 4 and 5, are shown in Figures 6 and 8 for two different orientations of the nut relative to the gripper. The MV-100 is trained to recognise objects by storing the processed gray level images in bit plane memory blocks under the DMA control of a microprocessor synchronised to the TV line and frame. The orientation of the stored image relative to the gripper jaws is chosen so that advantage can be taken of the V grooves. The best orientation for the nut is shown in Figure 5. With opposite corners in the grooves. The size of the nut image varies with distance and it is also necessary to store the reference image at the correct size corresponding to the jaw centre distance (l_g in Figure 2), in addition to the correct orientation.

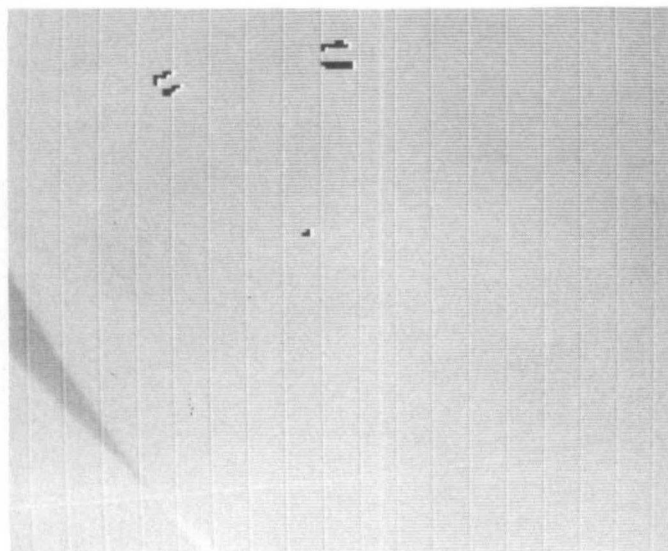The recognition and inspection algorithm[2] involves taking the exclusive-or (exor) function, pixel by pixel,

between an unknown component and all the stored components i.e. measuring the Hamming distances between them. For a perfect match, i.e. same shape, same size, same position and same orientation, the Hamming distance would be zero. In practice this never occurs due to noise in the pixel quantization process since there are always gradients on or near the threshold. A typical close match for the nut in Figure 6 gives the exor result of Figure 7 consisting mostly of isolated noise pixels that can be eliminated by a shift and multiply operation to give a zero Hamming distance, i.e. a perfect match.

In general the unknown component is also at an unknown position, distance and orientation. The position is found by forming the enclosing rectangle as shown in Figures 6 and 8. If the rectangle is not in the same position as the training rectangle the difference provide error signals to centre the component. A difference in the size of the observed and stored rectangles for the same component indicates a different distance and also whether the component is too far away or too close.

