Determination of the geometric parameters of a robot manipulator by visual data

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Development of high speed computers and high resolution video cameras has given rise to the application of vision systems to industrial robots. The main task of a vision system has been to search for the object to be manipulated and once found, determine its location and angular orientation, to replace the expensive work holding devices. Such a vision system can also be used to determine the geometric parameters of the working manipulator. This paper describes how to gather information concerning the topology of the manipulator, ranges of joint mobility, link lengths and offsets by incrementing the position commands to a certain mobility and observe the resulting motion by recording the position of a beacon located at the tip of the manipulator by a vision system. The work is a part of a *manipulator independent general purpose robot control software* which systematically actuates the manipulator mobilities one at a time while the others are kept fixed and obtains the geometric parameters used in the forward and inverse position equations generated according to the Denavit-Hartenberg representation.

Key words: geometric parameters, vision systems, robots

1. Introduction

The basic task of a robot manipulator is to bring an object to a specific location in space, at the required angular orientation. In general, the manipulator must have 6 degrees of freedom, at least 3 of which are rotational. Gross spatial displacement is obtained by a 3 degree of freedom arm, and a wrist assembly at the tip provides 3 or less rotational degrees of freedom facilitating angular orientation. In robot manipulators multi degree of freedom joints are unfavorable due to the requirement for multiple power generation and transmission elements to be packed in a small space and the greater bearing loads in comparison to that of single degree of freedom joints. Therefore, universally only single degree of freedom, single input--single output joints are utilized. These are the *revolute* and *prismatic* joints. This requirement put forth a generalized common structure, composed of a sequence

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of links connected to each other in an articulated manner by either a revolute or a prismatic joint. To generate the kinematic equations and control strategies, geometric parameters like types of joints and extent of their mobility, link lengths and joint offsets are required. These can be measured and externally given to the control computer, or joint positions can be recorded on line when the manipulator is brought to the required position by using a teach *pendant*. This second method eliminates the effect of any errors in geometric parameters and is widely used in commercially available robot systems. Manipulator independent control software requires the kinematic parameters which are externally defined. This can well be done by visual data if the robot system is equipped with a vision system.

In this work a systematic approach is presented to obtain the manipulator geometric parameters by visual data. A characteristic point attached to the tip of the manipulator is monitored by two cameras while only one of the joint positions is incremented by the control computer. The path of the point defines the joint in action. If the path is a circular arc, acting joint is *revolute* and if straight line, *prismatic*. Generally a circular arc is observed obliquely hence an elliptic curve comes up. To see it in true size, point of view must be rotated such that direction of view is perpendicular to the plane of this arc. Angle subtended by the arc defines the extent of the mobility. Coordinates of the centre of rotation are calculable. Similarly, the linear motion of a slideway is generally observed obliquely and hence to see it in true size appropriate rotations must be done. Then the length of the straight line gives the available stroke of this prismatic joint. The same process is repeated for each mobility. Joint parameters calculated then help to evaluate the link lengths and joint offsets. Kapucu [1] describes how joint parameters are substituted into a kinematics software package, where a forward kinematic equation and the Jacobian of the motion are automatically derived by a mathematical model based on Denavit-Hartenberg representation [2, 3, 4]. Once the Jacobian is found, it is transferred to the inverse kinematics package for inversion. Joint variables are calculated by Newton-Raphson method. In this paper, only the 3 degrees of freedom gross motion of the manipulator is considered, but end effector joint variables can also be determined in the same iterative manner.

2. Experimental set-up

2.1 Computer vision system

The hardware used in this work consists of two PULNIX TMC-74 (NTSC) colour video cameras, two Raster Ops Video Colour Board 364, and an Apple Macintosh FX II computer. Pulnix TMC colour cameras have a high resolution 2/3 inch imager having 768 × 493 light sensitive cells each of 11 × 13 microns size, and an automatic iris. Raster Ops Video Colour Board 364 has a palette size of

16.7 millions, each pixel definable by 1, 2, 3, 8, or 24 bits, and a resolution of 640 $\times$ 480 pixels. It works in NTSC mode with a scanning speed of 30 Hertz. Central processing unit of the computer is the MC 68030, with a 32 bit architecture. An MC 68882 Floating Point Unit Co-processor has been installed into it to speed up the arithmetic/logic operations.

2.2 The test manipulator and arrangement of the cameras

Manipulator under consideration is a heavy duty hydraulic machine of Stanford configuration. The manipulator arm has three degrees of freedom, facilitated by two revolute and one prismatic joints (RRP) as shown in Fig. 1. It is monitored by a pair of cameras fitted with lenses whose focal lengths are controlled via computer. Cameras are positioned parallel and at the same height. Distance between camera axes is 12.6 cm. Focal lengths are set to 1 cm (widest angle position) such that the whole of the manipulator is seen through both cameras. A right handed inertial Cartesian frame is set, whose origin is at the pinhole of the right camera. The optical axis outward from the camera is chosen as positive Z_{c} axis while the vertically upward direction from the pinhole is positive Y_{c} and rightward direction the positive X_{c} axes. This frame is fixed to the cameras and to the ground and is called the *camera coordinates.* A second right handed Cartesian inertial frame is assumed, as shown in Fig. 2, whose origin is fixed to the base of the manipulator and referred to as the *world coordinates.* In this frame, Z_{w} axis is vertically up, in line with the revolute axis of the first joint and X_{w} axis lagging the Z_{c} axis of camera coordinates arbitrarily by 126 degrees. Distance between the Y_{c} axis of the camera coordinates and Z_{w} axis of *world coordinates* is arbitrarily 454 cm. The origin of the *world coordinates* is about 78.5 cm below that of the camera coordinates. The actual calibration of the cameras is done experimentally. During the calibration of the cameras, a red light source situated at the tip of the manipulator is monitored. The parallelism of the cameras are ensured by observing the distance between two lines having a separation equal to that of the distance between the optical axes of the two cameras. The cameras see the plane on which these lines are drawn in true size. Right camera sees the line on the right at its own optical centre while the left camera sees the other at its optical centre. The plane containing the lines is translated along the Z_{c} axis to different locations and viewed through the cameras. If camera axes are parallel, the distance between the images of the observed lines do not change. Adjustments are done until this requirement is satisfied.

