DESIGN AND DEVELOPMENT OF A 6-DOF SYSTEM FOR VIRTUAL BICYCLE SIMULATOR

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Abstract

There are many variations of the competition that takes place in Olympic track cycling. Hence, a bicycle simulator will provide a number of benefits to coaches and athletes in practical training. It is extremely low cost compared to a real Velodrome track, which requires a long construction time due to the unique geometry and size. In this project, a 6-degree-of-freedom (6-DOF) motion platform is designed and developed to simulate the Velodrome track cycling. A parallel manipulator was chosen to control the moving platform due to its higher accuracy and greater weight to strength ratio compared to a serial manipulator. The 6-DOF platform is controlled by linear actuators and micro-controller. An optical encoder was installed for closed-loop position feedback control. An inverse kinematics model was developed to obtain the movement of the platform and validated with its CAD model. Furthermore, a design feasibility program was developed to determine the optimum design dimensions for the motion platform. All the positions (3-axes) and orientations (3-rotational axes) data are tracked for analysis purpose. A lab-scale prototype was successfully built for analysis and validation purposes. A standard Velodrome track dimensions was chosen for simulation. A gyro accelerometer was installed at the platform to acquire the actual motion of the platform. The data is used to validate the control algorithms and accuracy of the motion platform. The experiment was conducted and the results analysed for further development.

Keywords: Track cycling, motion platform, bicycle simulator, 6-DOF

Introduction

There are various virtual reality simulators widely used to perform testing and evaluation. Unfortunately, there is no advanced bicycle simulator in the market. This is because of the inherent unstable dynamics of the bicycle coupled with the human rider's dynamics. In the market, the typical commercial bicycle simulator is only able to provide a pedal resistance for the user, but is unable to simulate the motion of the bicycle for human sensation. In this project, a 6 degree-of-freedom Stewart platform mechanism will be applied to the bicycle simulator to simulate a more realistic virtual environment for the user.

Currently, most simulators use the Stewart platform (Stewart, 1965), which has greater accuracy and stiffness to create a virtually realistic environment for the user (Kwon et al., 2001). The Stewart platform is a kind of parallel manipulator which is able to move in six degrees of freedom. A parallel manipulator is a platform in which its spatial position is controlled by fixing the distance between the six points in the platform and the six points at the fixed base (Faugère & Lazard, 1995). This mechanism has a higher precision, greater stiffness. and greater load capacity compared to a serial manipulator (Merlet, 2004). However, its main drawback is that it has a smaller workspace and lower dexterity compared to a serial manipulator (Patel, 2012). This platform has been widely applied in motorcycle simulators (Ferrazzin, Barbagli, Avizzano, Di Pietro, & Bergamasco, 2003), helicopter simulators for landing and takeoff (Campos, Quintero, Saltaren, Ferre, & Aracil, 2008), offshore cargo simulators (Gonzalez, Dutra, & Lengerke, 2011) and risk analysis (Madsen, 2012).

There has been several research works on bicycle simulators, such as Interactive Bicycle Simulator by He and collaborator (2005), low cost 2-DOF interactive bicycle simulator (Chen, Chen, Huang, & Huang, 2007), KAIST interactive bicycle simulator (Kwon et al, 2002) for campus simulation, the FIVIS project (Schulzyk, Hartmann, Bongartz, Bildhauer, & Herpers, 2009) for real life traffic situations in a virtual environment and CUELA system for analysis of musculoskeletal strains (Herpers et al., 2010). However, there is no simulator specifically designed for sport training purposes.

The velodrome track

Based on the Cycle Sports Facilities Design Guide from Sport England, the standard dimension of various Velodrome track is provided. The tracks are constructed according to the metric distance of cycling events, which can be divided into 166.66m track, 200m track, 250m track, 333.33m track and 500m track (Webb, 2003). Different track lengths have different highest banking angles. The highest banking angle of a 250m track is up to 45° while highest banking angle for the 333.33m track is 28°. A Velodrome track with 333.33m track (3 laps = 1km) is recommended as a good solution to the need for general cycling activities from beginner to elite level, and provides a central arena area to accommodate a wide variety of sports.

