# DESIGN AND ANALYSIS FOR THE SPECIAL SERIAL MANIPULATOR

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**Abstract**: In recent years, robot has been used widely in industrial field and has been expanded as a result of continous research and development for high-speed and miniaturization.

The goal of this paper is to design the special serial manipulator through the understanding of the structure, mobility, and analysis of serial manipulator. Thereafter we control the position and orientation of end-effector with respect to time. In general, a structure of industrial robot consists of several links connected in series by various types of joints. Typically revolute and prismatic joints. The movement of these joints is determined in inverse kinematic analysis. Compared to the complicated structure of parallel and hybrid robot, open loop system retains the characteristic that each link is independent and is controlled easily by AC servomotor that is used to place the robot end-effector toward the accurate point with the desired speed and power while it is operated by position control algorithm.

The robot end-effector should trace the given trajectory within the appropriate time. The trajectory of 3D end-effector model made by OpenGL can be displayed on the monitor program simultaneously

**Keywords:** Robot Manipulator, Jacobian, Static, Dynamic, OpenGL, Monitoring Program

## 1. INTRODUCTION

The motivation for this research is to construct a serial robot manipulator that fits the desired movement. The requirement of this serial manipulator are to cover the desired work with the given speed and force.

Handling and assembling applications with parallel robots were examined early in the robotics. Today many of them are employed in industrial application, for instance for the high speed pick and place operation. In comparison to serial robots, the reduced working space has brought out the fast development of robots in the serial systems. There is a defect that most of parallel robot manipulators should be operated by numerical method and need a lot of calculations.

Serial mechanism devices are utilized in relatively low payload to manipulator weight ratio tasks requiring low to medium accuracy and a large work volume. The disadvantage of serial robot should be reduced because the performance and power of actuator is improving more and more.

As you know well, hybrid structure manipulators exploiting the advantages of both fully parallel and serial mechanism can potentially be developed. Otherwise, the kinematic analysis of hybrid robot manipulator must be difficult and impossible with the conventional theory.

Eventually, we are trying to develop the serial robot manipulator for the appropriate characteristics. These characteristics include reasonable work volume, high stiffness, accuracy, payload to manipulator weight ratio and dynamic performance, and work volume performance characteristics.

## 2. 3D.O.F SERIAL ROBOT MANIPULATOR

Fig.1 describes the schematic of the 3.D.O.F Serial Robot Manipulator that we design. Using the 3 D design Program Catia, we can obtain it below

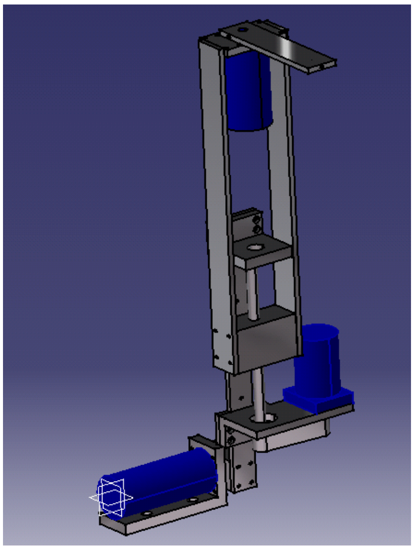

Fig. 1 Schematic of the 3D.O.F Robot Manipulator

This serial robot has three actuators that have 3 D.O.F in the space. First joint is revolute, second is prismatic in motion and last joint is revolute.

## 2.1 Kinematics of 3D.O.F Robot Manipulator

### 2.1.1 Forward Kinematic Analysis

The robot manipulator consists of three links connected in series by two revolute joints and one prismatic joint. The first and third joints are revolute and the second joint is prismatic.

According to the Denavit and Hartenberg's convention. We can get the D-H Parameters

Table 1 D-H Parameters of the 3D.O.F Robot Manipulator

| Joint i | $\theta_i$ | $d_i$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| 1 | $\theta_1(t)$ | $d_1$ | 0 | $-90^{\circ}$ |
| 2 | 0 | $d_2(t)$ | 0 | 0 |
| 3 | $\theta_3(t)$ | 0 | $-a_3$ | 0 |

Here, table 1 shows the D-H Parameters of 3D.O.F robot manipulator.