Once parallelism is assured, views containing the characteristic beacon are taken. Characteristic beacon is chosen to be at a distinctive colour for easy identification. A definition of the colour exists in the memory of the computer and computer searches the image for a pixel containing this specific colour definition by the *method of bisection* [5]. Once such a pixel is detected, a 90 $\times$ 90 pixel window around this pixel is defined which should supposedly contain the image of the

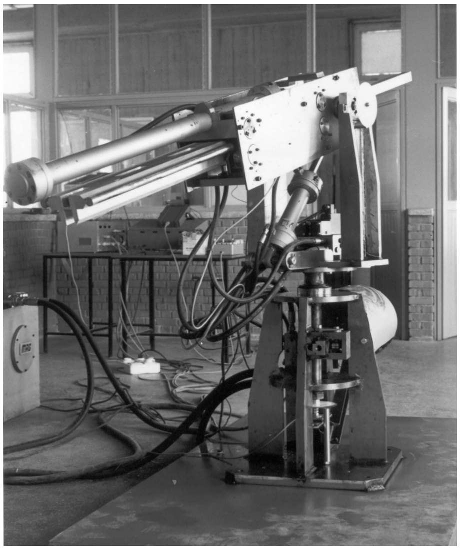


Fig. 1. Heavy duty hydraulic manipulator of RRP configuration under visual control.

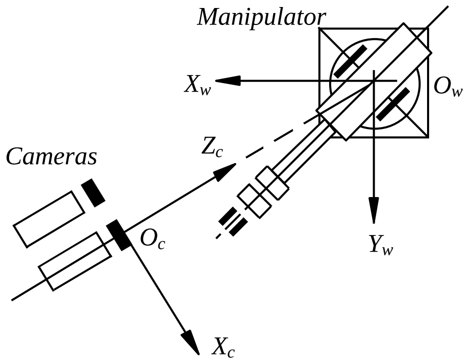


Fig. 2. Arrangement of the cameras and the manipulator (top view).

beacon completely and the window is searched pixel by pixel. After the beacon is fully developed, its centroid is found. The same procedure is repeated by the other camera. At this stage, two sets of image coordinates in pixels for the centroid of the characteristic beacon are at hand. Image coordinates in pixels are transformed into camera coordinates [6]. Camera coordinates describe the real position of the characteristic beacon on the manipulator with respect to the camera coordinates in centimeters. As camera coordinates are offset from the manipulator, calculation of manipulator kinematics and position commands with respect to it produces difficulties. Therefore, definition of a second inertial Cartesian frame, located at the base of the manipulator becomes necessary. Conversion of camera coordinates into world coordinates is done by multiplying them by a displacement matrix. The elements of the displacement matrix are found experimentally by a procedure called hand-eye calibration [7, 8].

3. Determination of link parameters

A rigid body motion in a plane may be translational or rotational or a combination of both. The links of a manipulator are connected to each other by either revolute or prismatic joints. The link connected by a revolute joint executes a rotational motion about this joint or the link connected by a prismatic joint executes a transitional motion with respect to the preceding link. By knowing three positions of a point on the link, type of motion and its axis can be found. If active joint is a revolute, 3 successive positions of the beacon lie on a circle, centre at the intersection of the perpendicular bisectors of the lines joining any two of these points. An infinite radius of curvature indicates that the active joint is prismatic. Normally only three positions are enough to define the type of the joint and its axis, but image data contain noise which affects the accuracy of the results [1, 9, 10]. To minimize the error, data points must be greater than 3 and taking the possible combinations of 3, several centres and radii of curvature are calculated. Applying the Chauvenet's criteria [11] for discarding possible inconsistent data and taking the mean value of the parameters calculated henceforth yield better results.

3.1 3-D algorithm

Even though observing and monitoring a beacon located at the tip of a manipulator are much simpler than observing and identifying its picture, some practical problems still exist. Firstly the beacon must be of a distinctive colour such that it can easily be noticed in a complicated image. In a previous work [5] of the same authors, how colours are identified in three different colour systems is described with their respective advantages and disadvantages. Example trials are given in finding out a crimson red spot in the image. Secondly the beacon must be observed by two cameras, the difference in its location in the images releasing its distance from the cameras. In another work [6] of the same authors results of example trials in finding the absolute coordinates of a beacon at the tip of a manipulator are presented with the means of camera calibration and accuracy achievements. In this paper, how the geometric parameters of an active manipulator joint are found is described by looking at the P_{ix}, P_{iy}, and P_{iz} coordinates of the beacon at point P_i. There is a set of coordinates for n many such points obtained by vision to start with. These coordinates are transformed into the 2-D space where the circle they form is seen in true size with the following steps:

Step 1: Select any 3 points from the data set as shown in Fig. 3.

Step 2: Translate the origin of the coordinate frame to point P_1 as seen in Fig. 4 using the following translation matrix to get a coordinate frame x', y', z':

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & -P_{1x} \\ 0 & 1 & 0 & -P_{1y} \\ 0 & 0 & 1 & -P_{1z} \\ 0 & 0 & 0 & 1 \end{bmatrix} . \tag{1}$$

Step 3: Rotate x', y', z' frame about z' by angle θ to get a new frame x'', y'', z'' at the end of which P_2 becomes in the x''-z'' plane by the following rotation

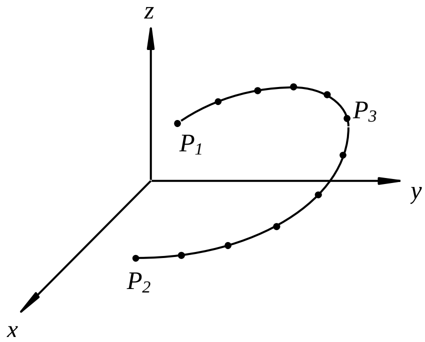


Fig. 3. An active revolute joint will lead a beacon at the tip of a manipulator along a circular track as shown. Centre of the circle, its radius and the axis perpendicular to the plane of the circle passing through the centre need to be defined. An infinite radius corresponds to an active prismatic joint.

