Kinematic Analysis and Implementation of a 5-DOF Robotic Arm for Object Manipulation in Human Environments

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Abstract

This paper presents a design of a 5-DOF robotic arm for grasping objects in human habitats such as houses, offices and laboratories. The inverse kinematic analysis is applied to determine the joint variable of the robotic arm for reaching the desired position. The kinematic and dynamic models of the robot are derived to facilitate controller design. The robotic arm is designed to work within 45 cm radius. The arm is actuated by four digital servo motors and the gripper is actuated by a digital servo motor. The gripper can grasp an object of 5-10 cm in diameter with the maximum load of 1 kg. A Microsoft Kinect camera is mounted at the top of the robot to detect, recognize and acquire the object coordinates. The acquired object coordinates are then passed on to the developed inverse kinematic model for computing the joint angles that are required to reach the targeted object position. A trajectory of the robotic arm is calculated based on the inverse kinematic model. Inverse kinematic equations are simulated to determine a non-collision path before actuation. The implementation results show that the error of the gripper positioning is in a range of ±2 cm, the error of reaching time from a reference position to a target position is within a range of ±500 ms with the distance of 50 cm compared with the simulation result. The proposed robotic arm and simulation method have a potential to become an excellent choice industrial applications to test and validate the advanced algorithms for object manipulation, grasping and path planning of the robotic arm before implementation, reducing cost and error and enhancing safety. It can also be implemented on educational training such as technical courses for robotic control system and image-processing.

Keywords: Inverse Kinematics, Service Robot, 5-DOF robotic arm

1. Introduction

There are many studies on robot development to perform tasks by interacting with a human or acting in human environment such as the assistive robots [1], the service robots [2,3], and the telekinetic robots [4]. However, a grasping task that specific for robot at home has not been well-studied [5-7]. Therefore, this study proposes the lightweight robotic arm and its inverse kinematics that could be an excellent choice for home applications. The robotic arm should be light-weight and have a suitable degree of freedom (DOF) like a human arm. However, a recent research which studied about the motion of a human arm [8] found that 6 DOF motion is complicated, the DOFs on the wrist occasionally are not used. Thus, in this work, the robot wrist is constrained to move parallel to the table. This helps the robotic arm reaching and grasping many objects with reduced DOF and simpler kinematic equations. Hence, the 6 DOF motion may not be necessarily applied for this study.

To create a functional robotic arm for domestic service task, the 5-DOF motion [9] is chosen. The designed robotics arm consists of 5 servo motors, easy-bending polypropylene fin-ray grasper [10] and light-weight aluminum frame. A servo motor allows the robotic arm to move and control the angular or linear position, velocity and acceleration precisely [11]. A servo motor consists of an appropriate motor combined with a sensor for position feedback making it possible to identify the position of the end-effector and increase the precision of object handling [12] [13].

2. Design of the Robotic Arm

Unlike industrial robotic arms, a structural design of a robot home application should consider just enough accuracy and torque to pick or lift objects. The working area should fit in a human space and its weight should not be too heavy. In this study, the robot can grab an object on a table in front of it with the maximum distance of 45 cm. It is considered as a usual human working area on a table, so it is set as the robot working space.

The weight of objects in a house that are frequently lifted up is not over one kilogram. Thus, this is set as the robot payload. The payload is later become a parameter to determine the motor torque. The length of the robotic arm is defined by the workspace as previously mentioned.

The light-weight structural design is crucial for a mobile robot at home because this helps the robot moving quickly from one place to another in the house. In this work, the robotic arm is made of aluminum truss as shown in Figure 1. Aluminum is strong and light-weight metal with the density of 2,700 kg/m^3 which is one-third of iron.

The payload of a robot is a parameter that specifies driving torques of the motors. The motor that is selected should be able to work even when the power supply is dropped to a certain amount. A digital servo motor is a good choice for robots at home since it gives high torque to weight ratio. It also feedbacks other additional data such as position, temperature, and load. It has a high resolution up to 0.06 degrees. However, disadvantages of the digital servo motor are expensive and its electrical circuit is easily damaged compared to DC-motors.

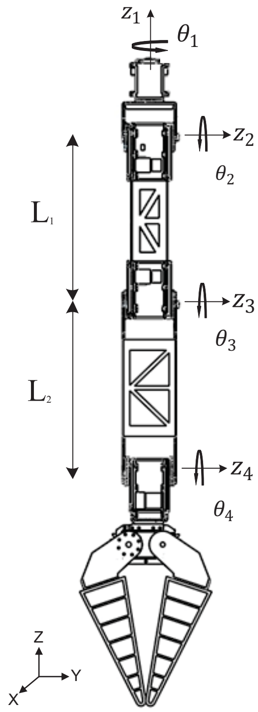

Figure 1. The 5-DOF arm for robot at home applications.