The following parameters are uniquely determined by the geometry of the axes:

$\theta_i$ : Joint angle between two incident normals of a joint axis

$d_i$: Translational distance between two incident normal of a joint axis

$a_i$ : Offset distance between two adjacent joint axes

$\alpha_i$ : Twist angle between two adjacent joint axes

For a robot to perform a specific task, the location of the end-effector relative to the base should be established first. This is called the position analysis problem. There are two types of position analysis problems: forward position or forward kinematics and inverse position or inverse kinematics problems. For forward kinematics, the joint variables are given and the problem is to find the location of the end-effector.

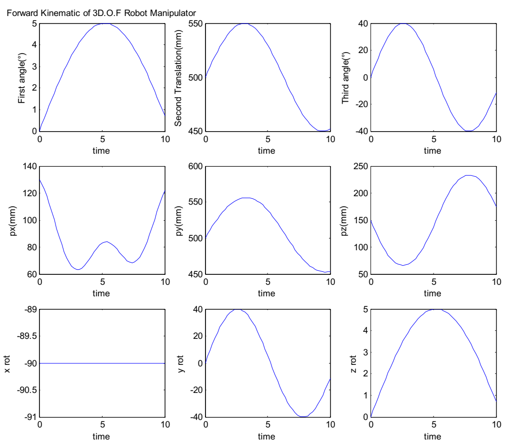


Fig. 2 Forward Kinematics of the 3D.O.F Robot Manipulator

Fig. 2 shows the forward kinematics of the 3D.O.F robot manipulator. The range of three actuators is determined arbitrarily. The first joint variable is $\pm 5^{\circ}$, the second joint variable is $\pm 50mm$, and the last joint variable is $\pm 40^{\circ}$.

### 2.1.2 INVERSE KINEMATIC ANALYSIS

In order to control the position and orientation of the end-effector of a serial robot manipulator, the inverse kinematics solution is more important. In other words, given the position and orientation of the end-effector of the robot and its joint and link parameters, we would like to find the corresponding joint angle of the robot so that the end-effector can be positioned as desired

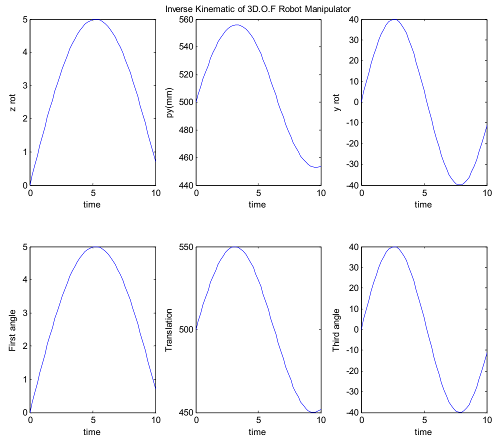


Fig. 3 Inverse Kinematics of the 3D.O.F Robot Manipulator

Figure 3 shows the inverse kinematics of the 3D.O.F robot manipulator. As shown in this figure, the result must be as same as the unknown input data of forward kinematic analysis.

## 2.2 Jocobian of 3D.O.F Robot Manipulator

For robot manipulators, the Jacobian is defined as the matrix that transforms the joint rates in the actuator space to the velocity state in the end-effector space. It is necessary to move the end-effector of a manipulator along some desired paths with a prescribed speed

The velocity of end-effector can be written as,

$$\dot{x} = [v_{3x}, v_{3y}, v_{3z}, \varpi_x, \varpi_y, \varpi_z]^T \qquad (1)$$