Bicycle specifications

The bicycle specification will be referring to the Union Cycliste Internationale (UCI) Bike Regulation: Part 3-Track Races where the bicycle should not be more than 185cm in length and 50cm in width. The weight of the bicycle shall be more than 6.8 kilograms. The plane from the highest point at the front and saddle shall be horizontal. Length of the saddle should be between 24cm to 30cm depending on the size of the cyclist. The wheel of the bicycle including the tire may vary in diameter within the range of 55cm to 70cm and shall have at least 12 spokes where the spokes can be round, flattened or oval in shape. There are requirements that must be fulfilled for the wheel. No element of the wheel may become detached and expelled outward when facing impact and a rupture must not present any sharp or serrated surfaces that may harm the user or other riders.

Importance of study

Nowadays, various virtual reality vehicle simulators have been developed to use for training and evaluation, such as the flight simulator. The main reason for virtual flight is because of the extremely high cost to build an actual flight simulator with various situations, as some of the situations are unfeasible to perform in real life. Similar to the virtual reality bicycle simulator, the cost of building the Velodrome track is extremely expensive, with the unique geometry and complexity of the track. Besides that, the maintenance cost of the Velodrome track is also high. On the other side, a bicycle simulator does not require a huge space and expenditure compared to a Velodrome track. It is relatively portable and able to place in the school or university. It is able to model some unfeasible situations for training purposes. For example, virtual competitors can be created to mimic the actual competition.

Methodology

There are many variations to the competition that takes place in the Olympic track cycling. Hence, a bicycle simulator will bring a lot of benefits to the coaches and the athletes in a practical training. In this project, a 6-degree-of-freedom (6-DOF) motion generation platform must be designed and developed to simulate the Velodrome track cycling. The parallel manipulator was chosen to control the moving platform because of a higher accuracy and greater weight to strength ratio compare to a serial manipulator. The Stewart Platform system, a parallel manipulator which has 6-DOF, was applied in this project. The 6-6 hexapod Stewart Platform was selected as the motion platform for the bicycle simulator. It consists of 6 extensible actuators. The “6-6” means that the Stewart Platform has 6 connecting points at the moving platform and 6 connecting points at the base. The connecting point is connected to the extensible actuators via spherical or universal joints. The "hexapod" refers to the shape of the platform and the base. The "hexapod" is symmetrical and there is an equilateral triangle where the edges are cut down by a short distance.

The 6-DOF platform consists of a base, a moving platform, 6 linear actuators, 12 universal joints, 12 pillow block bearings, Arduino Mega 2560, 3 switching power supply and 3 dual channel motor driver (Figure 1). An optical encoder was installed to every linear actuator to check the position of the stroke so that it is controllable. A set of inverse kinematics model was built and converted into programming system in order to control the movement of the platform. A 3D model of the 6-DOF platform was modelled to validate the inverse kinematics. A set of design feasibility program was built to find out the optimum design dimensions. Various types of data are provided in the program system in order to check the feasibilities of the design to fulfil the required movement. A prototype was successfully built for testing and analysis purposes. A standard Velodrome track dimension was chosen to be simulated by using the prototype. A gyro accelerometer was installed to conduct an experiment to test the error of the prototype. The experiment results were collected and plotted in several graphs for analysis. The data was compared between the actual and the desired results for analysis purposes.

Figure 1: Prototype of Steward platform for track cycling simulator

Inverse Kinematics

Inverse kinematics enable us to find out the lengths of the six extensible actuators from a given position and orientation of the motion platform. Initially, the dimensions of the base platform and moving platform have to be determined. Figure 2 shows the 4-length variables: two (2) for the dimensions of the base, and two (2) for the moving platform. An origin is set at the middle of the base so that the vectors of the 6 connecting points of base and moving platform can be determined through vector analysis. Firstly, the coordinates of the 6 points at the base (from B1 to B6) and the 6 points at the moving platform (from P1 to P6) have to be determined by substituting the dimension variables L, D, l and d into the derived formula:

L = the equilateral triangle length of the base.
D = the short distance between two base connecting points.
l = the equilateral triangle length of the moving platform.
d = the short distance between two platform connecting points

For the point at the platform, we assume that it is still coincident at the base. The following is the derived formula. Figure 2 shows the connecting points and Table 1 shows their coordinates accordingly.

