An Autonomous Image-guided Robotic System Simulating Industrial Applications

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Abstract–*This paper presents a robotic system based on a serial manipulator. The robot is a vertical articulated arm with 5 revolute joints having 6 Degree Of Freedom. Actuated with six precise servo motors, the system offers positional accuracy of ±0.5mm with a movement speed of 100mm/s. Forward and Inverse Kinematic model of the robot has been developed and its workspace has been analyzed to facilitate the use of robotic arm as a simulated industrial manipulator. Image processing has been done to make system more autonomous. Followed by a user's commands, the system acquires image of the environment using on-board camera. This image is processed to extract information about object's coordinates. Based on these coordinates, Inverse Kinematic model computes the required joint angles for the end-effector to reach at desired position and orientation thus enabling it to manipulate the object. The proposed system can be used in wide range of industrial applications involving pick and place, sorting and other object manipulation tasks. The system can also be potentially useful for heavy and 'giant' industrial applications after scaling up i.e. using huge robotic arm, employing multiple and better cameras and optimizing algorithms.*

Keywords: Robotic system, Manipulator arm, Industrial mechatronics

1 Introduction

The advancement in robotics has greatly influenced industrial automation processes. An industrial robot. according to Mikell Groover is "a general-purpose, programmable machine possessing certain anthropomorphic characteristics"[1]. Most of the industrial robots look like mechanical arms and many of these actually function like a human arm and are termed as articulated in scientific literature. Robot base turns around in a similar fashion as that of twisting torso of a human. On most articulated robotic arms, the shoulder and elbow pivots on the axis perpendicular to the arm axis and parallel to the plane containing the robot base. The wrist of articulated robotic arms offers motion in pitch while roll and yaw motions may or may not be there.

Industrial robots find their enormous applications in assembling, welding, spray painting, machine loading, manufacturing, construction, fabrication and so on. Considering an assembly task, following sequences are often executed [2]: (a) Pick up a complete part (or its piece) vertically from a horizontal work bench (b) Move the part in a horizontal plane to a point just above another place on the bench (c) Lower the part to the bench at the proper point thereby accomplishing the task. Not only in assembly, many other industrial applications require pick and place. Pick and place is probably the most common task in industry. Several industrial robots have the required capability to automate picking a part up from one location and placing it onto the other. They not only offer more accurate and fatigueless operations but they also speed up the process thereby increasing production rates. Most of the movements performed by pick and place robots are extremely cumbersome for the humans to do. Achieving repeatability and quality is essentially the outcome of consistent output of a robotic system. Moreover, in industrial robots, tooling can be interchanged as per application requirements.

A key word in the definition of an industrial robot is its programmability. These robots can be reprogrammed as per application scenario, operational environment and requirements of object to be manipulated. Although industrial robots are usually intended and trained for a specific task, some level of autonomy is certainly welcomed. Non-autonomous robotic systems need to be taught about the location of objects. This can be achieved by employing a teaching loader. Letting a robot know about the object location in this fashion is cumbersome, tedious and time consuming. Moreover, a robot will be needed to re-teach if the object location varies. This paper presents an autonomous robotic system having capability to detect objects through image guidance. Various sub-systems have been integrated to realize this concept. These sub-systems include mechanical, kinematics, electronics, computer vision and image processing .

The paper first briefly introduces overall system in Section 2. Developed kinematic model of the robotic arm is presented in Section 3. This includes forward kinematics as well as Inverse Kinematics (IK). Workspace analysis of the robot is also discussed in this section. Details of image guidance for object detection is explained in Section 4. Finally Section 5 comments on conclusions and future work.

2 Overall System

The overall system consists mainly of a Control Station (Standard PC), an on-board camera for image acquisition and a robotic arm with its controller interfaced with a PC. Block diagram of the overall system is illustrated in Figure 1.

The system waits for user command. As soon as it encounters a command, an image of the robot's surrounding is captured. The image is then processed using developed algorithm (Section 4) to extract the object centre coordinates. These coordinates are then used to calculate the necessary joint angles of the robot using IK model approach (Section 3). The values of the computed joint angles make sure that the gripper of the robot will reach at the required point as dictated by the object coordinates. If the object to be manipulated lies outside the robot's workspace, an error 'out of bound' is prompted to the user. Otherwise a low-level mapping routine converts the required joint angles into encoder ticks followed by the execution of the command. The system then iterates in the same loop unless user wants to exit. Detailed functional flowchart of the system is presented in Figure 2.