The velocity of three joints velocity can be written as,

$$\dot{q} = [\dot{\theta}_1, \dot{d}_2, \dot{\theta}_3]^T \qquad (2)$$

The time derivatives of $x$ can be written as a function of $\dot{q}$

$$\dot{\mathbf{x}} = J\dot{\mathbf{q}} \qquad (3)$$

The jocobian matrix can be written as,

$$J = \begin{bmatrix} -\cos(\theta_1)d_2 - a_3\sin(\theta_1)\cos(\theta_3), & -\sin(\theta_1), & -a_3\cos(\theta_1)\sin(\theta_3) \\ -\sin(\theta_1)d_2 + a_3\cos(\theta_1)\cos(\theta_3), & \cos(\theta_1), & -a_3\sin(\theta_1)\sin(\theta_3) \\ 0, & 0, & -a_3\cos(\theta_3) \\ 0, & 0, & -\sin(\theta_1) \\ 0, & 0, & -\cos(\theta_1) \\ 1, & 0, & 0 \end{bmatrix} \qquad (4)$$

### 2.3 Statics of 3D.O.F Robot Manipulator

Static force analysis is practical importance in determining the equality of force transmission through the various joints of a mechanism. It serves as a basis for sizing the links and bearings of a robot manipulator and for selecting appropriate actuators.

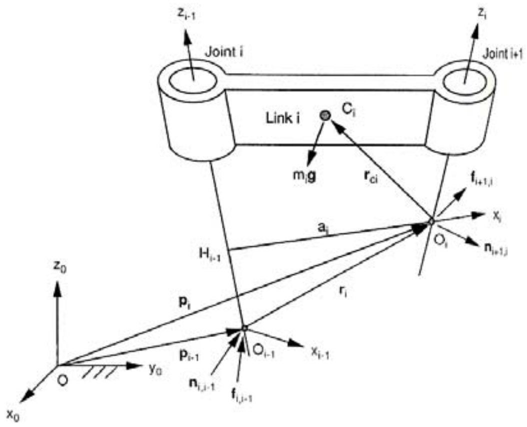


Fig. 4 Forces and Moments Acting on Link I

In a serial manipulator, each link is connected to one or two other links by various joints. Fig. 4 depicts the forces and moments acting on a typical link $i$ that is connected to link $i-1$ by joint I and to link $i+1$ by joint $i+1$.

The following notations are defined:

$\mathbf{f}_{i+1,i}$: Resulting force exerted on link $i+1$ by link I at $O_i, \mathbf{f}_{i,i+1} = -\mathbf{f}_{i+1,i}$.

$\mathbf{g}$: Acceleration of gravity.

$m_i$: Mass of link $i$.

$\mathbf{n}_{i+1,i}$: Resulting moment exerted on link $i+1$ by link $i$, about point $O_i$, $\mathbf{n}_{i,i+1} = -\mathbf{n}_{i+1,i}$.

$\mathbf{r}_{ci}$: Position vector of the center of mass of link $i$ relative to the $i$th link frame (i.e., $\mathbf{r}_{ci} = \overline{O_i C_i}$ ).

$\mathbf{r}_i$: Position vector of $O_i$ with respect to the $(i-1)$th link frame $(i.e., \mathbf{r}_i = \overline{O_{i-1} O_i})$.

First we consider the balance of forces. As shown in Fig. 4, there are three forces exerted on link $i$.
Hence a force balance equation can be written as

$$\mathbf{f}_{i,i-1} - \mathbf{f}_{i+1,i} + m_i \mathbf{g} = \mathbf{0}. \tag{5}$$

Next, we consider the balance of moments about the origin $O_i$. There are two moments acting on link $i$: $\mathbf{n}_{i,i-1}$ and $-\mathbf{n}_{i+1,i}$. In addition, the two forces $m_i\mathbf{g}$ and $\mathbf{f}_{i,i-1}$ produce moments about $O_i$. Summing these moments together, we obtain

$$\mathbf{n}_{i,i-1} - \mathbf{n}_{i+1,i} - \mathbf{r}_i \times \mathbf{f}_{i,i-1} + \mathbf{r}_{ci} \times m_i \mathbf{g} = \mathbf{0} \tag{6}$$

Where, ${}^i\mathbf{r}_i = \begin{bmatrix} a_i \\ d_i s\alpha_i \\ d_i c\alpha_i \end{bmatrix}$ $,\mathbf{r}_{ci} = {}^0R_i\,{}^i\mathbf{r}_{ci}$ $,\mathbf{r}_i = {}^0R_i\,{}^i\mathbf{r}_i$ .

