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Kinematic Analysis of Open-Source 5 Degree of Freedom Robot Arm

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ABSTRACT Today, it is especially estimated that robots will be more than 2 million between 2018-2021, with their increasing use in the industry, in the world. In the industrial environment, robots are used to neutralize toxic substances, explosives, or to replace certain repetitive tasks in the industry for human intervention. On the other hand, robotic systems are used in different areas such as office environment, military duties, and use in hospital environments. It is widespread the use of open-source design robot day by day, in addition to the increasing use of robots, which have invaluable effective uses in complex or dangerous processes. The use of open-source robotic systems is cheaper, developable, and has no usage restrictions due to copyright compared to equivalent robots used in the industry. For these reasons, in our study, a robotic arm with 5 degrees of freedom, printed with 3D printers at industrial scales, was developed. The printed robotic arm was developed to be used as an auxiliary equipment for hospital staff, especially in today's hospital environment. Kinematic analysis is required to determine the working space of the developed robotic arm. The working space of the robotic arm, which is intended to be used as auxiliary equipment in the hospital environment, was revealed by kinematic analysis.

KEYWORDS: Robotic Arm, Forward Kinematic, Inverse Kinematic

1. INTRODUCTION

The effects of developing technological innovations on our daily lives are increasing significantly. The example of these innovations is the prevalence of robots in our daily lives. The applications of robots can be listed in many areas such as office environment, military duties, hospital operations, hazardous environment, and agricultural practices. For instance, robots are indispensable in difficult or dangerous processes such as instead of human intervention to explosive chemicals, neutralizing bombs, or some special repetitive tasks in industries. Therefore, a robot can replace man to do work [1]. Robots perform very critical tasks in the machining and assembly of turbine blades, impellers, and parts with large composite surfaces. These processes are very hard for any workers especially in the aviation and automotive industry. Today, the usage of robots is at most 5% all over the world in the industry [2]. According to The International Federation of Robotics (IFR) data, this usage rate is estimated to be more than 2 million in the world between 2018 and 2021 [3].

Robots can be operated in many ways and can perform the desired tasks completely. It is the most important reason for the preferences. The programmed robots are inevitable to perform the given task whether simple or complex tasks. Robots are controllable and traceable only if in the working space. Different methods are used to monitor robot location within the working space. In conventional systems, feedback is usually made by calculating the angular values obtained from rotary encoders fixed to the joints. In advanced systems, an optical measuring device is used to calculate direct feedback for cooperative robots. Unlike conventional robot systems, the position of the robot is determined by the IR sensor and color sensor. The robotic arm can be directed to select and displace any object which position is known in the working space [4, 5].

On the other hand, the position control of the robot arm is significant for tracking the given mission. For instance, an arrangement of robot arms can assume a role in selecting and sorting various objects placed in a common working space. Notwithstanding knowing the situation of items in this working space, it is necessary to perform motion planning of the maneuvers to grasp the objects [6, 7]. These stages are required for robotic systems and it is conceivable with control policy and kinematic calculations.

Kinematics and control policy are important in robotic systems for collaborative workings. It is extremely important to know the positions and power of the robot arms to establish and design an effective system [8, 9]. It is currently witnessed the widespread usage of the robotic system in many aspects because of the indispensable features of the robotic system. In the last quarter-century, the robotic system is used in the field of health, in particular, as assistant robots, therapy robots, or surgical robots. Laparoscopic robots such as daVinci are examples of the robotic systems used in surgical operations [10 – 12].

In laparoscopic operations, precision is extremely significant. In robot-assisted surgical operations, while the primary surgeon remotely controls the robotic arms beside the patients' bed through the surgical console, the assistant surgeon assists the first surgeon to utilize the accessory port of the daVinci system [10, 13]. The use of the robotic surgical system can diminish the expenses of surgical operations as well as the most effective use of manpower [14].

In the hospital, there isn't always such a complicated task, in some cases, only the auxiliary robotic system can be required. For such cases, the robot arm may be manually controlled rather than autonomously controlled. It is important to decrease the workforce of hospital employees particularly in expanding infections such as corona-virus pandemics. For instance, more than one employee is required to perform the appropriate assessment of an obese patient in tasks such as adjusting the location of the MRI imaging or CT imaging. In such cases, the requisite maneuver can be provided to the obese patient with the assistance of a manually controllable robot arm. In this study, the robot arm with 5 degrees of freedom (DoF) was obtained from the 3D printer. Its kinematic analysis was done to determine working space of robot arm.