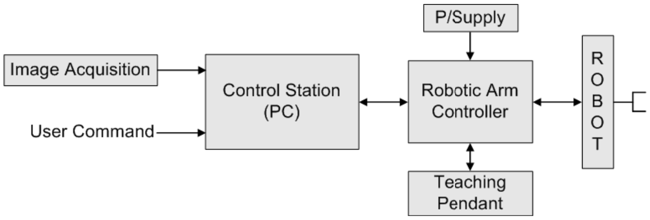


Figure 1. Block diagram of overall system

3 Kinematic Model of Robotic Arm

The system is primarily based on a 6 Degree Of Freedom (DOF) vertically articulated robotic arm, ED7220C. All its joints are revolute. Driven by six servomotors, the robot is equipped with optical encoders to close the feedback control loop. A gripper having capability to manipulate small sized objects (order of 0.5mm) is attached for object manipulation. The robot can mobilize itself provided the appropriate options are incorporated. This feature makes the robot a good candidate for simulating industrial tasks e.g. an automated assembly line or pick and place etc. Figure 3 shows the robotic arm while Table 1 depicts its joint and link specifications [3].

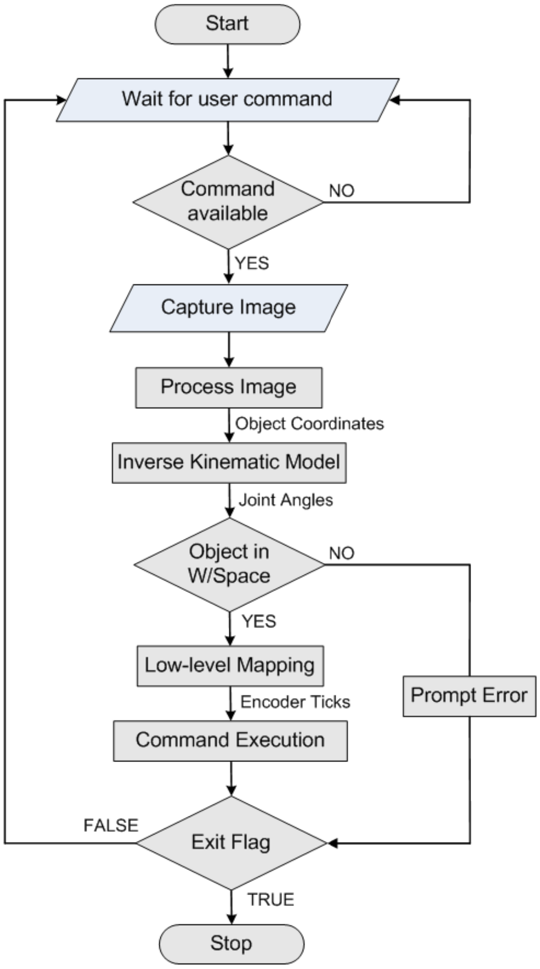


Figure 2. Functional flow chart

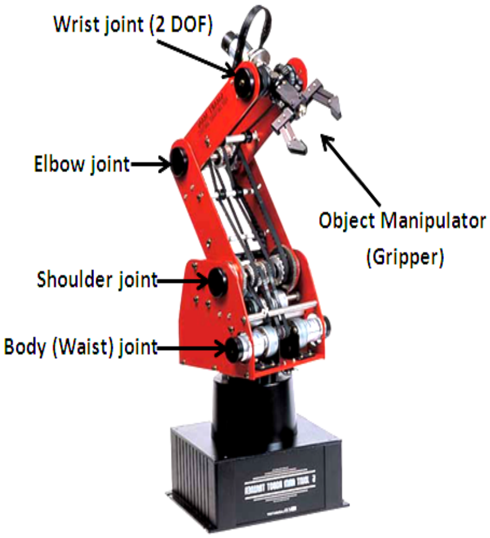


Figure 3. ED7220C–A 6 DOF articulated arm

Table 1. Arm joints and links specifications

Joint no.	Name	DOF	Link length [mm]
1	Waist	1	385
2	Shoulder	1	220
3	Elbow	1	220
4	Wrist	2	155

Kinematics is the study of motion without considering the forces involved in that motion. Kinematic analysis of a robotic mechanism essentially include: (a) Forward or direct kinematics (b) Inverse Kinematics.

3.1 Forward Kinematics

Given the link lengths and joint angles of a robotic manipulator, forward or direct kinematics computes the end-effector position and orientation. This always leads to a unique solution. Figure 4 illustrates the kinematic model.