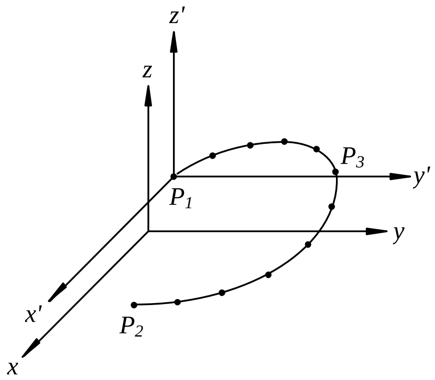


Fig. 4. Origin of the coordinate frame being translated to P_1.

matrix:

$$\mathbf{R}_{z,\theta} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

where

$$\sin\theta = \frac{P_{2y'}}{\sqrt{(P_{2x'})^2 + (P_{2y'})^2}}, \quad \cos\theta = \frac{P_{2x'}}{\sqrt{(P_{2x'})^2 + (P_{2y'})^2}}.$$

The frame is further rotated about y'' by angle β to get a new frame x''', y''', z''' (Fig. 5) at the end of which P_2 becomes on the x''' axis by the following rotation matrix:

$$\mathbf{R}_{y,\beta} = \begin{bmatrix} \cos\beta & 0 & \sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{3}$$

where

$$\sin\beta = \frac{P_{2z''}}{\sqrt{(P_{2x''})^2 + (P_{2z''})^2}} = \frac{P_{2z'}}{\sqrt{(P_{2x'})^2 + (P_{2y'})^2 + (P_{2z'})^2}},$$

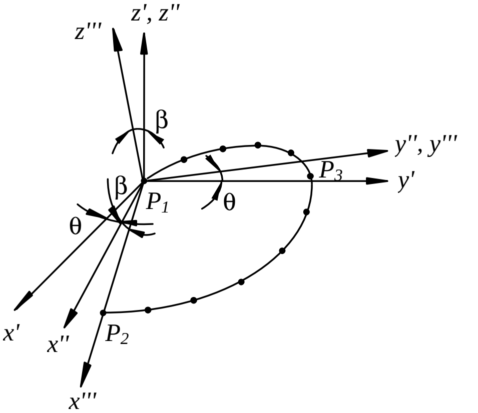


Fig. 5. Successive rotations of coordinate frame to align P_1 and P_2 on the x axis.

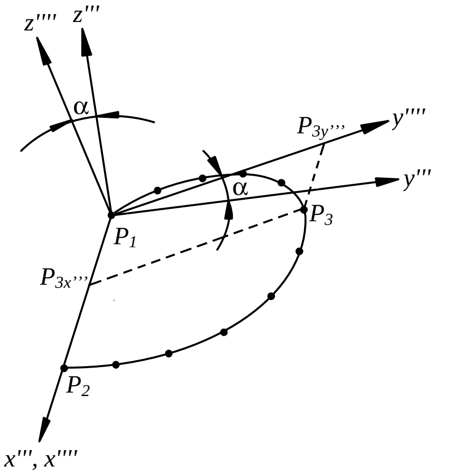


Fig. 6. Final rotation of the coordinate frame such that the z axis becomes perpendicular to the plane of the circle the data points form.

$$\cos\beta = \frac{P_{2x''}}{\sqrt{(P_{2x''})^2 + (P_{2z''})^2}} = \frac{\sqrt{(P_{2x'})^2 + (P_{2y'})^2}}{\sqrt{(P_{2x'})^2 + (P_{2y'})^2 + (P_{2z'})^2}}.$$

Step 4: Finally the frame is further rotated about x''' axis by an angle α to get a new frame x'''', y'''', z'''' at the end of which P_3 will lie in plane x''''-z'''', as shown in Fig. 6. Rotation matrix about x''' axis is as:

$$\mathbf{R}_{x,\alpha} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{4}$$

where

$$\sin\alpha = \frac{P_{3x'''}}{\sqrt{(P_{3y'''})^2 + (P_{3z'''})^2}}, \quad \cos\alpha = \frac{P_{2y'''}}{\sqrt{(P_{3y'''})^2 + (P_{3z'''})^2}}.$$

Step 5: Calculate the coordinates of all the other data points with respect to the x'''', y'''', z'''' frame using steps 3 and 4.

Step 6: If all the points lie only on the x'''' axis, then the joint type is prismatic and x'''' axis is the axis of the prismatic motion. This axis is the same as the z axis in

D-H convention. If points do not all lie on the x'''' axis the joint is revolute. Taking the combinations of these points circle centers are calculated. Chauvenet's criterion is applied to identify the possible inconsistent values which are then discarded. Then the mean values of the coordinates of the centre are calculated. A perpendicular line to the x''''-y'''' plane and passing through this centre is defined as the z axis by D-H convention [2]. Then centre point in 3-D and axis of motion (z) is found by taking the inverse transformation in the order of $\mathbf{R}_{x,\alpha}$, $\mathbf{R}_{y,\beta}$, $\mathbf{R}_{z,\theta}$.

Step 7: Steps 1 to 6 are repeated for the next joint of the manipulator while the others are fixed.

Step 8: In D-H convention a unique coordinate frame is set to define each joint and fixed to it. These coordinate frames are enumerated by a subscript. If the z_i and z_{i-1} axes intersect, the x_i axis has a direction determined by the cross product of z_i and z_{i-1} axes. If the z_i and z_{i-1} axes are parallel, then the direction of the x_i axis is assumed to be the same as that of x_{i-1} axis.

Step 9: In D-H convention, the y_i axis is determined by means of the right hand rule after z_i and x_i are determined so as to complete the Cartesian x_i, y_i, z_i coordinate system.

