4. FABRICATION DETAILS AND EXPERIMENTAL VERIFICATION

4.1 CONSTRUCTIONAL FEATURES

The proposed configuration, which is visualized and discussed in the chapter 2, is almost equivalent to a human arm. However, it is to be realized practically. The human arm is an ideal example of a robot manipulator mechanism considering its maneuverability, adaptability and joint operations. Basically, a human arm has three rotational movements obtained through one higher and one lower pair. The higher pair is the shoulder joint and the lower pair is the elbow joint. The actuation of higher pair is the complicated task since it has two (three) degrees of freedom. A compact design procedure is suggested to actuate the higher pair (spherical joint). The human arm has a six degrees of freedom out of which three degrees of freedom are obtained by the wrist. The wrist is between the end-effector and the configuration. The present work is on the analysis of the configuration; only three degrees of freedom are visualized. If the present manipulator is intended to be used as a human arm, a wrist mechanism can be included in between the end-effector and the configuration end point, which provides different orientation for the work piece. As explained in the chapter 2, the heart of this configuration is the spherical pair. The spherical pair is fabricated using an accurate machining technique and is mounted on two spherical cup bearings. The protruded lever attached to the spherical joint is used for carrying the load as well as for applying the load. A lower revolute pair is attached to one end of the protruded lever, which acts as an elbow joint and the lever acts as an upper arm. From the elbow joint, another link is used, which acts as a forearm. The end-effector is
connected at the end of the forearm. The other end of the protruding lever from spherical joint is connected to a sliding pair, which slides on a circular arc or sector arm. Thus, the forearm and the upper arm can move to different angles as the lever slides over the circular arc. It is obvious that the spherical joint acts as a fulcrum point in between the robot arm and the back sliding arm. This gives mechanical advantage by providing counter weight on the sliding arm, thus the torque required to lift the work piece can be reduced. The circular sliding pair assembly is rotated using a rotational pair, thus the full swing of the forearm and upper arm are obtained.

The Fig. 4.1 illustrates the realization of the proposed robot arm. An experimental model with simple structure is fabricated in the laboratory to visualize the proposed model of the robot arm. In the present fabrication, all the three angular movements are obtained through stepper motors. For the sliding pair and revolute pair, stepper motors of low torque rating are used where as for rotation, a higher torque stepper motor is used. All the operations are interfaced with computer for experimental verification. A hybrid system of actuation can also be used using pneumatic or hydraulic drives as well as direct current (DC) drives. Due to simplicity of electric drive, stepper motors are considered in the present model for actuation. The actuation can be performed such that the three rotations are obtained simultaneously or an individual joint is actuated at a time.
1 Support structure
2 Spherical ball with arm
3 Ball support structure with bearing
4 Slide-over sector arm
5 Slide drive
6 Elbow drive
7 Revolve with circular sector arm moving drive

Figure 4.1 Isometric view of the proposed manipulator
4.2 FABRICATION DETAILS

To demonstrate the basic principle of the developed robot configuration, a model is fabricated in the laboratory. The following are the sub-assemblies of the model.

1. The metallic support structure
2. A spherical ball with arm
3. Ball support structure with bearing
4. Slide over sector arm
5. Slide drive
6. Elbow joint and drive
7. Revolve with circular sector arm moving drive

The complete assembly drawing with part list is shown in Appendix A.

A box type supporting structure is fabricated using 25mm width x 3mm thick angle. The angles were cut into size and welded together to form a separate structure for the present manipulator. The provisions are made to mount stepper motor for rotary motion of the assembly. The provision is also made to support the spherical bearings to accommodate the ball joint.

A ball is machined on a lathe using a ball turning attachment. The ball is machined accurately to a dimension of 50mm. A hole of 10mm diameter is machined diametrically to accommodate an arm. The ball is further polished and buffed to get a high surface finish. The Fig. 4.2 and 4.3 illustrate the support structure and ball with arm respectively.
Figure 4.2 Support structure

SCALE 1:10

Angle sections
475mm length - 04nos.
360mm length - 08nos.