2. SYSTEM ARCHITECTURE

2.1 POWER SUPPLY

The used power supply provided the power needed for the movement of the robot arm. It provided 24V voltage and 12.5A current required for the movement, whether it supplied the required power from the battery or AC source. Strong power supply satisfied the power of the used stepper motor which was different properties for the movement of the robot arm such as Nema 23 stepper motor.

2.2 MOTHERBOARD

The robot arm was controlled with MKS Gen V1.4. MKS uses the 8-bit AVR RISC-based ATmega2560 microchip, which also stands out with its low power consumption with its advanced RISC architecture. There is a self-programmable flash memory for the 256KB system on the ATmega2560 microprocessor. Flash memory offers very high performance for the microcontroller. The microprocessor also has 8KB Ram and 4 KB SRAM. The microprocessor 4KB EEPROM, which stands out with its 16MHz operating speed, allows storing long character strings and hundreds of settings data of an advanced system. There are 100 pins on the microprocessor, 86 of the pins allow I/O to input and output data. It also includes 4 USART and Master / Slave SPI serial interfaces for the 16 channel 10 bit-ADC converter.

In addition to the high-performance microprocessor, it contains integrated Ramps a developer-friendly advantage card, and Ramps compatible firmware. On the other hand, it can be controlled via an LCD board with a display port. It also contains smart-controller features with an SD card connector. There are three AUX ports on the motherboard and three Servo motor control ports too. There are 5V and 12V output voltage on the motherboard and also this motherboard withstand voltage between 12V and 24V. It has a short circuit with the recoverable fuse. Five motors are controlled on this motherboard with its extended connection points [16, 17].

2.3 MOTOR DRIVER

The TB6560 motor driver was used for the movement of the manipulators. It provides high performance especially in the movement of high current and voltage stepper motors. It can withstand 35V regression and 3A current. It has 4 phase stepper motor driving capacity. The aluminum heatsink on the drive allows the heat on the chip to be dissipated quickly. Thanks to the cooler, the system shutdown is prevented [18].

The TB6560 motor driver is used in the robot arm system and it uses the Toshiba TB6560AHQ chip. It is a preferred driver especially for the operation of two-phase bipolar stepper motors. Even high-profile stepper motors such as Nema 23 are controlled with the 3A provided by the drive. The chip on the drive has many security functions such as overcurrent, low voltage shutdown, and overheat protection. On the other hand, despite all the precautions, there is no voltage protection on the drive. The optimum voltage value for the driver is 24V voltage, however, it can even stand 10V-35V voltage range. The drive also has a capacity that can withstand up to 3.5A current, while the optimum operating current is 3A current. The sensitivity range of the driver, which has options such as motor step control, is in the range of 1, 1/2, 1/8, 1/16 micro-step. The driver also maintains current control to prevent the motors that it controls from overcurrent. The current control rate is 100%, 75%, 50% and 25% [19, 20].

2.4 STEPPER MOTOR

Stepper motors take a very important role among known motors. It is widely used especially in measurement and control applications, robot applications, CNC applications, etc. [21].

3. APPLICATION

3.1 ROBOT ARM

The open-source BCN3D Moveo robot arm was used from its webpage and it was obtained by printing from a 3D printer. The robot arm has one horizontal and 3 vertical moving axes. Stepper motors and motor drivers actualize two dimensions horizontal and vertical displacement of the robot arm manipulators. The developed robot arm can access any objects in the working space because the horizontal angle of rotational is more than 180 degrees and the first vertical axis has a rotation angle of 220 degrees. The only thing to do for this is to program the horizontal axis with a rotation angle of at least 180 degrees. Simulation is shown in the figure below (figure 1).

For instance, it can be used ancillary robot systems in a hospital environment in a situation like pandemic corona-virus today. It is important to be open source and to be developed as a model.