Step 10: Steps 8 and 9 are repeated for each degree of freedom for the coordinate frame of each link.

Step 11: In D-H convention, angle α_i, the angle between the z axes of two successive joints can now be defined. It is measured from z_{i-1} to z_i, the positive sense being determined by the right hand rule in $+x_i$.

Now the values at hand are the coordinates of the joint centres X_{c_i}, Y_{c_i}, Z_{c_i}, i being a counter for the joints, axes of motion and frame coordinates attached at each joint according to D-H convention. A manipulator independent robot control software must be capable of automatically generating the forward and/or inverse kinematic model of a manipulator. D-H convention provides an easy and versatile description and hence steps 6 to 11 described above seek the parameters used in this convention. From this data a_i, α_i, d_i and θ_i for the ith mobility must be extracted to complete the requirements of the D-H convention which can be constants or variables according to the manipulator configuration [12, 13].The manipulator independent robot control software referred to in this work has a program segment containing mathematical models of different manipulator arm configurations.

4. An example

In this section an example of defining the kinematic parameters of a robot manipulator by viewing it through a pair of video cameras is given. The manipulator under consideration is of Stanford type, with 3 degrees of freedom. First mobility, nearest to the ground is a revolute joint about a vertical axis. Second is also a revolute joint whose axis is intersecting and perpendicular to the first joint axis.

Third mobility is a prismatic joint whose axis is passing through the intersection point of the axes of the first two joints. To obtain a mathematical description of the joint axes and type of motion as revolute or prismatic, the actuators are incremented one joint at a time by the control computer and the image of a red beacon located at the tip of the manipulator is recorded and image coordinates of its centroid are calculated.

To identify the first joint, position commands to the associated actuator are incremented and the locations of the beacon or the characteristic point at the tip are recorded. 10 readings are taken by each camera as shown in Fig. 7. Since the motion is rotational, the characteristic point traces a horizontal circle. The camera plane is below this circle and so the circle appears as an ellipse, major axis horizontal in both cameras. Because the cameras are identical, the elliptic paths they see are identical except a horizontal offset due to the separation between the cameras which is called the *baseline distance*. The coordinates of points in the image are in pixels and each point has two image coordinates, on the right camera image as X_R, Y_R and on the left camera image as X_L, Y_L. These are then converted into real positions in centimeters with respect to the camera coordinates. The appearance of 10 data points in camera coordinate system is shown in Fig. 8. Figure 8a shows a plan view of the circular path in Z_c-Y_c plane, hence data points are scattered about a horizontal straight line 65 cm above the plane formed by the optical axes of the cameras. View of the circle in X_c-Y_c plane is also a straight line at the same altitude as shown in Fig. 8b. There are position errors as expected, but they do not affect clear understanding of the shape of the path and its geometry. The circle in Fig. 8c drawn to fit the data points has a radius of 96 cm. The circle radius and altitude obtained by visual data fit to the actual results measured from the rig. Appearance of the data points in the world coordinate frame is shown in Fig. 9. Figures 9a and b show the plan view of the circular path as a horizontal straight line 146 cm above the origin fixed to the manipulator base. Figure 9c shows the path in true size, a circle of radius 96 cm, same as in camera coordinate system.

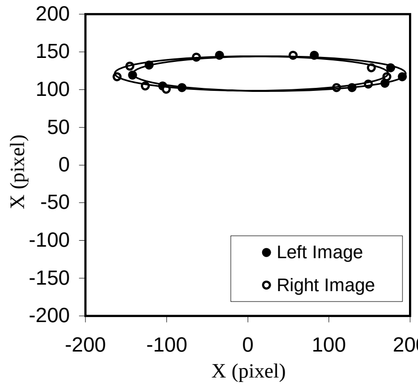


Fig. 7. Left and right camera images of the characteristic point at the tip of the manipulator when the first joint is in action. The associated actuator is incremented 10 times and the position of the beacon at 10 different locations is recorded.

The second joint of the manipulator is also a revolute with axis of rotation horizontal and intersecting with the vertical rotation axis of the first joint. The

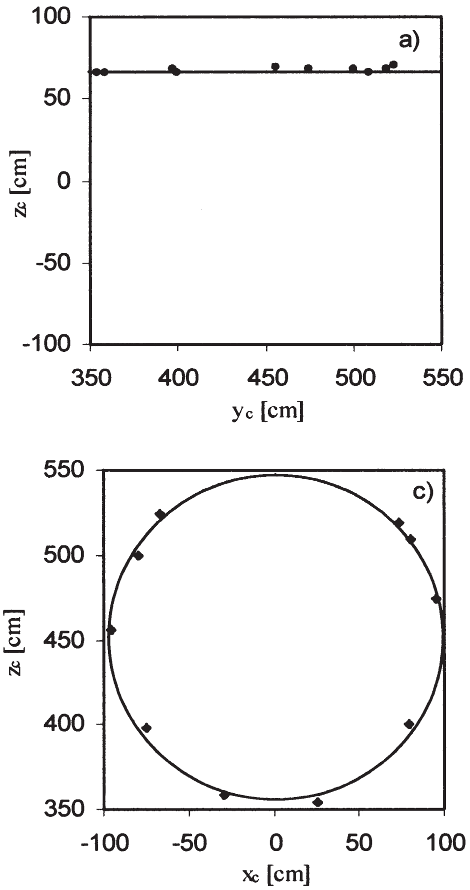


Fig. 8. Views in 3 different planes of the characteristic point at the tip of the manipulator when the first joint is in action with respect to the camera coordinate frame.