With the 5-DOF robotic arm mentioned previously, the robot can reach an object under usual situations which may found in a house, for example, objects are placed on a table as shown in Figure 2.

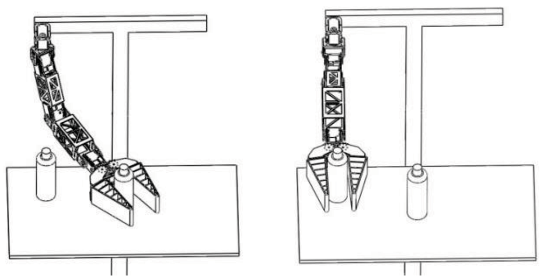

Figure 2. The robotic arm configurations for object grasping on a table.

3. Platform Description

This section describes in details of the main structure and system software that are designed for this work. The platform is setup for experiments as a scene of a robot trying to grasp the recognized objects on a table with its robotic arm as shown in Figure 3.

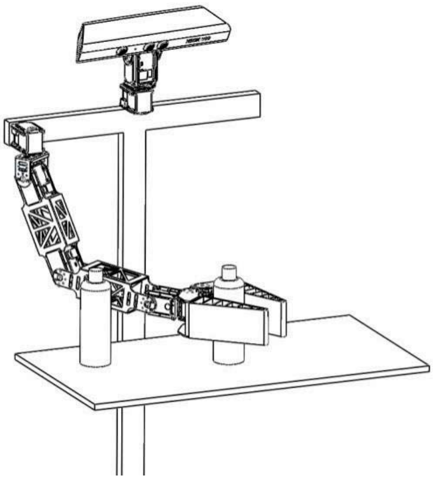

Figure 3. Design of the robotic arm and camera.

According to Figure 3, there are two systems on a robot platform which are an image processing system for object recognition and the robotic arm for object manipulation. Both systems are related, the shapes and colors of the objects are trained and recognized via a Microsoft Kinect camera by image processing algorithms. However, this paper focuses on the robotic arm kinematic solution and implementation. The robot working area is illustrated in Figure 4.

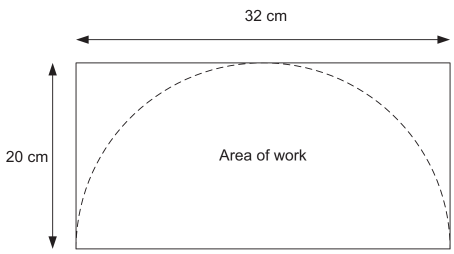

Figure 4. Working area for object grasping on a table.

In the experiment, the height of the camera from the floor is 135 cm, and the height of the table from the floor is 75 cm. The camera tilts down to horizon line with the angle of 35 degrees. Therefore, making the vision to cover the area of 20cm x 32cm on the table, but the robot workspace which the robotic arm can reach to grasp is a half circle as shown in Figure 4.

3.1. The robotic arm structure

In this work, a computer is embedded as the main processing unit and controller. Dynamixel RX-64 and EX-106 servo motors manufactured by ROBOTIS Company are used for driving the robotic arm. The control flow diagram of the robotic arm is shown in Figure 5.

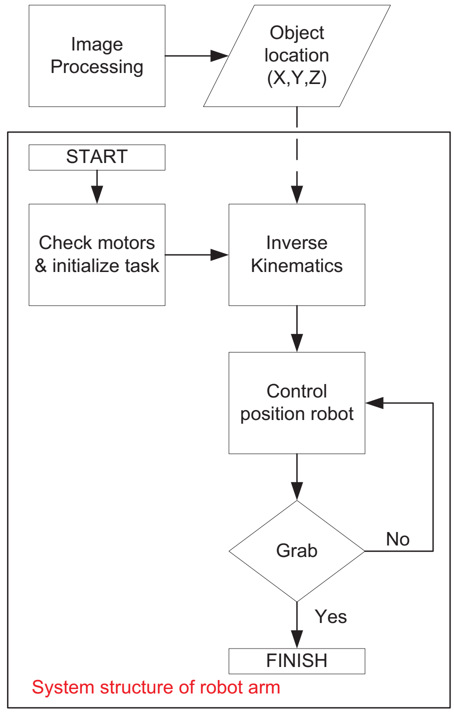

Figure 5. Control flow diagram of the robotic arm.

The robot arm joints and links consists of a shoulder yaw joint, a shoulder pitch joint, an upper arm link, an elbow pitch joint, a lower arm link, a wrist pitch joint and a gripper. The robotic arm has 5 degrees of freedom: two degrees of freedom located at the shoulder, one at the elbow, one at the wrist and one for the grasping action. The length of the upper arm link is 17.5 cm, and the length of the lower arm link is 18.5 cm. Figure 6 shows the structure of the robotic arm.