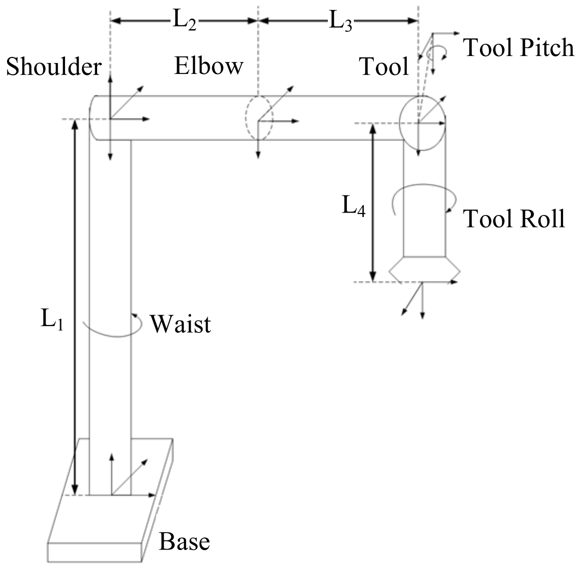


Figure 4. Kinematic model of ED7220C

The well known convention using Denavit-Hartenberg (DH) parameters has been followed. The frame assignment of various joints is elaborated in Figure 5. Wrist having 2 DOF is represented as tool roll and tool pitch.

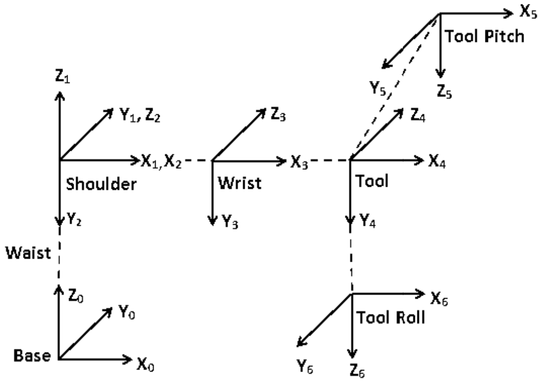


Figure 5.Frame assignment

After frame assignment, DH parameters of the robotic arm have been determined (Table 2). The nomenclature is as follows:

α_{i-1} = Angle from Z_{i-1} to Z_i measured about X_{i-1}
a_{i-1} = Distance from Z_{i-1} to Z_i measured along X_{i-1}
d_i = Distance from X_{i-1} to X_i measured along Z_i
θ_i = Angle from X_{i-1} to X_i measured about Z_i

Table 2. DH parameters of the robot

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	L_1	θ_1
2	-90°	0	0	θ_2
3	0	L_2	0	θ_3
4	0	L_3	0	θ_4
5	-90°	0	0	θ_5
6	0	0	L_4	0

Based on these DH parameters of the robot, each joint frame has been expressed in its preceding frame using general transformation matrix (1) [4]

$$ {}^{i-1}_{\ \ i}T = \begin{bmatrix} \mathrm{C}\,\theta_i & -\mathrm{S}\,\theta_i & 0 & a_{i-1} \\ \mathrm{S}\,\theta_i\,\mathrm{C}\,\alpha_{i-1} & \mathrm{C}\,\theta_i\,\mathrm{C}\,\alpha_{i-1} & -\mathrm{S}\,\alpha_{i-1} & -d_i\,\mathrm{S}\,\alpha_{i-1} \\ \mathrm{S}\,\theta_i\,\mathrm{S}\,\alpha_{i-1} & \mathrm{C}\,\theta_i\,\mathrm{S}\,\alpha_{i-1} & \mathrm{C}\,\alpha_{i-1} & d_i\,\mathrm{C}\,\alpha_{i-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

Having obtained the transformation matrix for each joint, exploiting the compound transformation property yields the overall transformation matrix from end-effector to base of the robot (2). The symbols A and B in (2) are given by (3) and (4) respectively.

$$ {}^0_6T = \begin{bmatrix} C_1C_5C_{234}+S_1S_5 & -C_1C_{234}S_5+S_1C_5 & -C_1S_{234} & C_1A \\ S_1C_5S_{234}-C_1S_5 & -S_1S_{234}C_5+C_1C_5 & -S_1S_{234} & S_1A \\ -S_{234}C_5 & S_{234}S_5 & -C_{234} & B \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

$$ \mathrm{A} = L_2C_2 + L_3C_{23} - L_4S_{234} \quad (3) $$

$$ \mathrm{B} = L_1 - L_2S_2 - L_3S_{23} - L_4C_{234} \quad (4) $$

Where sin and cosine terms involve summation of the corresponding angles e.g.

