Kinematic Implementation of 3-DOF 2-Link Type Vehicle Simulator

(Kinematic analysis and motion control method for 3-DOF 2-link type vehicle simulator)

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***Abstract*—The vehicle simulator aims to provide the user with a driving experience that reproduces the sensations experienced in a real vehicle. The important thing is to duplicate the motion. Therefore various parallel manipulator have been developed like six and three degree of freedom motion platform(vehicle simulator). In this paper, we present kinematic analysis of a manipulator with new type of 2-link structure and motion cueing through inverse kinematics. For accurate calculation, Matlab and a recursive method was used.**

Keywords: inverse kinematics; forward kinematics; parallel robots

I. INTRODUCTION

The vehicle simulator uses a parallel manipulator to provide motion signals to the user. Parallel manipulators consist of a fixed base and many kinematic chains connected to a moving platform [1]. Gough developed the first parallel manipulator for tire testing machines [2]. Stewart developed a six-degree-of-freedom parallel manipulator that is often used as a flight simulator [3]. As the development of the Stewart platform progresses, various applications of the Stewart platform have been investigated for use as mechanized [4]. The kinematic and practical design considerations of the Stewart platform for use as an operator were considered in [5] and [6]. As the development of the 6-degree-of-freedom platform progressed, easier form of motion platform began to be developed as follows [7]. Because Due to complex forward kinematics and difficulty to manufacture spherical joints at low cost. Lee and Shah presented a closed solution for the forward and inverse kinematics of a 3-DOF parallel manipulator [8] [9]. Yang et al. [10] developed a low-cost driving simulator using the 3-RPS manipulator. In addition, research on this robot has been determined in various ways, and development or research using software has been proceeded recently. For example, SimMechanics is a toolbox that provides a multibody simulation environment which allows the modelling and simulation of mechanical systems using their geometric layout and structural properties [11]. Yu et al [12] developed a simulation system to verify the inverse kinematic equations for a 3-DOF motion platform in Matlab/Simulink, using the SimMechanics toolbox. Ciprian-Radu et al [13] suggest that a numerical implementation using Matlab and J. Schadlbauer et al [14] considered algebraic analysis of 3-RPS parallel manipulator. More recently, T Kadar et al [15] developed simulation system to aid a design of vehicle simulator. Most of researches and developments are parallel types like RPS or TPS. In this paper, different type, 3-DOF 2-link type simulator is developed.