range of motion is limited in comparison with the first joint. To define the joint axis geometry visually, the control computer has incremented this degree of freedom and the beacon at the characteristic point is viewed by the cameras to take 10 data points. The actual arc is in vertical plane whose centre is 47 cm above the optical axis of the right camera. Due to the relative positions of the camera and manipulator the actual circular arc traced is seen as an elliptic arc as seen in Fig. 10. Views obtained by right and left cameras are identical and the horizontal offset is due to the baseline distance. The pixel coordinates of data points obtained from the images of Fig. 10 are first converted into camera coordinates and then, to world coordinates. Appearance of the points in 3 mutually perpendicular planes of the camera coordinate frame is shown in Fig. 11 in real positions, units being cm. Path followed is a vertical circle which appears as ellipses in X_c-Y_c and Y_c-Z_c planes as seen in Figs. 11a and c. The vertical plane of the manipulator is about 36 degrees

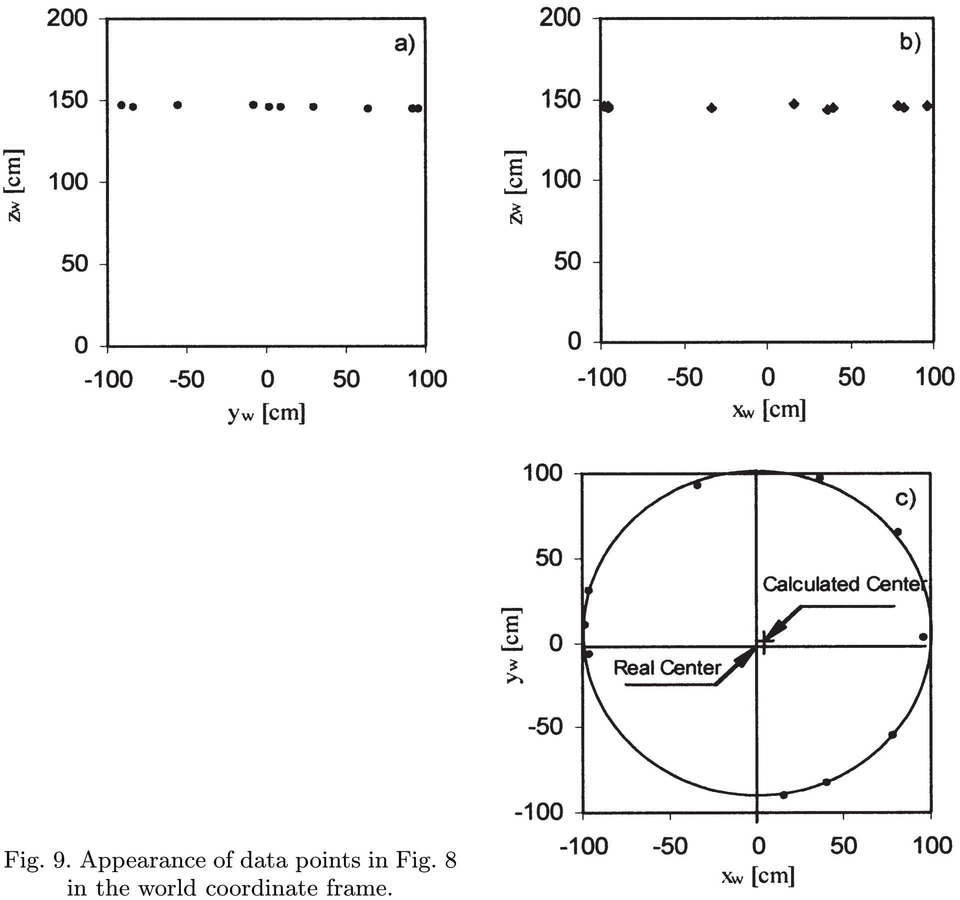


Fig. 9. Appearance of data points in Fig. 8 in the world coordinate frame.

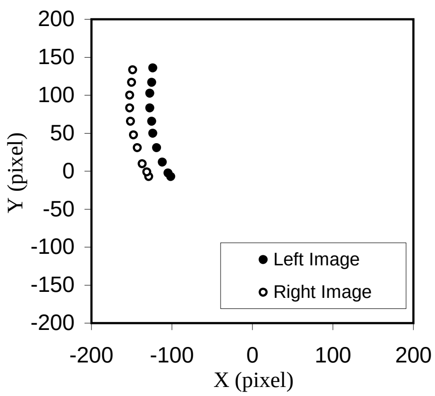
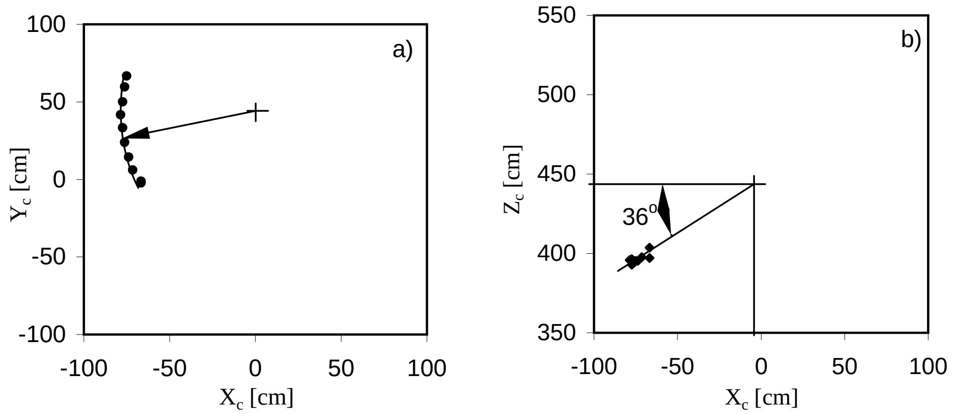


Fig. 10. Left and right images of the path that the characteristic point traces when the second joint is in action.