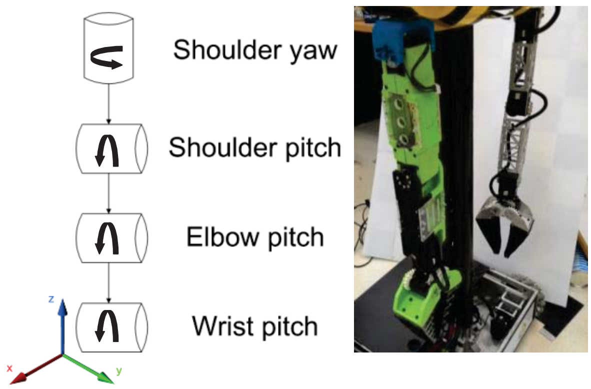

Figure 6. The robotic arm joints and links.

3.2. Kinematics of the 5-DOF robotic arm

Based on Denavit-Hartenberg principle and the assigned coordinate system of the robotic arm in Figure 3, the robot parameters are shown in Table 1.

Table 1. Robot parameters of the robotic arm.

n	α_{n-1}	a_{n-1}	d_n	θ_n	Joint range
1	0	0	0	θ_1	-30°- 30°
2	$-90°$	0	0	θ_2	-30°- 30°
3	0	L_1	0	θ_3	-90°- 90°
4	0	L_2	0	θ_4	-45°- 45°

The homogeneous transformation matrix T of the joint n with respected to joint n-1 can be expressed as [14] [15]

$$T_n^{n-1} = \begin{bmatrix} c\theta_n & -s\theta_n & 0 & a_n \\ s\theta_n c\alpha_{n-1} & c\theta_n c\alpha_{n-1} & -s\alpha_{n-1} & -d_n s\alpha_{n-1} \\ s\theta_n s\alpha_{n-1} & c\theta_n s\alpha_{n-1} & c\alpha_{n-1} & d_n c\alpha_{n-1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where $sx \equiv \sin[x]$ and $cx \equiv \cos[x]$. Accordingly, the transformation matrixes of the robotic arms are

$$T_1^0 = \begin{pmatrix} \cos[\theta_1] & -\sin[\theta_1] & 0 & 0 \\ \sin[\theta_1] & \cos[\theta_1] & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$T_2^1 = \begin{pmatrix} \cos[\theta] & -\sin[\theta_2] & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin[\theta_2] & -\cos[\theta_2] & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$T_3^2 = \begin{pmatrix} \cos[\theta_3] & -\sin[\theta_3] & 0 & L_1 \\ \sin[\theta_3] & \cos[\theta_3] & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

and

$$T_4^3 = \begin{pmatrix} \cos[\theta_4] & -\sin[\theta_4] & 0 & L_2 \\ \sin[\theta_4] & \cos[\theta_4] & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

3.2.1 Inverse Kinematics

To determine the joint angles that give the desired end-effector target and configuration. The joint variables in Table 1 have to be obtained for the transformation matrix of the robot hand with respect to the robot base as

$$T_4^0 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where (n_x, n_y, n_z) is the normal vector, (o_x, o_y, o_z) is the orientation vector, (a_x, a_y, a_z) is the approach vector and (p_x, p_y, p_z) is the position vector. In some cases, the 5-DOF robot cannot pick up objects due to difficulty of gestures. Thus, there will be a modified solution to reach the object by letting the wrist joint parallel to the table. The modified kinematic solution can be expressed as

$$T_4^0 = \begin{bmatrix} 1 & 0 & 0 & p_x \\ 0 & 1 & 0 & p_y \\ 0 & 0 & 1 & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

After solving for inverse kinematics solution of the robotic arm, the results for the joint variables are as follows,

$$\theta_1 = \tan^{-1}(Y/Z) \quad (4)$$
$$\theta_2 = \tan^{-1}(Z/X) - \tan^{-1}(k_2/k_1) \quad (5)$$
$$\theta_3 = \tan^{-1}(\sin\theta_3/\cos\theta_3) \quad (6)$$
$$\theta_4 = \tan^{-1}\left(\frac{S_\emptyset}{C_\emptyset}\right) - \theta_2 - \theta_3 \quad (7)$$

when

$$k_1 = a_1 + a_2 cos\theta_3$$
$$k_2 = a_2 sin\theta_3$$
$$C_\emptyset = \cos(\theta_2 + \theta_3 + \theta_4)$$
$$S_\emptyset = \sin(\theta_2 + \theta_3 + \theta_4)$$
$$\cos\theta_3 = \frac{x^2 + z^2 - a_1^2 - a_2^2}{2a_1a_2}$$
$$\sin\theta_3 = \pm\sqrt{1 - \cos\theta_3^2}$$
$$X = a_1\cos\theta_2 - a_2\cos(\theta_2 + \theta_3)$$
$$Y = Z\tan\theta_1$$
$$Z = a_1\sin\theta_2 + a_2\sin(\theta_2 + \theta_3)$$

4. Testing and Result

The robotic arm is set on a mobile robot which is designed for home service applications as shown in Figure 7. The test focuses on accuracy of positioning, reaching time by moving the end effector to various target positions on a table within the area of 45x30 cm. The test are repeated 10 times for validating the kinematic solution and testing accuracy of the hardware operation.