It is assumed that output force and moment are neglected and the center of mass is located at the midpoint of each link and the effect of gravity is considered. Also let the acceleration of gravity be pointing along the negative $y_0$-direction and. We can find the joint reaction forces and moments.

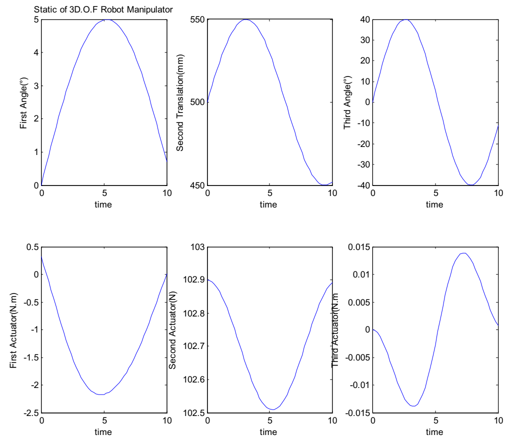


Fig. 5 Torque and Force of 3D.O.F Robot Manipulator

The reaction forces in the joints are known and the actuator forces or torques can be determined. For a serial manipulator, an actuator that exerts either a force or a torque between two adjacent links drives each joint. These actuator forces or torques can be found by projecting the reaction forces onto their corresponding joint axes.

For a prismatic joint, the actuator force is exerted along the $i$th joint axis. Assuming that frictional force at the joint is negligible, the actuator force,

$$\tau_i = \mathbf{z}_{i-1}^T \mathbf{f}_{i,i-1} \tag{7}$$

Similarly, for a revolute joint, the actuator exerts a torque instead of force about the $i$th joint axis. This actuator torque,

$$\tau_i = \mathbf{z}_{i-1}^T \mathbf{n}_{i,i-1}. \tag{8}$$

Where $\mathbf{z}_{i-1}$ is a unit vector pointing along the positive $i$th joint axis.

## 2.4 Dynamics of 3D.O.F Serial Manipulator

The dynamical equations of motion can be formulated by several methods. One approach is application of the Newton and Euler laws and another approach is application of the principle of d'Alembert or Hamilton. Alternatively, one can apply Lagrange's equation of motion. Or Kane's method. This paper uses a recursive Newton-Euler formulation for the dynamical analysis of serial manipulator. The Newton-Euler formulation incorporates all the forces acting on the individual links of a robot arm. Hence the resulting dynamical equations include all the forces of constraint between two adjacent links.

These forces of constraint are useful for sizing the links and bearings during the design stage. The method consists of a forward computation of the velocities and accelerations of each link, followed by a backward computation of the forces and moments in each links.

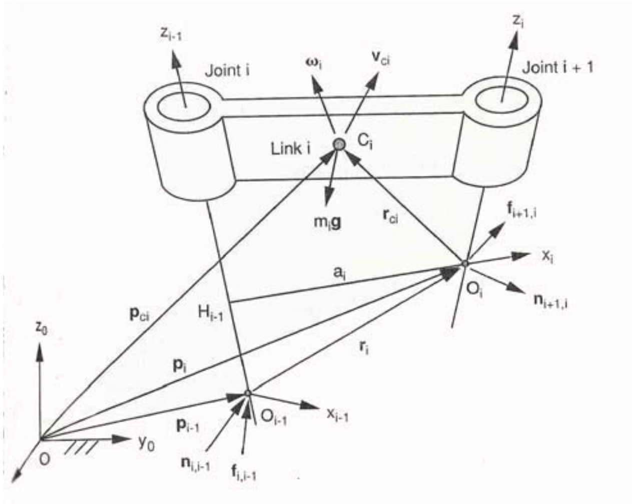


Fig. 6 Forces and moments exerted on link I

The forces and moments acting on a typical link i of a serial manipulator are shown in Fig 6.