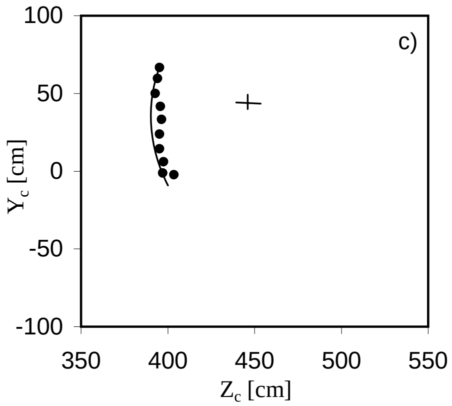
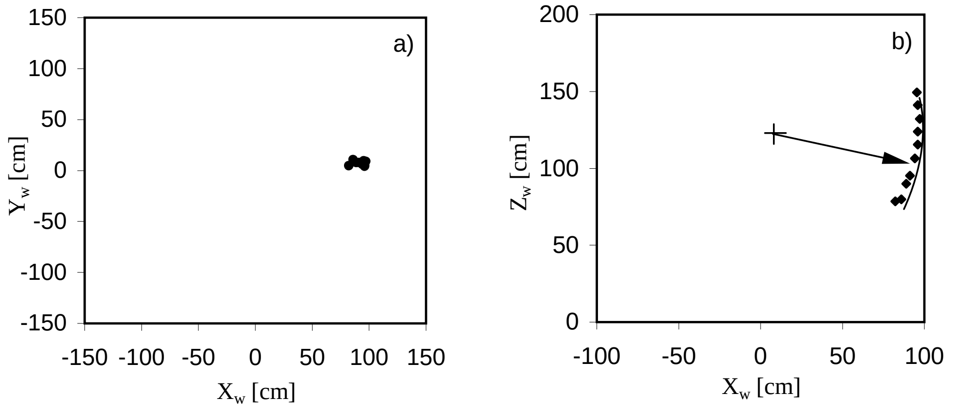


Fig. 11. Views in 3 different planes of the characteristic point at the tip of the manipulator when the second joint is in action, with respect to the camera coordinate frame.

oblique to the cameras as seen in Fig. 11b. Z_c-X_c view should show a distribution about a straight line since it is the plane view of the circular path. The angle of the manipulator plane with respect to the camera coordinates is seen in this view in true size. Figure 12 shows the data points in the world coordinate system.

Third joint of the manipulator is prismatic. The rails carrying the third moving link are made symmetrical with respect to the first and second degrees of freedom. Since this motion is a translation, all the points on the third link have the same kinematics. They all have the same velocity in magnitude and direction and they trace the same path, straight lines parallel to the rails. Therefore in kinematic consideration, the prismatic axis can be assumed any line parallel to the rails. Normally the position of the characteristic point is important, hence for example, a gripper holding an object will be there. To see how the characteristic point moves with this joint, associated actuator is incremented by the control computer and the beacon at this point viewed by the cameras at 10 different locations. The images



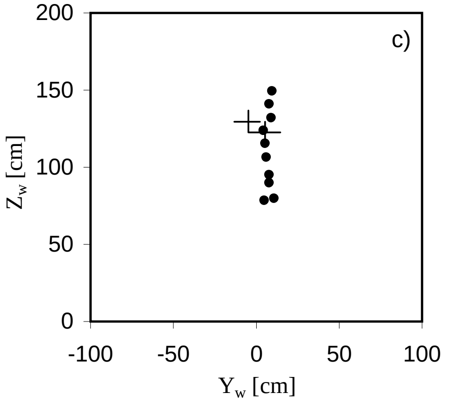


Fig. 12. Appearance of data points in Fig. 11 in the world coordinate frame.

of the characteristic point viewed by cameras are shown in Fig. 13. As expected, loci of the characteristic point viewed by both cameras are identical straight lines with horizontal offset due to the baseline distance. Figure 14 shows the data points in 3 mutually perpendicular planes of the camera coordinate system. In Fig. 14a the locus appears as a sloping straight line. As the prismatic pair was at such a position during the experiment. The straight line is about 15 cm above the centre of the revolute joint of the second mobility. The beacon is actually placed this much above the rails of the prismatic joint. Figure 14b shows a top view of the locus which is again a straight line. The axis of the first revolute joint appears as a point in this view and rails of the prismatic joint are symmetrical with respect to it, but the characteristic point is not at the axis of symmetry but has some offset. Figure 14c shows the locus in Z_c-Y_c plane. Figure 15 shows the data points and their locus in the world coordinate frame. Points in all views indicate a clear straight line displacement.

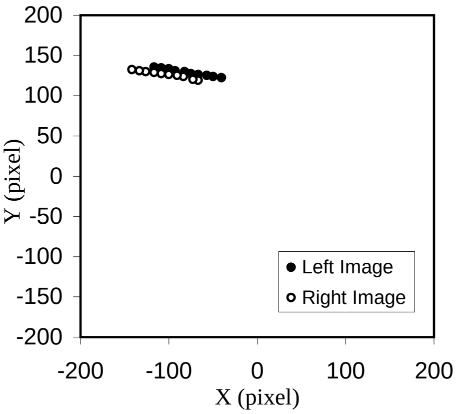


Fig. 13. Left and right camera images of the characteristic point at the tip of the manipulator when the third joint is in action.

When the data point coordinates shown in Fig. 9 are examined, the centre of the circular arc they form is calculated to be at coordinates $X_\mathrm{w} = -0.28$ cm, $Y_\mathrm{w} = 4.29$ cm, and radius = 95.75 cm. In reality centre coordinates should be at $X_\mathrm{w} = 0.0$ cm, $Y_\mathrm{w} = 0.0$ cm and radius = 96.0 cm. For this joint, centre coordinates are measured 4.29 cm off the actual. Error in radius is negligible.

Processing of the world coordinates of the data points taken when the second joint is in action, as shown in Fig. 12, yields the information that the mobility is via a revolute joint. The coordinates of the circle centre are: $X_\mathrm{w} = 6.73$ cm, $Y_\mathrm{w} = -8.51$ cm, $Z_\mathrm{w} = 120.70$ cm, and radius = 90.34 cm. In reality, centre coordinates should be at $X_\mathrm{w} = 0.0$ cm, $Y_\mathrm{w} = -5.5$ cm, $Z_\mathrm{w} = 127.0$ cm, and radius = 96.0 cm. Centre is calculated as about 9.69 cm displaced from real coordinates. Radius contains 5.66 cm error. Error in radius is less than 6 %.