The experimental setup is done under office light room condition. The robot servo motors have position feedbacks, hence the position accuracy depends on the feedback controller, not the motor speed. The controller gains are determined and tuned based on a simulation before the implementation.

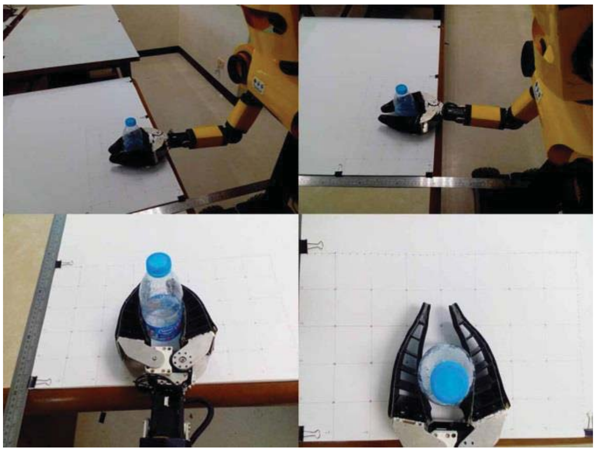

Figure 7. Experimental setup.

4.1 Accuracy of positioning

Accuracy of positioning is tested by moving the end effectors to an object located on the table. Examples of the object in this test are things which often used in house such as a bottle of water, a bottle of green tea, a can of soft drink and a box of chips. There are four target positions which are repeated ten times for each position and measured on a table with the area of 45x30 centimeters. The table is divided into a resolution of one square centimeter to compare the final position of the end effector with the target position sending from the control program. From Table 2, it is found that there is an error range -1 to 1 cm in horizontal direction and error range 0 to -3 cm in the vertical direction due to the weight of the robotic arm. This can be corrected by adding 5-10% to the calculated joint angles. As a result, the error reduces to a range of 0 to -2 cm in vertical. However, the result is acceptable because the designed gripper still works within the range of 2 cm.

4.2 Reaching time

The test is done in the same environment. The reaching time of the robotic arm is tested by repeatedly moving the robot hand from a parking position to a target position with 45 cm distance. From the Table 2, it is found that the simulation and experimental results of the reaching time differ by less than 500 ms with exact the same reaching and grasping actions. This means that the simulation could be used to evaluate the robot action before the implementation.

Table 2. Experimental and simulation results

Input position (cm)			End-effector position (cm)			Reaching time (s)	
X	Y	Z	X	Y	Z	Simulation	Real
35	15	-25	36	14	-25	30.23	30.65
35	10	-25	35	9	-25	29.54	29.77
35	5	-25	34	5	-25	27.21	27.33
35	0	-25	35	0	-25	26.67	26.74
35	-5	-25	35	-5	-25	26.42	26.20
35	-10	-25	34	-9	-25	26.21	25.89
35	-15	-25	34	-15	-25	26.12	25.67
40	15	-25	41	13	-25	31.42	31.65
40	10	-25	41	9	-25	30.21	30.33
40	5	-25	40	5	-25	27.56	27.62
40	0	-25	40	0	-25	27.44	27.44
40	-5	-25	40	-5	-25	27.42	27.21
40	-10	-25	41	-10	-25	27.12	26.84
40	-15	-25	41	-15	-25	27.03	26.71
45	15	-25	44	14	-25	32.21	32.69
45	10	-25	44	9	-25	31.12	31.53
45	5	-25	45	5	-25	28.76	29.00
45	0	-25	45	0	-25	28.52	28.67
45	-5	-25	44	-5	-25	28.44	28.22
45	-10	-25	44	-10	-25	28.32	27.90
45	-15	-25	44	-15	-25	28.21	27.71

5. Conclusion

This paper presents a design of 5-DOF robotic arm for a home service robot. The forward and inverse kinematics equations are proposed. The testing has shown the validity of the forward and inverse kinematics equations. Velocity of the robotic arm movement has an effect on the target positioning. The slower movement yields better the target positioning. In this work, the target positioning errors at any speed are still good enough for the robot to grasp objects. Error due to the body weight can be compensated by programming. The inverse kinematics solution of this work can be applied to the robotic arm of the same design in any size.

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