$$ C_{234} = \cos(\theta_2 + \theta_3 + \theta_4) $$

The first part (3X3) of the given transformation matrix determines the orientation of the end-factor with reference to base while the last column expresses its position ((5)-(7)).

$$ \mathrm{X} = C_1A \quad (5) $$

$$ \mathrm{Y} = S_1A \quad (6) $$

$$ \mathrm{Z} = \mathrm{B} \quad (7) $$

3.2 Inverse Kinematics

Inverse kinematics (IK) being more useful in industrial robotic applications than forward kinematics, determines how much joints of a robot should be manipulated to reach a specific position and orientation. IK can be computed using analytical, geometrical or numerical iterative approach. Modeling a robotic arm for its IK is a complex challenge as it does not converge to a unique solution. At least two solutions (termed as 'Elbow-up and Elbow-down in literature) are always obtained. The IK algorithm in real industrial robots addresses which solution a robot should opt for in such circumstances of multiple solutions.

Both analytical and geometrical techniques have been used to develop IK model of the robot arm (ED7220C). Analytical approach computes equations for the first three joints including waist, shoulder and elbow (θ_1,θ_2,θ_3) while for joint angle θ_4 (tool pitch), geometrical method is utilized. The last angle θ_5 (tool roll) has been computed using the image processing algorithm (Section 4).

Considering first three joint angles, the general form of the transformation matrix from elbow to base is given by

$$ {}^{Base}_{Elbow}T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8} $$

Now computing the inverse of homogeneous transformation matrix of frame {1} represented in base, (9) is obtained.

$$ ({}^0_1T)^{-1} = \begin{bmatrix} C_1 & S_1 & 0 & 0 \\ -S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & -l_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9} $$

Multiplying (8) and (9) and then comparing the product with the result of$({}^0_1T)^{-1}({}^0_4T)$, equations (10), (13) and (16) can be written for required joint angles (θ_1,θ_3,θ_2).

$$ \theta_1 = Atan2(p_x, p_y) \tag{10} $$

$$ c_3 = \frac{(c_1p_x + s_1p_y)^2 + (p_z - l_1)^2 - {l_2}^2 - {l_3}^2}{2l_2l_3} \tag{11} $$

$$ s_3 = \pm\sqrt{1 - {c_3}^2} \tag{12} $$

$$ \theta_3 = Atan2(s_3, c_3) \tag{13} $$

$$ c_2 = \frac{(c_1p_x + s_1p_y)(c_3l_3 + l_2) - (p_z - l_1)s_3l_3}{(c_3l_3 + l_2)^2 + {s_3}^2{l_3}^2} \tag{14} $$

$$ s_2 = -\frac{(c_1p_x + s_1p_y)s_3l_3 + (p_z - l_1)(c_3l_3 + l_2)}{(c_3l_3 + l_2)^2 + {s_3}^2{l_3}^2} \tag{15} $$

$$ \theta_2 = Atan2(s_2, c_2) \tag{16} $$

Having calculated values of θ_2 and θ_3, θ_4 has been computed as

$$ \theta_4 = \theta - (90\,° + \theta_2 + \theta_3) \tag{17} $$

Where θ is an element of the user-defined matrix (18). The matrix lists priority wise values of desired angles with which end-effector should approach the object for manipulation.

$$ \theta = [\theta_a \quad \theta_b \quad \theta_c \quad \theta_d \dots] \tag{18} $$

For the present work, the most priority angle value (θ_a) has been set to 90°. This employs that the best possible scenario for the end-effector to manipulate the object is exactly at its top vertically.

3.3 Workspace Analysis

An essential parameter to design a robotic arm based system is the analysis of robot's workspace. Workspace of a robotic arm is primarily a function of Range Of Motion (ROM) of its joints and associated link lengths. Table 3 mentions ROM of ED7220C joints while link lengths have been tabulated in Table 1.

Table 3. ROM of ED7220C joints

Joint no.	Name	ROM [Degrees]
1	Waist	-244→66
2	Shoulder	-120→-30
3	Elbow	-106→66
4	Wrist	Pitch: -220→40 Roll: 0→360

Based on the mentioned link lengths and ROM of ED7220C, (2)-(4) have been used to determine overall robotic workspace. Figure 6 illustrates the top view of the workspace. Because of the constraints on joint ROM, the robot can manipulate in the radius of 580 mm in a defined region. The 'V' shaped region in Figure is because of ROM constraint of the waist joint.