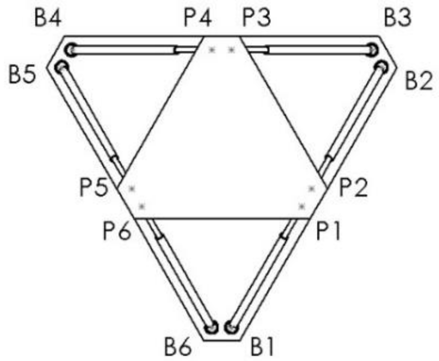

Figure 2: Connecting points in the Stewart platform

Table 1: Coordinates for the connecting points.

Location	Coordinates		
Base	$\boldsymbol{B_1} = \begin{bmatrix} \frac{2}{3}\sqrt{L^2 - \frac{L^2}{4}} - \sqrt{D^2 - \frac{D^2}{4}} \\ D/2 \\ 0 \end{bmatrix}$	$\boldsymbol{B_2} = \begin{bmatrix} \sqrt{D^2 - \frac{D^2}{4}} - \frac{1}{3}\sqrt{L^2 - \frac{L^2}{4}} \\ \frac{1}{2}(L - D) \\ 0 \end{bmatrix}$	$\boldsymbol{B_3} = \begin{bmatrix} -\frac{1}{3}\sqrt{L^2 - \frac{L^2}{4}} \\ L/2 - D \\ 0 \end{bmatrix}$
	$\boldsymbol{B_4} = \begin{bmatrix} -\frac{1}{3}\sqrt{L^2 - \frac{L^2}{4}} \\ D - L/2 \\ 0 \end{bmatrix}$	$\boldsymbol{B_5} = \begin{bmatrix} \sqrt{D^2 - \frac{D^2}{4}} - \frac{1}{3}\sqrt{L^2 - \frac{L^2}{4}} \\ \frac{1}{2}(D - L) \\ 0 \end{bmatrix}$	$\boldsymbol{B_6} = \begin{bmatrix} \frac{2}{3}\sqrt{L^2 - \frac{L^2}{4}} - \sqrt{D^2 - \frac{D^2}{4}} \\ -D/2 \\ 0 \end{bmatrix}$
Platform	$\boldsymbol{P_1} = \begin{bmatrix} \frac{1}{3}\sqrt{l^2 - \frac{l^2}{4}} \\ l/2 - d \\ 0 \end{bmatrix}$	$\boldsymbol{P_2} = \begin{bmatrix} \frac{1}{3}\sqrt{l^2 - \frac{l^2}{4}} - \sqrt{d^2 - \frac{d^2}{4}} \\ \frac{1}{2}(l - d) \\ 0 \end{bmatrix}$	$\boldsymbol{P_3} = \begin{bmatrix} \sqrt{d^2 - \frac{d^2}{4}} - \frac{2}{3}\sqrt{l^2 - \frac{l^2}{4}} \\ d/2 \\ 0 \end{bmatrix}$
	$\boldsymbol{P_4} = \begin{bmatrix} \sqrt{d^2 - \frac{d^2}{4}} - \frac{2}{3}\sqrt{l^2 - \frac{l^2}{4}} \\ -d/2 \\ 0 \end{bmatrix}$	$\boldsymbol{P_5} = \begin{bmatrix} \frac{1}{3}\sqrt{l^2 - \frac{l^2}{4}} - \sqrt{d^2 - \frac{d^2}{4}} \\ \frac{1}{2}(d - l) \\ 0 \end{bmatrix}$	$\boldsymbol{P_6} = \begin{bmatrix} \frac{1}{3}\sqrt{l^2 - \frac{l^2}{4}} \\ d - l/2 \\ 0 \end{bmatrix}$

Next, we can use Roll, Yaw, and Pitch Angles to determine the orientation of the moving platform. Roll, Yaw, and Pitch Angles are a sequence of 3 rotations about the current *n*, *o*, and *a* axes respectively, which are able to determine the orientation of the motion platform.