Actuator torques or forces $\tau_i$ are obtained by projecting the forces of constraint onto their corresponding axes: that is,

For a prismatic joint, the actuator force is exerted along the $i$ th joint axis. Assuming that frictional force at the joint is negligible, the actuator force,

$$\tau_i = {}^{i-1}\mathbf{n}^T_{i,i-1}\,{}^{i-1}\mathbf{z}_{i-1}$$

Similarly, for a revolute joint, the actuator exerts a torque instead of force about the $i$ th joint axis. This actuator torque,

$$\tau_i = {}^{i-1}\mathbf{f}^T_{i,i-1}\,{}^{i-1}\mathbf{z}_{i-1}$$

Where $\mathbf{z}_{i-1}$ is a unit vector pointing along the positive $i$ th joint axis.

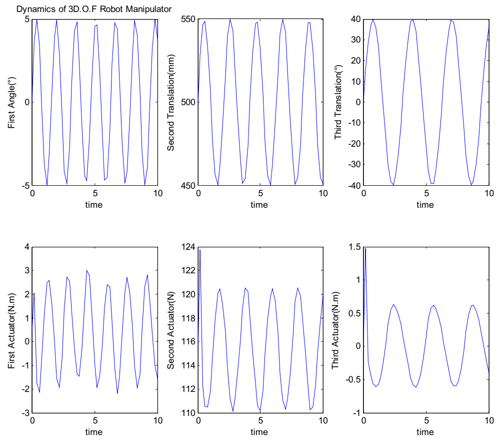


Fig.7 Torque and Force of 3D.O.F Robot Manipulator

Fig 7 shows the actuator torque and force of each link according to the variation of each parameter. The range of three actuators is determined arbitrarily. The first joint variable is $\pm 5^\circ$, the second joint variable is $\pm 50mm$, and the last joint variable is $\pm 40^\circ$.

After the force of each actuator is loaded on, we can choose the appropriate motor that we want to operate the robot manipulator.

## 3. SOFTWARE

### 3.1 Monitoring Program

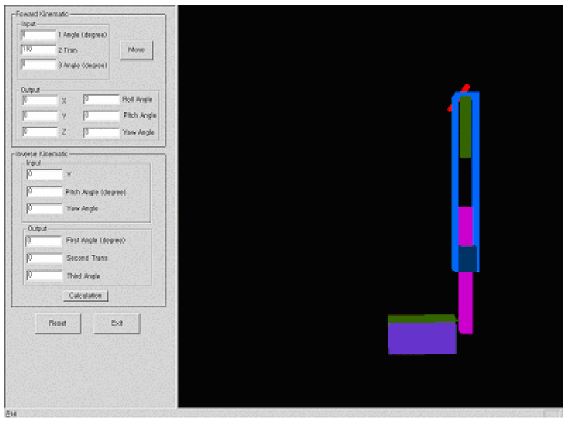

Fig. 8 Monitoring Program of 3D.O.F Robot Manipulator

As shown in Fig. 8, the left diagram displays the icons that control the motion in forward kinematic analysis and determine the parameter of link length and angle. The right windows show the Robot Manipulator by using OpenGL.