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II. KINEMATIC ANALYSIS

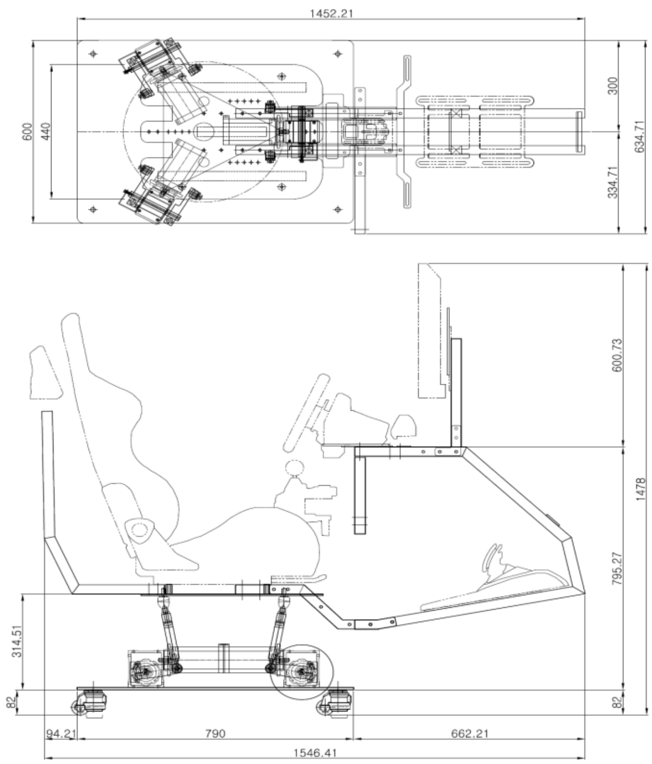

Fig. 1. Product drawing of 3-DOF 2-Link Type Motion Platform

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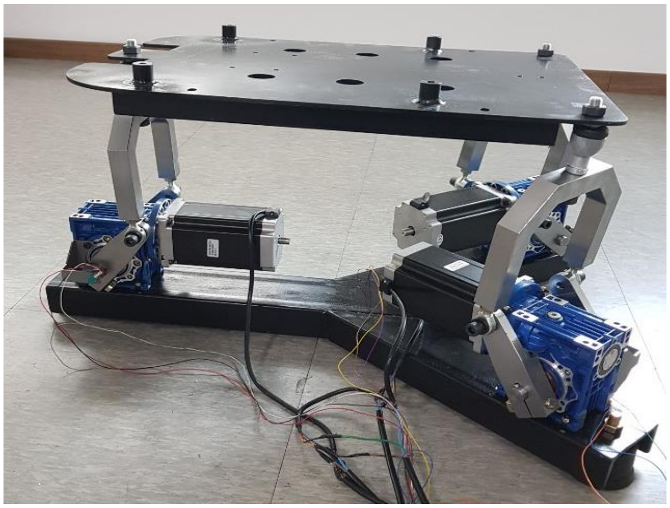

Fig. 2. Prototype of 3-DOF 2-Link Type Motion Platform

Fig. 1 is a design drawing in the product development stage. The overall structure and the exact resources of each component can be identified from this. And we can get data about parts that are difficult to measure. Fig. 2 is developed prototype. This is used to correct errors that occurred during product processing and to make a modeling.

For the kinematic modeling and analysis of the motion platform, we need to know the exact structure, exact figures and types of connection. This is done with reference to product drawing, Fig. 1 and prototype product, Fig. 2.

A. Basic structure and simplification

Fig. 3 is schematic diagram of the motion platform which is simplified. The reason for simplification makes calculations easier than the kinematic approach of a real machine and easy to visualization. The point that is raised by the height of the center of rotation of the motor in the z-axis direction from the origin of the bottom plate fixed to the bottom surface is designated as O, and the coordinate reference point for modeling. And ignore the effect on the volume of the link itself and the effect of the ball joint located at point C_n.

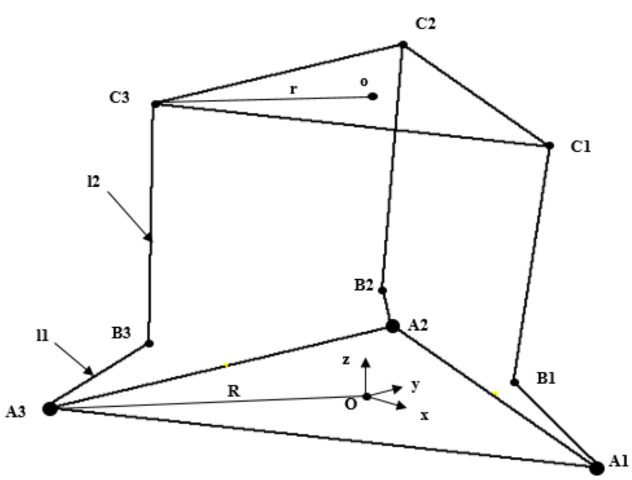

Fig. 3. Schematics of 3-DOF Motion Platform

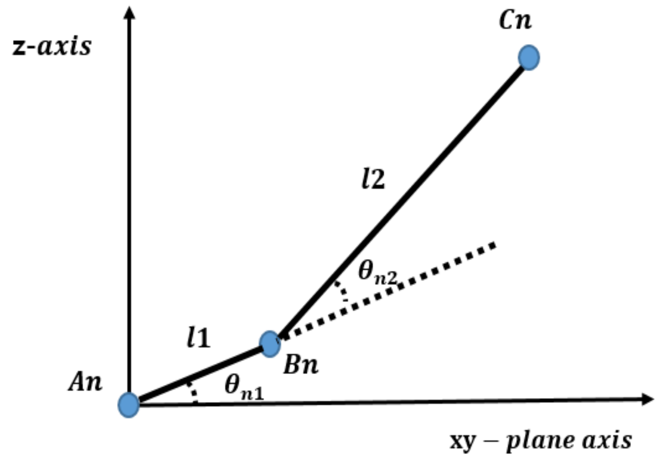

Fig. 4. Kinematic Analysis of n^{th} link

Then the center point O and the rotation point of each motor are located on the same x-y plane, and are located at 120 degree intervals by the distance of R from the O point. Each of these points is defined as A_1, A_2 and A_3 in the order of the motor.(A motor which is located front side as a player is A_1, and backside 2 are A_2 and A_3) Each of these points can be considered as the center point of the drive shaft of each motor to which the link is connected, and is expressed as a point because it has the same rotational speed and angle.