$$Rot(\theta_a, \theta_o, \theta_n) = Rot(a, \theta_a)Rot(o, \theta_o)Rot(n, \theta_n) \tag{1}$$

$$= \begin{bmatrix} \cos\theta_a \cos\theta_o & \cos\theta_a \sin\theta_o \sin\theta_n - \sin\theta_a \cos\theta_n & \cos\theta_a \sin\theta_o \cos\theta_n + \sin\theta_a \sin\theta_n & 0 \\ \sin\theta_a \theta_o & \sin\theta_a \sin\theta_o \sin\theta_n + \cos\theta_a \cos\theta_n & \sin\theta_a \sin\theta_o \cos\theta_n - \cos\theta_a \sin\theta_n & 0 \\ -\sin\theta_o & \cos\theta_o \sin\theta_n & \cos\theta_o \cos\theta_n & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where,

θ_n *is the angle of rotation about* $\boldsymbol{n}$ *axis(current x axis) called roll.*
θ_o *is the angle of rotation about* $\boldsymbol{o}$ *axis(current y axis) called pitch.*
θ_a *is the angle of rotation about* $\boldsymbol{a}$ *axis(current z axis) called yaw.*

After the orientation is given, we have to determine the platform's coordinate as ***C.***

$$\boldsymbol{C} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{2}$$

The six new positions' vectors (N_i) after the orientation and translation at the moving platform are determined by the matrix transformation below.

$$\boldsymbol{N_i} = \boldsymbol{C} \times Rot(\theta_a, \theta_o, \theta_n) \times \boldsymbol{P_i} \quad where\ i = 1,2, \dots, 6 \tag{3}$$

The length (L_i) of the extensible actuators is determined by taking the distance between the new position and the base point. The equation is as below.

$$\boldsymbol{L_i} = |\boldsymbol{N_i} - \boldsymbol{B_i}| \quad where\ i = 1,2, \dots, 6 \tag{4}$$

Validation with CAD Model

The derived formula was converted into C++ language for testing and calculation. A 3D CAD model was created for the validation purpose of the calculation. The dimensions of both base and the platform (*L*, *D*, *l*, *d*) acts as an input for the program. The desired position (*x*, *y*, *z*) and the orientation ($\theta_a, \theta_o, \theta_n$) are the next input for the program. The above equations were used to calculate the lengths of the six extensible actuators ($L_1, L_2, L_3, L_4, L_5, L_6$). After determining the lengths of the six extensible actuators, a validation was performed using a 3D CAD model. The moving platform is placed to the desired position and orientation to obtain the length of the six extensible actuators. Table 2 shows the example of the input parameters and 3D CAD model during validation.

Table 2: Example of inverse kinematics validation with CAD model

<table>
<tr><th>Input Parameter
(dimensions, positions & orientation)</th><th>Output Parameter
(Inverse Kinematics)</th><th>Output Parameter
(CAD Model)</th></tr>
<tr><td>

- *d* = 150mm, *l* = 1500mm
D = 150mm, *L* = 2550mm
- *x*=100, *y*=50, *z*=800
- $\theta_a = 20°$, $\theta_o = -15°$, $\theta_n = -10°$

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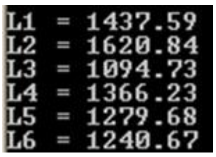

L1 = 1437.59
L2 = 1620.84
L3 = 1094.73
L4 = 1366.23
L5 = 1279.68
L6 = 1240.67

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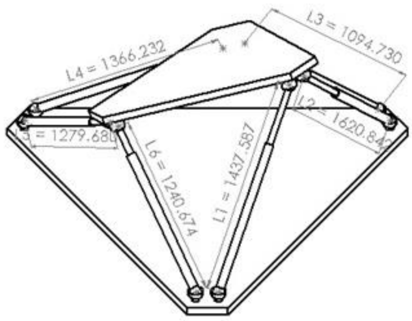

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Optimum design parameter

There are some constraints for the Stewart Platform. For example, the moving platform cannot go under the base; the spherical joint has an angle constraint that ensures it will not over turn; and there is a maximum extensible actuators' stroke percentage. To determine these constraints and errors, additional calculations have to be made and converted into the C++ language and added into the program.