Processing of the world coordinates taken when the third joint is in action, given in Fig. 15, indicate that the mobility is via a prismatic joint. As seen in Fig. 15b the locus of the characteristic point is a straight line 18.0 cm offset upward from the calculated axis of the second revolute joint. In reality, this offset is only 10.0 cm. The offset of the locus from the actual axis of the second revolute joint can be measured to be 11.52 cm from the same figure.

The world coordinates of the data points observed during the motion of each degree of freedom are processed by a routine to yield the D-H model parameters as shown in Table 1a. The same parameters taken from the rig are shown in Table 1b where a and d are distances in centimeters, α and θ are angles in degrees. A D-H model of the manipulator with the associated parameters is shown in Fig. 16. During experimentation, origin of the inertial world coordinates is assumed to be at the base of the robot. Z_0 axis is vertically up and passing through the intersection point of the first and second revolute axes. a_1 is a possible offset between these two revolute axes in X_1 direction. d_1 is the distance between the second revolute axis and origin. In reality a_1 is zero and d_1 is 127 cm. In a_1, there is an error less than 3 mm which is negligible. In d_1 error is about 7 cm, which is 5.5 %. While viewing the manipulator plane in real size, the offset between the revolute axis of the first joint which is vertical and seen in true size and the axis of the second

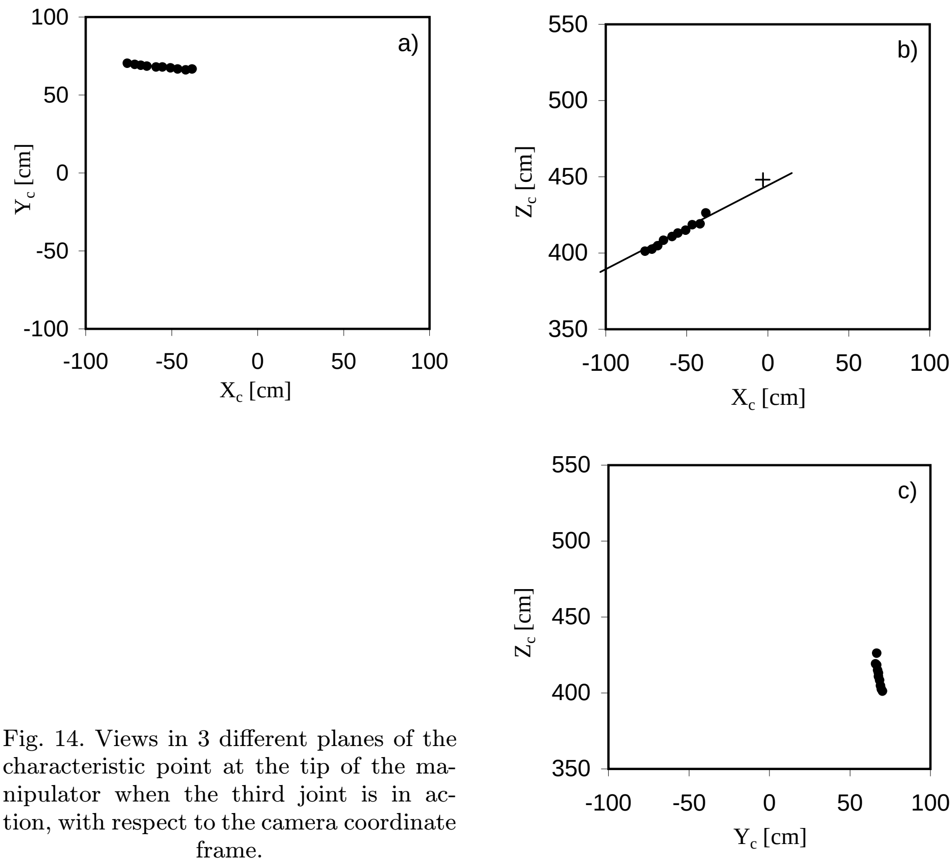


Fig. 14. Views in 3 different planes of the characteristic point at the tip of the manipulator when the third joint is in action, with respect to the camera coordinate frame.

revolute joint which is horizontal and seen in point view, is a_2. This is 10 cm on the rig and calculated as 9.78 cm by the computer, error being less than 2.5 %. d_2 is the offset between the second and third joints in the horizontal plane. This of course refers to the characteristic point, which is placed in 5 cm offset from the first joint revolute axis. Program calculates this from visual data as 4.69 cm and in proper direction, error being 6.5 %. For the third joint, a_3 is the offset between the centroid of the characteristic point and the second revolute axis. Normally it is made zero to simplify kinematic equations. In visual kinematic identification it also came up as zero. d_3 is the net displacement covered by the characteristic point during the experiment along the prismatic axis direction, which is a variable. This is calculated to be 46.3 cm by the computer which is the measurement taken from an arbitrary prismatic position. The manipulator has a total range of 1 meter in this mobility. α_i is the relative rotation angle between the positive z_{i-1} and z_i axes of coordinate frames fixed to the manipulator links. They are calculated as