Links connected to the rotation axis of each motor are sequentially connected from the axis to each of the two links having a length of l_1, and a large Y-shaped link is connected to the two ends. Then the center point of the end of the y-shaped large link and the connection point with the top plate is C_n, and are C_1, C_2 and C_3 according to the numbering of the motor at under-plate.

Next, two links move according to the rotation of the motor, point of upper-plate, C_n is finally determined. Here, the link structure with two l_1 length links and the Y-shaped link are the same as the structure in which one l_1 length link(A_nB_n link) and l_2 length link(B_nC_n link) are connected from point A_n to C_n. Finally, $B_n$is a connect point between A_nB_n link and B_nC_n link.

Fig. 4 is a Kinematic Analysis of n^{th} link structure from A_n to C_n. Each link structure moves in three dimensions, but considering the rotation characteristics of the motor, each link moves only on a specific two-dimensional plane (A_nO straight line with x axis and z axis with y axis). Therefore, as shown in Fig. 4, 3D motion can be re-analyzed in 2D.

At Fig. 4, an angle between A_nO and A_nB_n is θ_{n1}(it doesn't have to consider direction, because there is only one.). And another one θ_{n1} is angle between extension of A_nB_n and B_nC_n which only one direction.

B. Formulation of Forward Kinematic Equation

Forward kinematics can be obtained by focusing on the fact that the length of the link does not change and the movement only occurs at an angle that depends on the motion of the motor. So in terms of Z-Y-X Euler angles and transform equation, each link structure can be arranged through the transformation operators. These are

$$T_{A1}^{O} = \begin{bmatrix} 1 & 0 & 0 & R \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$T_{B1}^{A1} = \begin{bmatrix} \cos(\theta_{11}) & 0 & \sin(\theta_{11}) & -l_1\cos(\theta_{11}) \\ 0 & 1 & 0 & 0 \\ -\sin(\theta_{11}) & 0 & \cos(\theta_{11}) & l_1\sin(\theta_{11}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$T_{C1}^{B1} = \begin{bmatrix} \cos(\theta_{12}) & 0 & \sin(\theta_{12}) & -l_2\cos(\theta_{12}) \\ 0 & 1 & 0 & 0 \\ -\sin(\theta_{12}) & 0 & \cos(\theta_{12}) & l_2\sin(\theta_{12}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$T_{A2}^{O} = \begin{bmatrix} \frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 & -\frac{R}{2} \\ \frac{1}{2} & \frac{\sqrt{3}}{2} & 0 & \frac{\sqrt{3}}{2}R \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$T_{B2}^{A2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta_{21}) & \sin(\theta_{21}) & -l_1\cos(\theta_{21}) \\ 0 & -\sin(\theta_{21}) & \cos(\theta_{21}) & l_1\sin(\theta_{21}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$T_{C2}^{B2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta_{22}) & \sin(\theta_{22}) & -l_2\cos(\theta_{22}) \\ 0 & -\sin(\theta_{22}) & \cos(\theta_{22}) & l_2\sin(\theta_{22}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

$$T_{A3}^{O} = \begin{bmatrix} \frac{1}{2} & -\frac{\sqrt{3}}{2} & 0 & -\frac{R}{2} \\ \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 & -\frac{\sqrt{3}}{2}R \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

$$T_{B3}^{A3} = \begin{bmatrix} \cos(\theta_{31}) & 0 & -\sin(\theta_{31}) & l_1\cos(\theta_{31}) \\ 0 & 1 & 0 & 0 \\ \sin(\theta_{31}) & 0 & \cos(\theta_{31}) & l_1\sin(\theta_{31}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

$$T_{C3}^{B3} = \begin{bmatrix} \cos(\theta_{31}) & 0 & -\sin(\theta_{31}) & l_1\cos(\theta_{31}) \\ 0 & 1 & 0 & 0 \\ \sin(\theta_{31}) & 0 & \cos(\theta_{31}) & l_1\sin(\theta_{31}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

Then calculate the following to obtain the position of each points.

$$\begin{aligned} T_{C1}^{O} &= T_{A1}^{O} * T_{B1}^{A1} * T_{C1}^{B1} \\ T_{C2}^{O} &= T_{A2}^{O} * T_{B2}^{A2} * T_{C2}^{B2} \\ T_{C3}^{O} &= T_{A3}^{O} * T_{B3}^{A3} * T_{C3}^{B3} \end{aligned} \tag{10}$$