PARTS LIST

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Figure 4.3 Spherical ball with arm

SCALE 1:2

Spherical ball with buffing
A spherical ball is allowed to seat on two spherical cup-bearing arrangements. The cup-bearings are manufactured and fastened to 20mm rod where axial adjustment is possible through screw mechanism. The hardened cup-bearing with set of balls is mounted at the end of each rod. This provides a perfect seating for the spherical ball. Two support bearings on either side of the ball provide a good ball and socket joint arrangement without much play. The play is adjusted with fine screw so that smooth movement of the ball is achieved. A lock nut arrangement is also provided to lock the ball supporting cup-bearing to a particular position. Adjustments are provided to minimize the play between the support bearings and the spherical ball. The Fig. 4.4 illustrates the spherical ball bearing assembly.

A circular sector arm is essential to achieve angular motion in one plane and the circular rotation in another plane. The accuracy of this circular section is important since it acts as a joint of two degrees of freedom. For achieving high accuracy, the circular ring is manufactured from a 180mm diameter bar stock of 25mm length. It is machined on a lathe to get inner radius of 75mm and outer radius of 85mm. Then by parting the ring to half, the required circular section is made. The surface grinding is also done to achieve good surface finish for better movement of the slider mechanism.

The slide mechanism is illustrated in Fig. 4.5, which is mounted on one end of the arm of the spherical element. The slider is machined from rectangular mild steel block and 10mm slots are provided for the smooth resting of the circular sector arm. On either side of the slot, brass plates are mounted, which act as the
Figure 4.4 Ball support structure with bearing assembly

Figure 4.5 Slide over sector arm assembly

<table>
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bearing for smooth sliding of the circular sector arm. These plates can be replaced whenever they wear out and also used to adjust the play between the slide for fine movement.

The protruding lever at the other end of the spherical ball, projecting outward acts as an upper arm of the manipulator. The upper arm is actuated by a stepper motor. An arrangement is made to convert the rotary motion of stepper motor into translatory motion of the upper arm. A screw-nut mechanism is used for this purpose. The Fig. 4.6 illustrates the corresponding slide drive assembly. As the motor rotates in either direction, the screw leads or retracts. This motion is used to slide one end of the arm of the spherical ball on the circular sector arm. Since circular sector arm has large radius, the length movement is to be non-linear. Hence the screw mounting and stepper motor mounting are provided with hinge support so that the angular shift of the screw-nut mechanism is taken care of. A metric 8mm (M8 x 1) fine thread screws are used for converting rotary motion into linear motion. One end of the bolt is brazed with a cup so that when it is rotated, the cup pushes the slider to the required distance. At the end of the upper arm, an elbow joint and drive assembly is mounted. An elbow attached to the joint acts as a forearm. This joint is also actuated using a stepper motor. The Fig. 4.7 illustrates the elbow drive assembly.

The revolving assembly with circular sector arm is rotated through a high torque stepper motor. The shaft from the sector arm is supported by a ball bearing and other end is coupled to a motor.
Figure 4.6 Slide drive assembly

Figure 4.7 Elbow drive assembly
4.3 EXPERIMENTAL SETUP

After the successful fabrication of the proposed manipulator in the laboratory, an experiment is performed to verify the analytically obtained results. The stepper motors are interfaced with a computer through 8255PPI card. An interactive program is written in ‘C’ to actuate the stepper motors. The provisions are made to simulate and present graphically the robot arm for a given input by the user. The output in the form of a coordinate point reached by the end of arm is also displayed. This simulated result is again experimentally verified using traveling microscopes. The assembly of the robot is kept on a surface plate and two traveling microscopes are used to measure the coordinates in different planes. Initially, for particular end of arm position, the microscopes are set to (0,0,0). Then control program is executed after receiving the inputs. The readings are taken from the microscope after five minutes allowing for the manipulator to reach stability. This procedure is repeated for number of inputs and the results are tabulated. Fig. 4.8 illustrates the details of the parts of the proposed robot configuration in exploded view. Fig. 4.9 shows the photograph of the model.
Figure 4.8 Exploded view of the proposed manipulator model
Figure 4.9 Photograph of the proposed manipulator assembly
4.4 RESULTS AND DISCUSSION