Fig. 13. The template difference image (Figure 12) can be cleaned up by a local operator to show the coordinates of the missing parts.
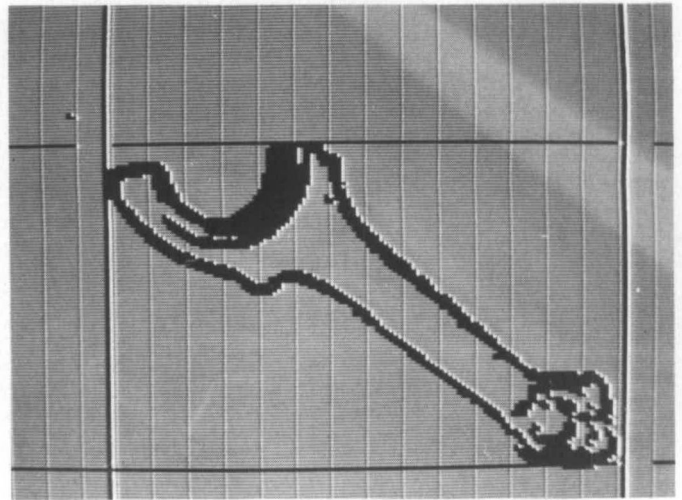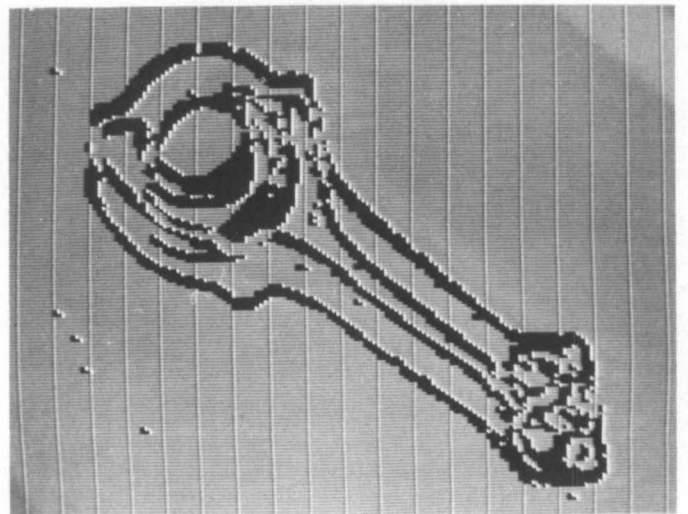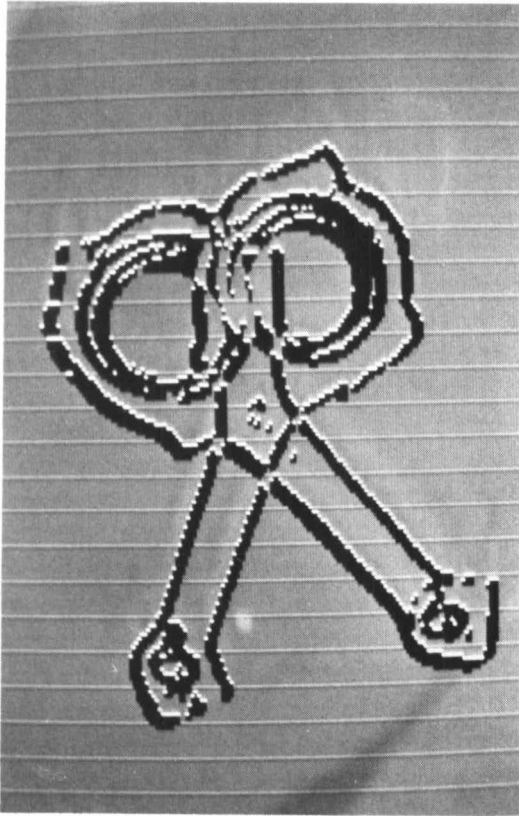

Fig. 15

Fig. 16. A component at the wrong orientation is readily detected by the large mismatch as compared with Figure 11 for the correct orientation.
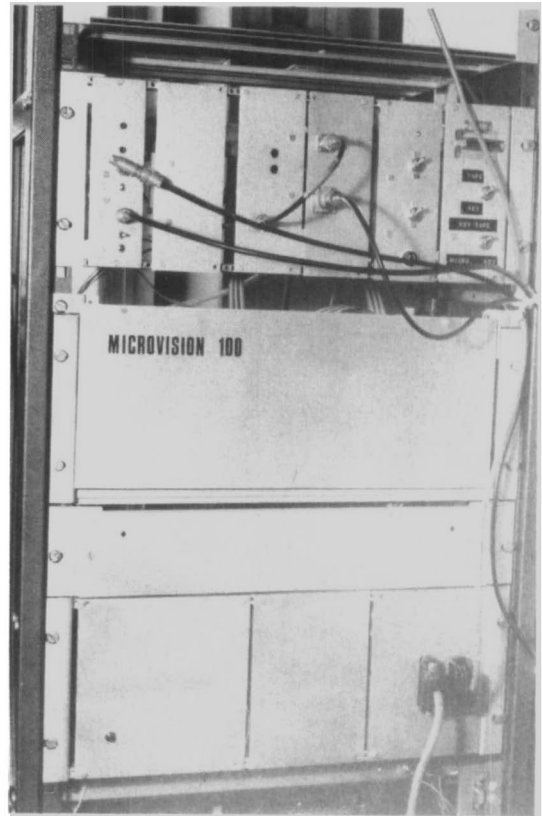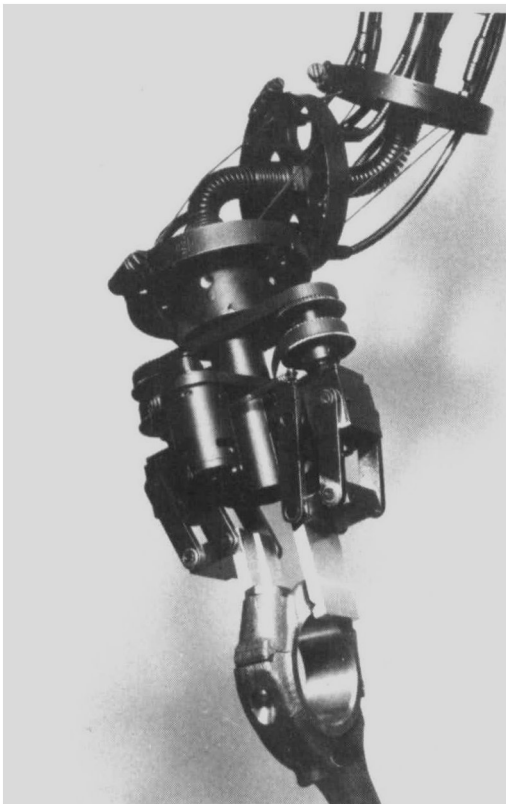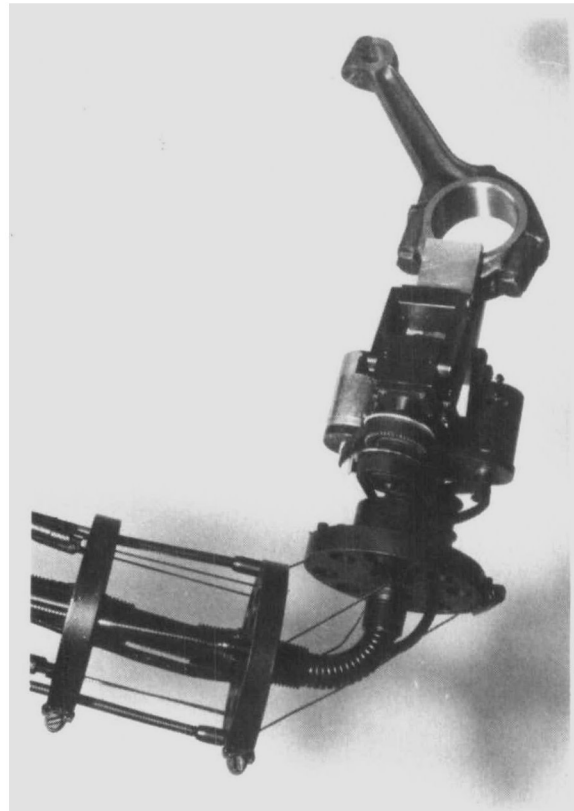