For the percentage of the extensible actuator, the equation is just for one position and orientation, meaning it is not true for other positions and orientations. This feature in the program ensures that the position and orientation will not cause an infeasible stroke. The percentage of the stroke length (S%) can be obtained using the following equation:

$$S\% = \left(\frac{L_{max}}{L_{min}} - 1\right) \times 100\% \tag{5}$$

The stroke percentage is the maximum length divided by the minimum length of the extensible actuator. The stroke percentage cannot be more than or equal to 100%. It should not be more than a certain percentage to ensure that the actuators are strong enough, and the joint size must still be considered into the actuators' length, causing the stoke percentage to decrease.

An equation has been developed to determine the angle between the base and the extensible actuators ($\emptyset_{bi}$):

$$\emptyset_{bi} = cos^{-1}\frac{(L_{ix}{}^2+L_{iy}{}^2)}{(L_{ix}{}^2+L_{iy}{}^2+L_{iz}{}^2)} where\ i = 1,2,\dots,6 \quad (6)$$

For the angle between the actuator and platform ($\emptyset_{pi}$), the normal vector to the moving platform has to be determined first before the angle is determined, as shown in Figure 3. Thus, in order to determine the normal vector of the moving platform ($\boldsymbol{V_n}$), the matrix cross product for two vectors between the points at the moving platform has to be calculated in advance:

$$V_n = (P_3 - P_1) \times (P_1 - P_2) \quad (7)$$

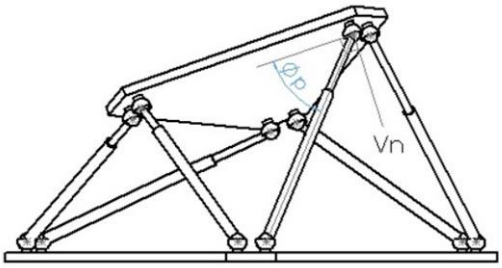


Figure 3: Moving platform angle ($\emptyset_{pi}$)

Then, the dot product between the extensible actuator vector and the unit normal vector of the moving platform needs to be determined for the projection length (X_n) of the extensible length on the normal of the moving platform:

$$X_n = \frac{\boldsymbol{V_n}}{|\boldsymbol{V_n}|} \cdot \boldsymbol{L_i} \quad (8)$$

Finally, the angle of the platform and the actuator ($\emptyset_{pi}$) can be determined using the following formula.

$$\emptyset_{pi} = sin^{-1}\frac{X_n}{(L_{ix}{}^2+L_{iy}{}^2+L_{iz}{}^2)} where\ i = 1,2,\dots,6 \quad (9)$$

Result and analysis

The orientations of the moving platform were detected using gyro accelerometer and the data collected. The target data was also collected in order to compare the actual one in the graph for further analysis. Figure 4 shows the orientation data of the moving platform when simulating the track surface.

In order to get the positioning data, the acceleration of the moving platform was detected using an accelerometer and then integrated twice. Unfortunately, the noise of the data was amplified after integration and the error was accumulated along the time. Therefore, noise in the acceleration data must be eliminated. After eliminating the noise, the actual trends in the graph are closer to the desired one. The following are graphs (Figure 5) showing the positions of the moving platform.