If sort above out by calculation, each transformation equation become a 4X4 matrix. Here (1,4), (2,4) and (3,4) represent the coordinates of C_n, respectively, and these can be expressed as functions for θ_{n1} and θ_{n2}. When the position of $C_n = (x_{Cn}, y_{Cn}, z_{Cn})$, it can obtain this form.

$$T_{Cn}^{O} = \begin{bmatrix} a & b & c & x_{Cn} \\ d & e & f & y_{Cn} \\ g & h & i & z_{Cn} \\ j & k & l & 1 \end{bmatrix} \tag{11}$$

In other words, the coordinates of C_n determine the position of the top plate can be obtained as follows.

$$\begin{aligned} x_{Cn} &= f_{n1}(\theta_{n1}, \theta_{n2}) \\ y_{Cn} &= f_{n2}(\theta_{n1}, \theta_{n2}) \\ z_{Cn} &= f_{n3}(\theta_{n1}, \theta_{n2}) \end{aligned} \tag{12}$$

Above (12) is final forward kinematic equation which is estimate the location of upper plate with three of motor angle and three of middle angle.

C. Formulation of Constraints

In order to calculate the position based on the above equations, some constraints need to be added. This is because there are a total of six variables for positioning. Therefore, by formulating and applying some conditions, it make it possible to solve the kinematic equations. In other words, inverse kinematics can be applied to this formula. Constraints are

$$\begin{aligned} \sqrt{3}\mathrm{r} &= \sqrt{(x_{C1} - x_{C2})^2 + (y_{C1} - y_{C2})^2 + (z_{C1} - z_{C2})^2} \\ &= \sqrt{(x_{C1} - x_{C3})^2 + (y_{C1} - y_{C3})^2 + (z_{C1} - z_{C3})^2} \\ &= \sqrt{(x_{C3} - x_{C2})^2 + (y_{C3} - y_{C2})^2 + (z_{C3} - z_{C2})^2} \end{aligned} \tag{13}$$

(13) is three 4-variable equation can used as a condition to inverse kinematics. Then the state values that we need can be obtained. In most cases, there are several solutions due to the nonlinearity of the trigonometric function. In this case, the recursive method is used to select the answer compared to the previous value.

III. Simulation

The motion of the platform is specified by three independent end effector parameters. This includes translational motion along the z-axis (heave) and rotational motion around the x-axis (roll) and y-axis (pitch). T Kader el al [15].

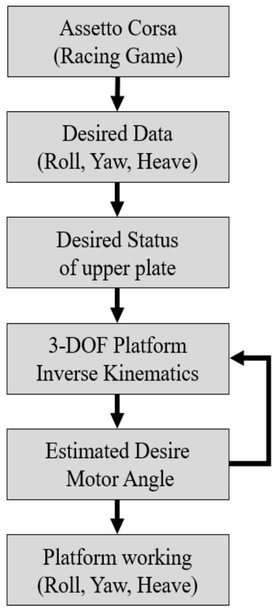

Fig. 5. Simulation Scheme for 3-DOF Motion Platform

Since operation need a data to operate the platform, so the data of the racing game called *ASSETTO CORSA* is used by hooking with C ++ code. Because of this, other process is needed. Game data are types of end effector parameters not a status of upper plate which needed.

The motor of this Platform is stepper motor 34HS59-5004D. Due to the specifications of this stepper motor, the rotation speed is not fast enough, and angle control is performed instead of speed or torque control like other motor. In this regard, the drive signal of the motor was given as the maximum value and command of the movement focuses only on the position, not the speed and acceleration.

Roll, Pitch and Heave can easily be made by making the operation of each motor different. For example, roll is only effected to motor 2, 3(behind-side motor to player) and the pitch is made by tuning the ratio of the first motor and the second and third motors based on the midpoint of the top plate(exactly, a center of chair upon plate).

In order to interpolate the error caused by the position control of the motor, a simulation configuration in which the gain k is added to the calculated angle is presented.

Fig. 5 is shown that the overall process of simulation. Valid data from racing game are used as input, and the rotation angle of the motor is obtained through conversion and calculation through inverse kinematics. Then the 3-DOF motion platform make three movement by inputting it to the each motor.

The method of controlling the motor was performed using C++ code with conversed (12) and (13) and recursive method. Also, the motor driver and UNO R3 board are used through serial communication. The details of this method are not discussed separately.

Before proceeding with the overall simulation, in order to verify that the theoretically derived equations and methodologies are correct, Autodesk Inventor 3D CAD S/W and MATLAB (syms tool box) are used to experiment with specific conditions. As shown in Fig. 6, in two situations, plotting graphs of calculated values(right side) are not a big difference with CAD S/W calculation results(left side). This is a numerical comparison.