It is obvious that the coordinate transformation of the end point of robot depends on three angular rotations $\theta_1$, $\theta_2$ and $\theta_3$. Initially, it was confirmed that the robot end point has unique coordinate position for a particular angular twist. Basically, there are three parameters to control the coordinate point of present robot viz. $\theta_1$, $\theta_2$ and $\theta_3$. Initially, the experiment is carried out by varying one of the parameters at a time while keeping the other two parameters constant. The Fig. 4.10 and Fig. 4.11 illustrate the XY plot of the end-effector for the variation of $\theta_1$ keeping $\theta_2$ and $\theta_3$ at constant values. The obtained results exactly match with analytical values obtained through direct kinematic analysis. The experiment is repeated for determining the coordinate position and the results are verified. The Fig. 4.12, 4.13 and 4.14 illustrate the graphical coordinate position of the robot arm for changes in different angles $\theta_2$ and $\theta_3$ in XY, YZ and ZX plots respectively. The results are compared with the analytical results obtained in chapter 3. The maximum error obtained in Z-direction (X-Y plane) is a larger value of 3.66mm (discrepancy of 6% with analytical value) where as in X and Y-directions, the maximum error is 2.86mm and 1.19mm respectively. The error in the experimental result is attributed to number of factors such as alignment error, bearing play, actuator resolution etc. Since all the power actuation is made through stepper motors, there is always a possibility of ±1 step error in the stepper motor. The resolution of the stepper motor is 1.8°.
$\theta_1 = 0^\circ$ to $360^\circ$
in steps of $30^\circ$
$\theta_2 = 0^\circ$
$\theta_3 = 30^\circ$
Link lengths: $L_1 = 81$mm
$L_2 = 83$mm

--- Analytical
--- Experimental

Figure 4.10 X-Y plot for comparison of work envelope with $\theta_1$ as variable and $\theta_2$ and $\theta_3$ as constants

$\theta_1 = 0^\circ$ to $360^\circ$
in steps of $30^\circ$
$\theta_2 = 15^\circ$
$\theta_3 = 30^\circ$
Link lengths: $L_1 = 81$mm
$L_2 = 83$mm

--- Analytical
--- Experimental

Figure 4.11 X-Y plot for comparison of work envelope with $\theta_1$ as variable and $\theta_2$ and $\theta_3$ as constants
Figure 4.12 X-Y plot for comparison of work envelope with $\theta_1$ as constant and $\theta_2$ and $\theta_3$ as variables

$\theta_1$ = constant 30°
$\theta_2$ = 0° to 45°
in steps of 15°
$\theta_3$ = 0° to 90°
in steps of 15°
Link lengths:
$L_1$ = 81mm
$L_2$ = 83mm

---

Figure 4.13 Y-Z plot for comparison of work envelope with $\theta_1$ as constant and $\theta_2$ and $\theta_3$ as variables

$\theta_1$ = constant 30°
$\theta_2$ = 0° to 45°
in steps of 15°
$\theta_3$ = 0° to 90°
in steps of 15°
Link lengths:
$L_1$ = 81mm
$L_2$ = 83mm

---
Figure 4.14 Z-X plot for comparison of work envelope with $\theta_1$ as constant and $\theta_2$ and $\theta_3$ as variables

$\theta_1 = \text{constant } 30^\circ$
$\theta_2 = 0^\circ \text{ to } 45^\circ$
    in steps of $15^\circ$
$\theta_3 = 0^\circ \text{ to } 90^\circ$
    in steps of $15^\circ$

Link lengths:
$L_1 = 81\text{mm}$
$L_2 = 83\text{mm}$

--- Analytical
--- Experimental