Fig. 17. Microvision-100 Robot Vision System.

(a)

(b)

Fig. 18a–b. Two Orientations of the parallel Jaw-gripper and Last Two Sections of the Curvilinear Robot. The Fibre Optic Image Guide Passes through the Central Tube.

Assuming that the nut in Figure 8 is at the same distance as the reference nut in Figure 6 but has an incorrect orientation there are twelve large mismatches at the corners as shown in Figure 9, i.e. a large Hamming distance H. On rotating the gripper through 30° H falls to zero indicating that the nut is the correct shape and size and also in the correct position and orientation for the gripper.

Inspection of components for small errors in manufacture is illustrated in Figures 10–15. The car engine connecting rod in Figure 10 is stored in the reference orientation as shown. A similar connecting rod in the same position and orientation gives the small mismatch H shown in Figure 11 that can be reduced to zero by eliminating all very small groups of pixels. If, however, the bolts holding the big end in position are missing there are larger mismatches at the bolt head positions as shown in Figure 12. Again by eliminating small groups of pixels the positions of the two missing bolts are found (Figure 13) and the component can be picked up and deposited in a special reject bin for missing bolts. Another possible fault is the complete absence of half the big end as in Figure 14. The enclosing rectangle is reduced in size and the number of mismatch pixels becomes very large since the remainder of the connecting rod is moved to a different central position. Equally large mismatches are produced at incorrect orientations of normal connecting rods (Figure 16). If mismatch is plotted as a function of gripper rotation, with the image guide locked to the gripper, a sharp minimum is obtained at the component training angle. This minimum is detected and stops gripper rotation so that the component can be picked up in the specified position and orientation.

4. CONCLUSIONS

The curvilinear robot has a number of advantages compared with conventional robots the most important being high manoeuvreability for avoiding obstacles, a protected central "spinal" cord for the image guide fibres and low cost lightweight interchangeable disc modules giving greater than unity ratio of maximum load mass to robot mass. By incorporating sliprings and a clutch in the gripper both locked and independent continuous rotation of the gripper and image guide is possible. Disadvantages include reduced stiffness to twisting, but this can be improved significantly by including two opposing diagonal twist control cables in addition to the four bending cables per disc. The MV-100 vision system (Figs. 17 & 18) provides positioning accuracy by compensating for cable stretch under load, in addition to automatic inspection.

References

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