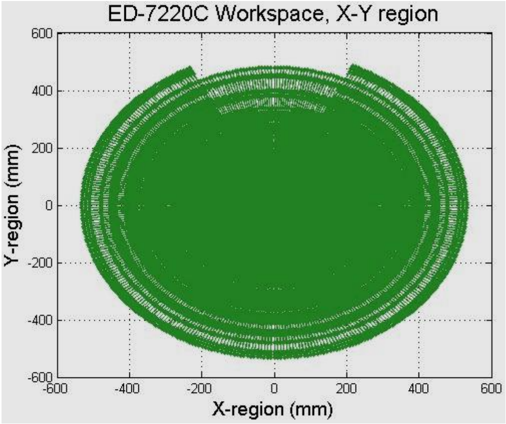
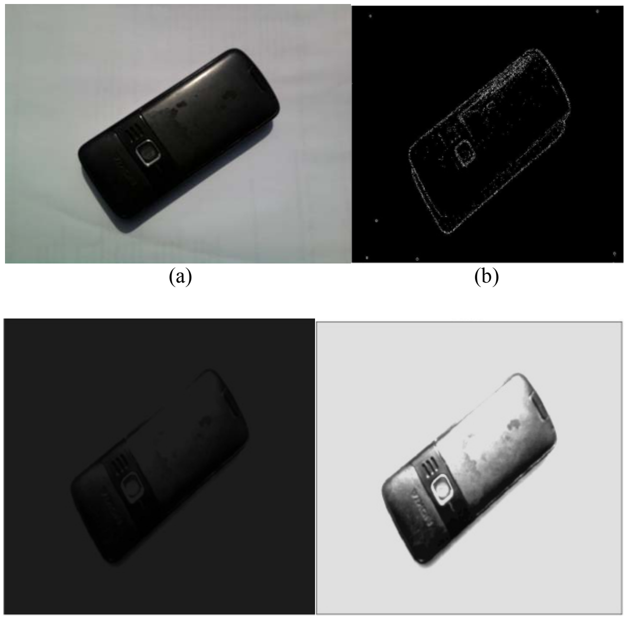


Figure 6. Workspace in XY Region

4 Image Guidance for Target Detection

The proposed system is autonomous in the sense that it does not have to rely on a manual teaching to know the object's coordinates. Employing computer vision enhanced robot autonomy. User just has to input the object of interest. Together with the developed robot model and image processing algorithm, the robot navigates to the required point for object manipulation thus accomplishing its task.

The main aim of the developed image processing algorithm is to detect the target object's whereabouts by extracting its center point and the orientation at which it has been placed. Figure 7a shows a sample original captured image while result of edge detection without improving the picture attributes is illustrated in Figure b. To cope with non-linearities and shading problem, the image has been pre-processed before edge detection. The image has been first smoothened using averaging filter (Figure c) and then sharpened-up to enhance edges of the original object using Laplacian filter (Figure d) followed by edge detection (Figure e) [5]. Finally based on the extracted corner point indices (Figure f), centre coordinates of the object and thus orientation θ_5(tool roll) have been computed. The results from image processing algorithm are then fed to IK model as discussed in Section 3.


(a) (b)

(c) (d)


(e) (f)

Figure 7.Image processing on sample image: (a) Original image (b) Simple edges (c) Averaging filter (d) Laplacian filter (e) Edge detection (f) Center and corner points

5 Conclusions

This work combines image processing with robot modeling to simulate industrial application. Image processing provides autonomy to the system. Prior to extraction of necessary features from image, various filtering techniques have been applied on captured image. Object's coordinates form input of the developed robot model. A complete solution to the IK of a widely used 6 DOF robotic arm, ED7220C has been derived. The derived IK model always provides accurate joint angles to make sure that the end-effector points to the required position and orientation, provided the point of interest is in robot's workspace. In case the object is out of workspace, the model prompts the user. Overall system integrated with on-board web cam is shown in Figure 8. Teaching pendant is also shown here. However use of computer vision in the proposed system has eliminated the role of pendant. To demonstrate the concept, a common task in industrial automation i.e. pick and place has been considered. After testing and verifying individual subsystems, the complete system has been already integrated and currently undergoing in-lab trials. Multiple irregular shaped objects will be considered in the future.

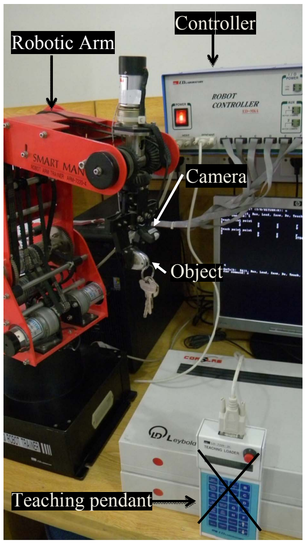


Figure 8. Overall System

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