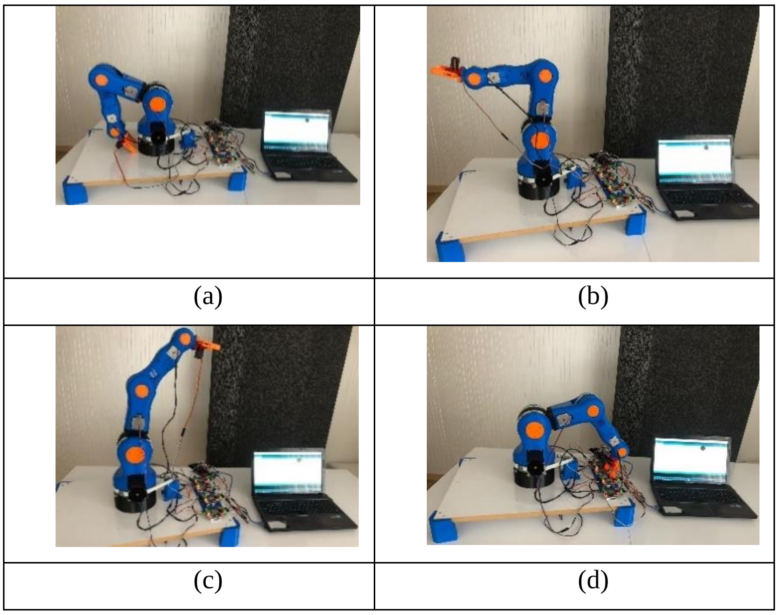

Figure 1: Open-source robot arm

If the strength of the robot arm components is increased, it will be gotten more strength robotic systems printed with 3D printers, especially according to the variety of the material used during printing. For example, the strength of the carbon fiber filament is harder than the PLA filament, which is common to use. In this case, robotic systems with high joint strength can be used. The use of open source designed robotic systems is getting widespread every day [22]. The widespread robotic systems are prepared through design programs such as SolidWorks, and then the assembly simulation can be previewed for the robotic system.

The movement of the robot arm is controlled by a motherboard using an Arduino compatible ATmega2560 processor. The feature of the used motherboard does the joint movements step-by-step. The disadvantage of the study is the fact that more than one joint movement cannot be done simultaneously. In the next stage of this study, it will be performed with the motherboard which enables multi-joint movement simultaneously.

3.2 ROBOT ARM KINEMATIC ANALYZE

Kinematic analysis of the robot arm is to analyze the motion geometry according to the time function by referring to the coordinate system. Forward kinematic analysis is the definition of the joint points and vector of a particular manipulator. It is additionally called the analysis process required for the position and direction of the endpoint relative to the fixed axis sets through the defined parameters of all manipulators within the robot arm. On the other hand, inverse kinematic analysis is the analysis of the accessibility and even the accessibility of the determined endpoint to the desired position with the arm parameters on the fixed reference axis set.

The difficulty of inverse kinematics analysis from robotic systems is due to the complexity of nonlinear problems utilized in the analysis. Compared to inverse kinematics analysis, there is no such difficulty in forward kinematics analysis. Nonlinear equations cannot also be combined and don’t have any unique solutions. In other words, mathematical equations can emerge that can’t be solved physically [23]. In the study, it was analyzed that the kinematic analysis of an industrial scale professional robot arm delivered from an open-source with 5 Degree of Freedom (DoF) degree of freedom and printed 3D printer. The robot arm is placed on a fixed base and therefore the coordinate frame assignment is shown in figure 2.

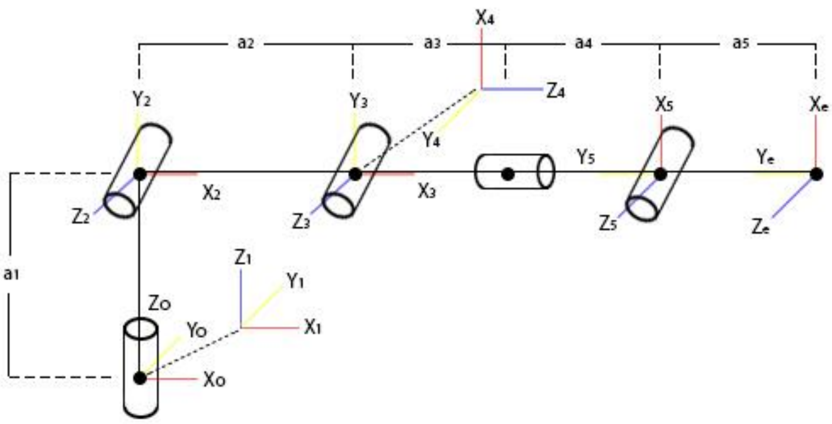

Figure 2: Coordinate frame of robot arm

3.3 FORWARD KINEMATIC ANALYZE AND HOMOGENOUS TRANSFORMATIONS

Kinematic analysis is to perform to determine the end effector location depending on the degree of freedom of the robot arm. Likewise, the working space is significantly determined by the position of end effector on the coordinate axis within forward kinematic analysis. The analytical method or D-H method is the most common method used for forward kinematic analysis [24]. Figure 2 shows the rotational joints of each robot axis with 5 DoF, and a transformation matrix is to define the relationship between the adjacent joint on the coordinate system of each joint. It is shown as ${}^{i-1}_{i}\boldsymbol{T}$ by the transformation matrix of the relationship between the two neighbors. Here i indicates the joint number. The transformation matrix between the mainframe and the endpoint of the robot arm is shown below.