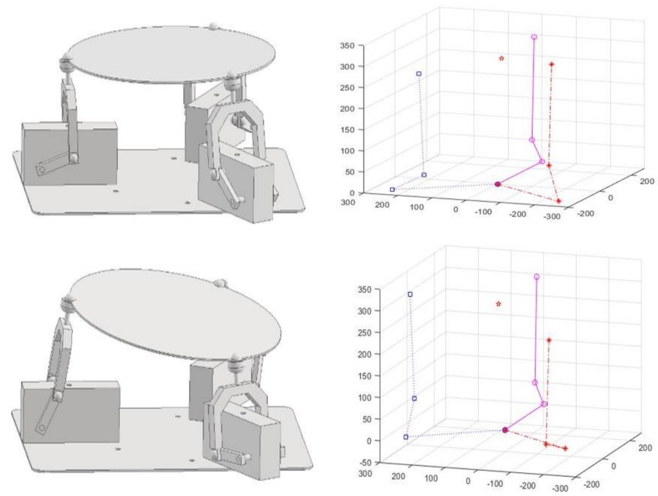

Fig. 6. Visualization Test between 3D CAD and Calculated Result

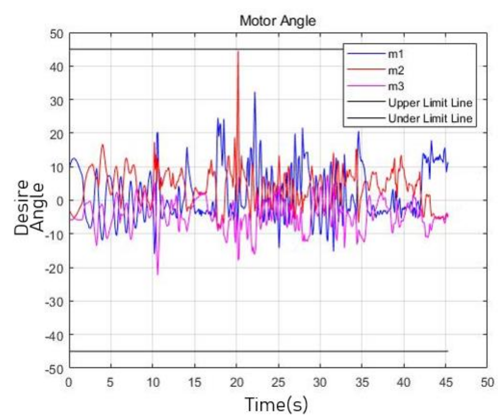

Fig. 7. Results of calculated motor angles

The results of each calculated motor are shown in Fig. 7. The input data is 50 seconds driving data in a racing game. This is a motor angle value to implement game status to users through the platform. And the desired angle data are only calculated within a certain range due to the physical limitations of the motor rotation range due to the safety guide protecting the link and the body frame.

$$-45^\circ \leq Motor\ Angle \leq 45^\circ \tag{14}$$

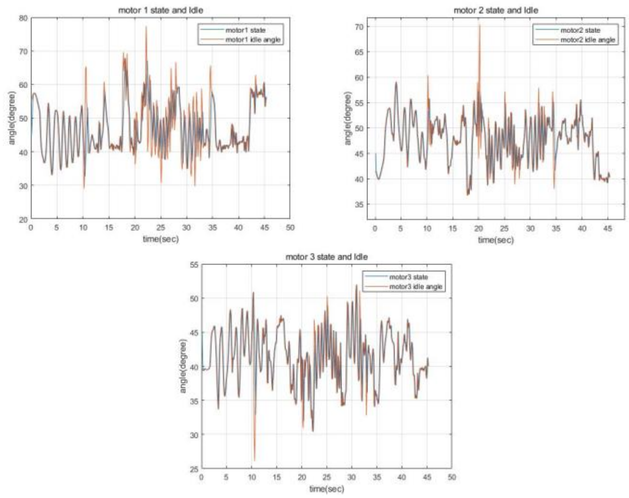

Fig. 8. Comparision between Desired and Real angle

TABLE I. PARAMETERS FOR SIMULATION

Symbol	***Description***	***Value***	***Unit***
R	Distanc O to A_n(Under Plate radius)	281.33	mm
r	Distanc o to C_n(Upper Plate radius)	230	mm
l_1	Length of link 1	90	mm
l_2	Length og link 2	241.63	mm

Fig. 8 is result graph of each motor's calculated desire angle and actual moving angle. As we can see, each motor follows the required angle of the input signal well, but due to the slow speed of the stepper motor, it was not possible to fully follow it. And Table 1.is parameters for simulation calculation.

IV. CONCLUSION

An implementation of the kinematics for a 3-DOF 2-link type motion platform using was presented in this paper. First, the basic structure of the robot was presented with her particularities. Then it is modeled in an easy structure based on kinematic characteristics. After this, Inverse kinematics is expressed in a form that can be calculated using forward kinematics which Z-Y-X Euler angle shape and other constraints. For implementation, Matlab and Autodesk Inventor was used as tool. Finally, C ++ code, serial communication, and Arduino board were used for the operation of the machine.

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