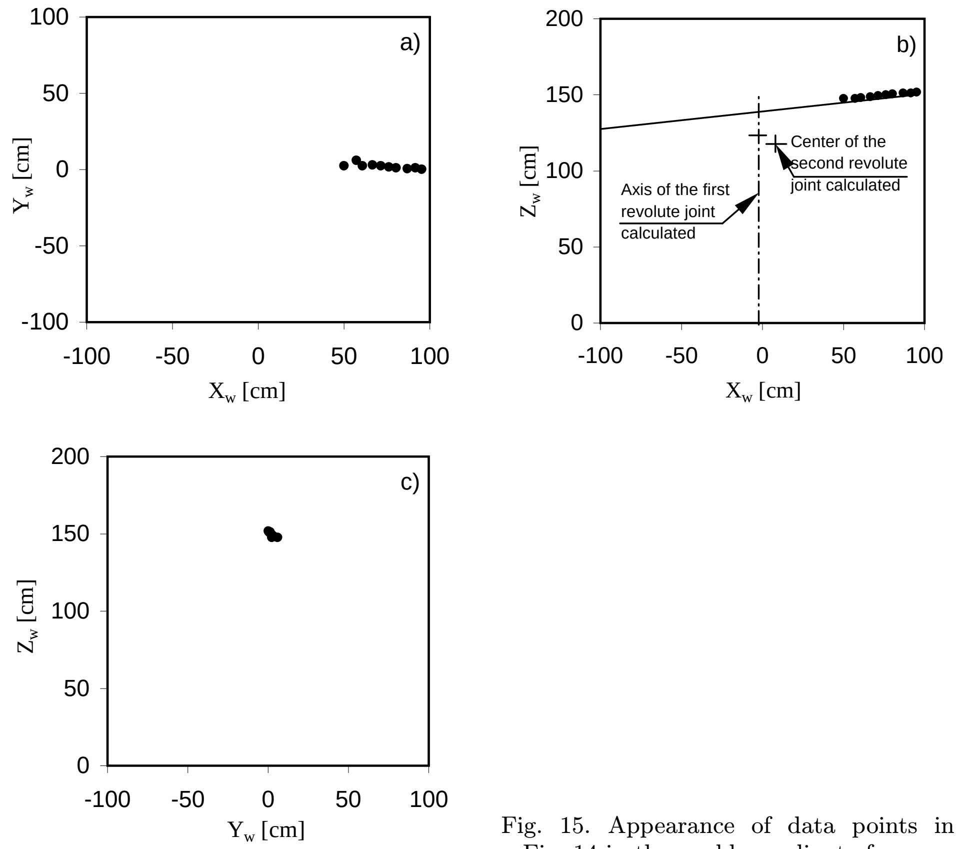


Fig. 15. Appearance of data points in Fig. 14 in the world coordinate frame.

90, 90 and 0 degrees for the 3 joint in succession, which are correct. These sets of measurements are calculated within a tolerance of ± 0.02 radians. θ_i is the relative rotation angle between x_{i-1} and x_i. In the first joint, θ_1 is the mobility itself and is incremented by the computer. The numerical value of 356 degrees shown in Table 1a is the angular position of the first data point which is the measurement taken from an arbitrary revolute position and is not of importance in the model. θ_2 is the mobility of the second revolute joint and similarly the value 106.7 degrees shown in Table 1a is the numerical value arbitrarily taken from the first data point. For the third joint, θ_3 is constant and should be zero. The computer calculated it also zero.

5. Conclusion

The algorithm presented in this work is capable of generating the kinematic formulas for any type of spatial manipulator composed of revolute and prismatic

T a b l e 1. Calculated (a) and actual (b) parameters of the manipulator shown in Fig. 1 according to D-H convention

	a [cm]	d [cm]	α [deg]	θ [deg]
First link	−0.28	120.71	90	356.0
Second link	9.78	−4.69	90	106.7
Third link	0.00	46.30	0	0.0

(a)

	a [cm]	d [cm]	α [deg]	θ [deg]
First link	0.00	127.00	90	variable
Second link	10.00	−5.00	90	variable
Third link	0.00	variable	0	0.00

(b)

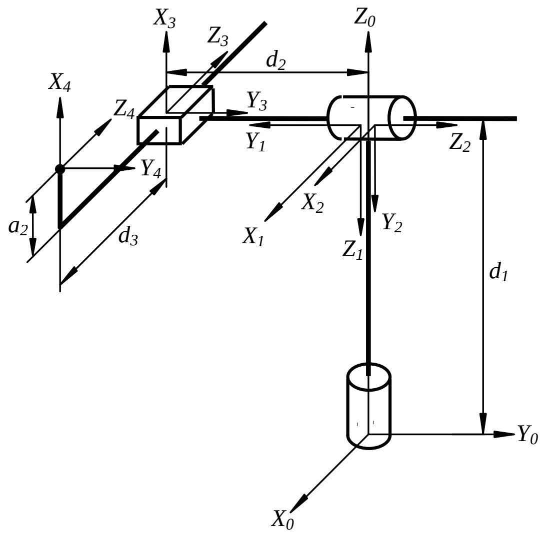


Fig. 16. D-H model of the Stanford type manipulator shown in Fig. 1, parameters and configuration identified by visual data.

joints. Visual data collection provides a simple off-the-hands method for coordinate measurement and is used in the determination of link parameters in this work. The main source of error is on the vision side of the experiment [1, 9, 10]. The basic reasons of error and feasible cures are as follows:

– Higher resolution cameras, much better than those used in this work are now available and more accurate pixel coordinates hence can feasibly be obtained.

– All camera lenses induce image distortions to some extent and true coordinates of a point in the image hence contain position errors. Distortions can be partially eliminated by mathematical manipulations on data, but certainly a better quality lens will reduce distortion errors.

– Identifying a certain colour among the pixels forming the image is not an easy task. Colour data contains noise, which can be partially filtered by mathematical manipulations, but lenses themselves cause the generation of erroneous data with the optical aberrations they impose. Illumination is also important. A monochromatic lighting will reduce false points in the image.

– In the work described here, cameras are located 454 cm away from the manipulator, and hence, any error in pixel coordinates is amplified greatly on world coordinates. Observing the beacon through an optical zooming will improve accuracy. The whole software may perhaps be modified to use a computer controlled zooming lens and setting the focal length to a new adaptively selected position.

The experimental accuracy obtained in this work may or may not be tolerable according to the nature of the work, but nevertheless, a consistent method is set to determine the kinematic parameters of an undefined robot manipulator automatically.

Acknowledgements

The material presented in this paper is obtained from an experimental rig which had been purchased via a grant of the State Planning Organization with grant number 91 K 120 830.

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Received: 10.11.2004
Revised: 6.4.2005