Table 1: Homogenous transformation

	θ	α	a	d
1	θ_1	90	0	a_1
2	θ_2	0	a_2	0
3	0	90	0	0
4	θ_4	90	$a_3 + a_4$	0
5	θ_5	0	a_5	0

The location of the joints and the directions of rigid bodies can be defined by coordinate systems fixed according to the joints [25]. For this reason, it was deemed necessary to ascertain a coordinate system on each active joint. It is shown in figure 2 the coordinate system of the BCN3D Moveo open-source robot arm [26]. The coordinate system of the robotic arm is created with the coordinate system 1 and coincides with the basic coordinate system 0. For convenience, the Z-axis is parallel to the axis of every rotational joint, and the direction of the Z-axis is defined by the direction of rotation traditionally fixed by the right-hand rule. Each ongoing axis after the first axis is exactly consistent with the previous axis. The last axis of the system is again determined by the right-hand rule and therefore the dimension parameters in the coordinate system are shown in the figure 2.

According to the homogeneous transformation formula

$$ {}^{i-1}_{i}T = \begin{bmatrix} & {}^{i-1}_{i}R & & D \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Then all the matrices are obtained: ${}^{0}_{e}\boldsymbol{T} = {}^{0}_{1}\boldsymbol{T}{}^{1}_{2}\boldsymbol{T}{}^{2}_{3}\boldsymbol{T}{}^{3}_{4}\boldsymbol{T}{}^{4}_{5}\boldsymbol{T}{}^{5}_{e}\boldsymbol{T}$. The character "e" represents the end effector on the coordinate axis, ${}^{i-1}_{i}\boldsymbol{T}$ expressing the transformation relationship between coordinates i to i-1, and ${}^{i-1}_{i}\boldsymbol{R}$ expressing the motion relationship between coordinate i to i-1. While calculating other matrices, the base coordinate is obtained from the transformation matrix and end effector coordinate [27, 28].

Homogeneous coordinate system of open-source robot arm

While calculating other matrices, the transformation matrix is obtained from the end-effector coordinate to the base coordinate.

$$ {}^{0}_{e}T = {}^{0}_{1}T{}^{1}_{2}T{}^{2}_{3}T{}^{3}_{4}T{}^{4}_{5}T{}^{5}_{e}T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$n_x = C_5(C_1C_4(C_3C_2 + S_2S_3) + S_1S_4) - C_1S_5(C_3S_2 - C_2S_3) \quad (1)$$

$$n_y = C_5(S_1C_4(C_3C_2 + S_2S_3) - C_1S_4) - S_1S_5(C_3S_2 - C_2S_3) \quad (2)$$

$$n_z = C_4C_5(C_3S_2 + C_2S_3) - S_5(C_3C_2 - S_2S_3) \quad (3)$$

$$o_x = C_1C_5(C_2S_3 - C_3S_2) - S_5(C_1C_4(C_2C_3 + S_2S_3) + S_1S_4) \quad (4)$$

$$o_y = S_1C_5(C_2S_3 - C_3S_2) - S_5(S_1C_4(C_2C_3 - S_2S_3) - C_1S_4) \quad (5)$$

$$o_z = C_5(C_2C_3 + S_2S_3) - C_4S_5(S_2C_3 + C_2S_3) \quad (6)$$

$$a_x = -S_1C_4 + C_1C_2C_3S_4 + C_1S_2S_3S_4 \quad (7)$$

$$a_y = C_1C_4 + S_1C_2C_3S_4 + S_1S_2S_3S_4 \quad (8)$$

$$a_z = S_2C_3S_4 + C_2S_3S_4 \quad (9)$$

$$p_x = C_1\big(C_3\big(C_2\big(a_{(3+4)}C_4\big) - a_5S_2S_5\big) + S_2S_3\big(a_{(3+4)}S_4 + a_5C_4S_5\big) + a_2C_2 + a_5C_2S_3S_5\big) + S_1\big(a_{(3+4)}S_4 + a_5S_4C_5\big) \quad (10)$$

$$p_y = S_1\big(C_3\big(C_2\big(a_{(3+4)}C_4\big) - a_5S_2S_5\big) + S_2S_3\big(a_{(3+4)}S_4 + a_5C_4S_5\big) + a_2C_2 + a_5C_2S_3S_5\big) - C_1\big(a_{(3+4)}S_4 + a_5S_4C_5\big) \quad (11)$$

$$p_z = a_1 + a_2S_2 + C_3\big(S_2\big(a_{(3+4)}C_4 + a_5C_4C_5\big) - a_5C_2S_5\big) + S_3\big(C_2\big(a_{(3+4)}C_4 + a_5C_4C_5\big) + a_5S_2S_5\big) \quad (12)$$