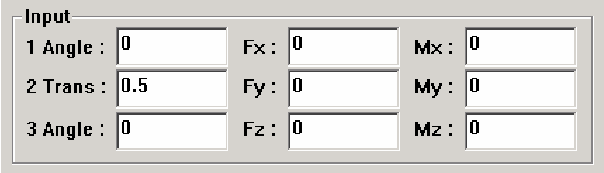


Fig. 9 Input of Static for 3D.O.F Robot Manipulator

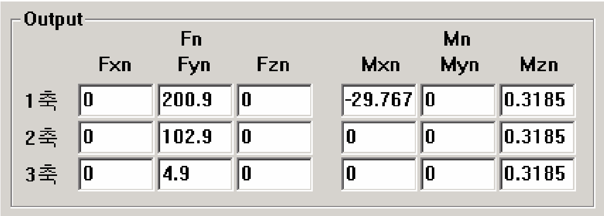


Fig. 10 Output of Static for 3D.O.F Robot Manipulator

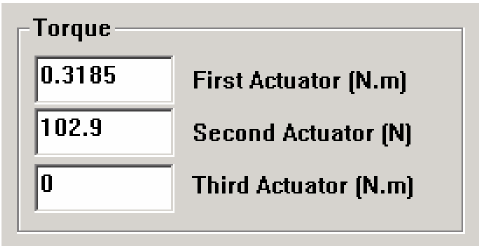


Fig. 11 Torque and Force of 3D.O.F

Fig. 9 shows the input box in the monitoring program. There are three input boxes of first link angle, second link translation, third link angle and six input box of forces and moments on the end-effecter.

We can acquire two results after we input the value to the input box in the monitoring program. Fig. 10 and Fig. 11 show the results. Fig. 10 shows the forces and moments on the each link. Fig. 11 shows the torque at the each actuator.

Table 1 Maximum Torque & Force

| | First Angle(°) | Second Translation(mm) | Third Angle(°) | Torque & Force |
|---|---|---|---|---|
| **First Actuator** | -4.9808 | 539.68 | 4.662 | 2.8418(N.m) |
| **Second Actuator** | 0.10795 | 450.03 | -34.051 | 102.9(N) |
| **Third Actuator** | 4.8436 | 545.87 | 39.286 | -0.0170(N.m) |

Table 1 shows the maximum torque and force at the each actuator in case we input the random value. So we can select the each actuator using these results

According to the use of OpenGL in program, we model the serial robot manipulator in the program. We easily monitor the trajectory of the serial manipulator. Once the parameters are determined in dialogue box, movement of the robot is displayed on the monitor and we see the end-effector's trajectory in real space simultaneously.

## 4. EQUIPMENT

Fig. 12 3D.O.F Serial Manipulator

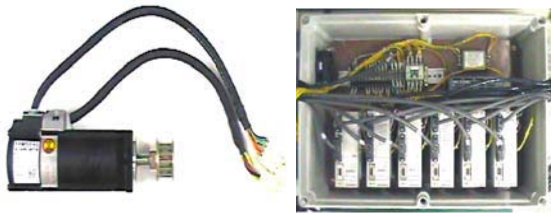

Fig. 13 Motor and Driver of Equipment Device

Fig. 14 MMC Board

We are trying to make the serial robot manipulator that consists of two Samsung AC servomotors, CSMZ-01BA1, and one Panasonic AC servomotor, MFM042A1C. Fig. 9 shows us the 3D.O.F Manipulator we make. Fig. 13 shows the motor and servo-driver. Fig 14 shows the MMC Board. Through this MMC Board, we can control the each motor.

## 5. CONCLUSION

An electric motor has linear characteristics and is more precise than a hydraulic actuator. So the electric motor is selected. A robot hand is attached to the last link of the three degrees of serial robot manipulator. In order to possess these three motions that are z-axis rotation, y-axis rotation, and y-axis translation, the serial robot manipulator needs at least three actuators.

In this research, first we solve the static analysis and the dynamic analysis about the 3D.O.F Serial Manipulator. Second we determine the performance of motor. Second we program the monitoring program. The advantages of this program easily calculate the forces, moments and torque on the each link and monitor the trajectory of the robot manipulator using OpenGL. Thereafter the 3 D.O.P Serial Manipulator was manufactured through the results of analysis. Using the MMCBODPV81 that can do synchronous control, we control the AC servomotor of robot while the trajectory of the end-effector display on the monitor.

In the future, we input the sine wave function to the system respectively and design the control logic of this manipulator following the trajectory that we want to operate 3D.O.F Manipulator

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