3.4 INVERSE KINEMATICS

The most significant issue in robotic system is that the difficulty in performing inverse kinematic calculations, particularly the position of the robot and the calculation of all joint angles corresponding to the position pose serious issues [27].

The most common method for controlling robotic arms, on the other hand, is still based on manually crafted scanning tables [29]. Inverse kinematic analysis is the accessibility of the determined end effector to the specified position within the arm parameters via the fixed reference axis set. Additionally, in inverse kinematic computations, analysis ought to be done on how many different configurations of accessibility are done. The geometric approach was used to analyze the inverse kinematic of the medical robot arm (figure 3).

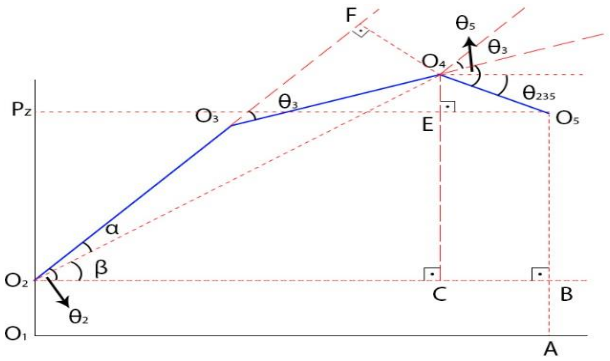

Figure 3: Geometric approach of robot arm

$$|O_2O_5| = \sqrt{P_x^2 + P_y^2 + P_z^2} \quad (14)$$

$$\theta_1 = tan^{-1}(P_x, P_y) \quad (15)$$

$$|O_2B| = d = \sqrt{P_x^2 + P_y^2} \quad (16)$$

Assume

$$|O_3O_4| = u = a_3 + a_4 \,;\, |O_2O_3| = a_2 \quad (17)$$

$$-cos(\theta_3) = \frac{(a_2)^2 + u^2}{2a_2u} \quad (18)$$

$$|O_2C| = \sqrt{P_x^2 + P_y^2} - a_5c_{235} \quad (19)$$

$$|O_2O_4|^2 = |O_2C|^2 + |O_4C|^2 \quad (20)$$

$$|O_2O_4|^2 = |O_2O_3|^2 + |O_3O_4|^2 - 2|O_2O_3||O_3O_4|\cos(180 - \theta_3) \quad (21)$$

$$\theta_3 = tan^{-1}(S_3\,, C_3) \quad (22)$$

$$\alpha = tan^{-1}(|O_4F|\,, |O_2F|) \quad (23)$$

$$\beta = tan^{-1}(|O_4C|\,, |O_2C|) \quad (24)$$

$$|O_4C| = P_z - a_1 + a_5S_{235} \quad (25)$$

$$|O_2C| = a_1 + \sqrt{P_x^2 + P_y^2} - a_5C_{235} \quad (26)$$

4. CONCLUSIONS

A robot arm with 360 degrees accessed any objects in the working space. The robot arm has the option of gripping any object with autonomous control. The system has an autonomous feature too. Motherboard use ATmega2560 microprocessor which stands out with its functional features.

The robot arm is manually controllable and the main purpose of the prototype robot arm is to use in specific tasks such as hazardous areas. It is a prototype study developed for use in rapid decision-making processes, especially in first aid recovery in industrial production enterprises or it is used in the hospital environment for reducing the workforce of hospital employees when transferring obese patients for such tasks.

It is extremely important in the development and popularization of open-source robots that especially no copyright issues and being cheaper compared to their industrial equivalents. The control software is open-source software that controls the 5 DoF robot arm and develops in the study. The working area was revealed by performing the kinematic analysis of the robot.

Thus, it was solved that the most important component required for the control of the robot arm used as auxiliary equipment for healthcare staffs. In the later stages of the study, it is aimed to add sound control and image enhancement process and develop control methods with software studies that will be enriched with deep learning methods. For example, reading the barcode on the health worker with the voicemail message and leaving the desired material at the target point.

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