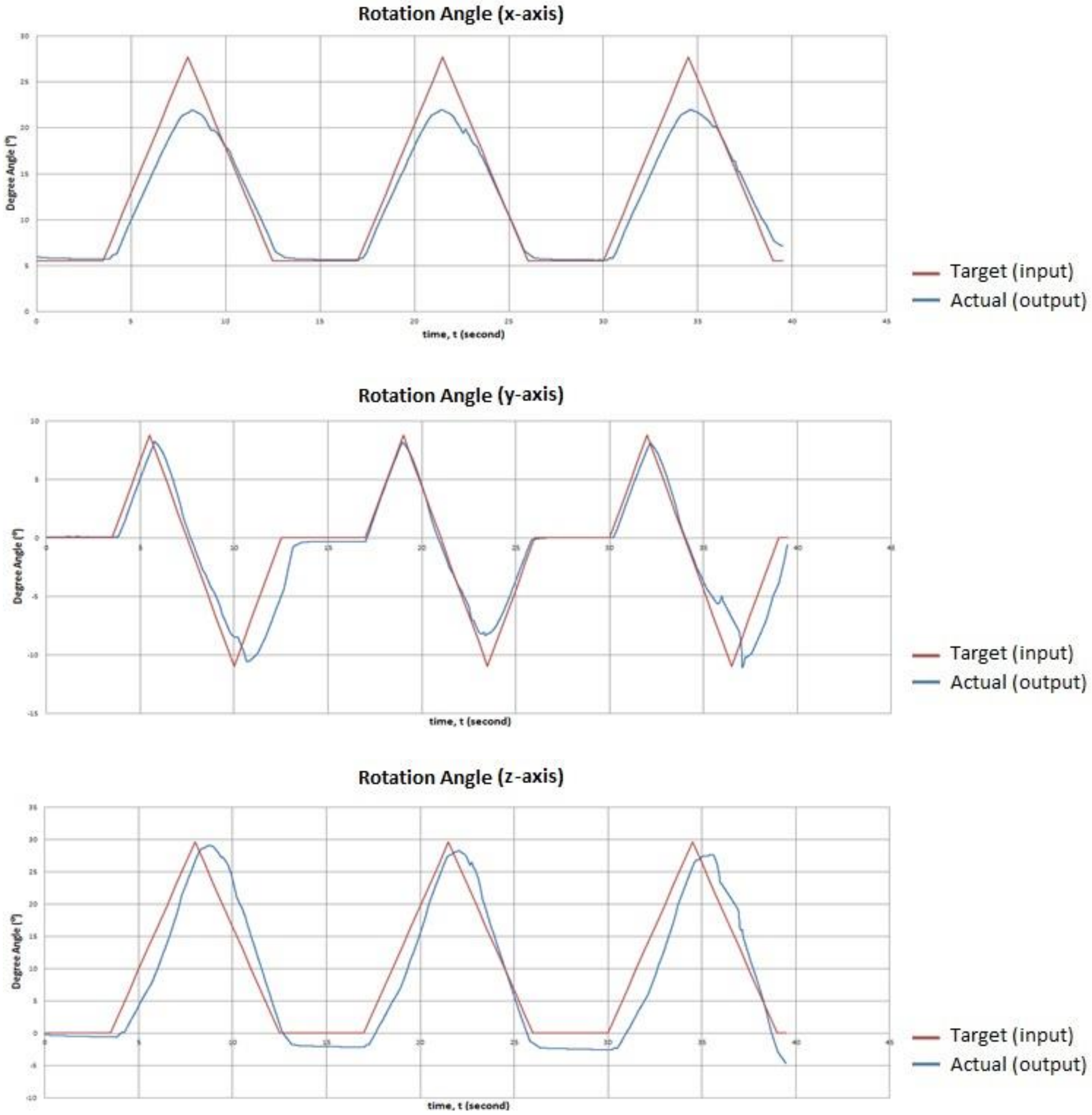
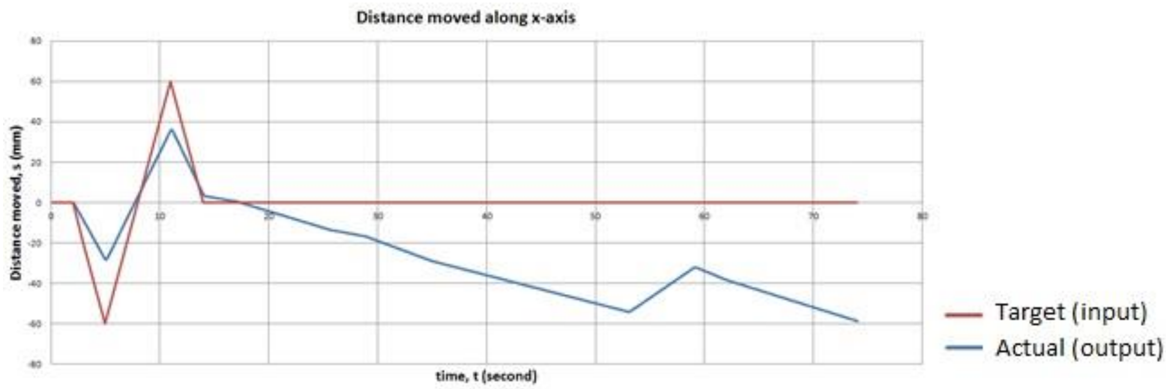


Figure 4: Experiment data for orientations



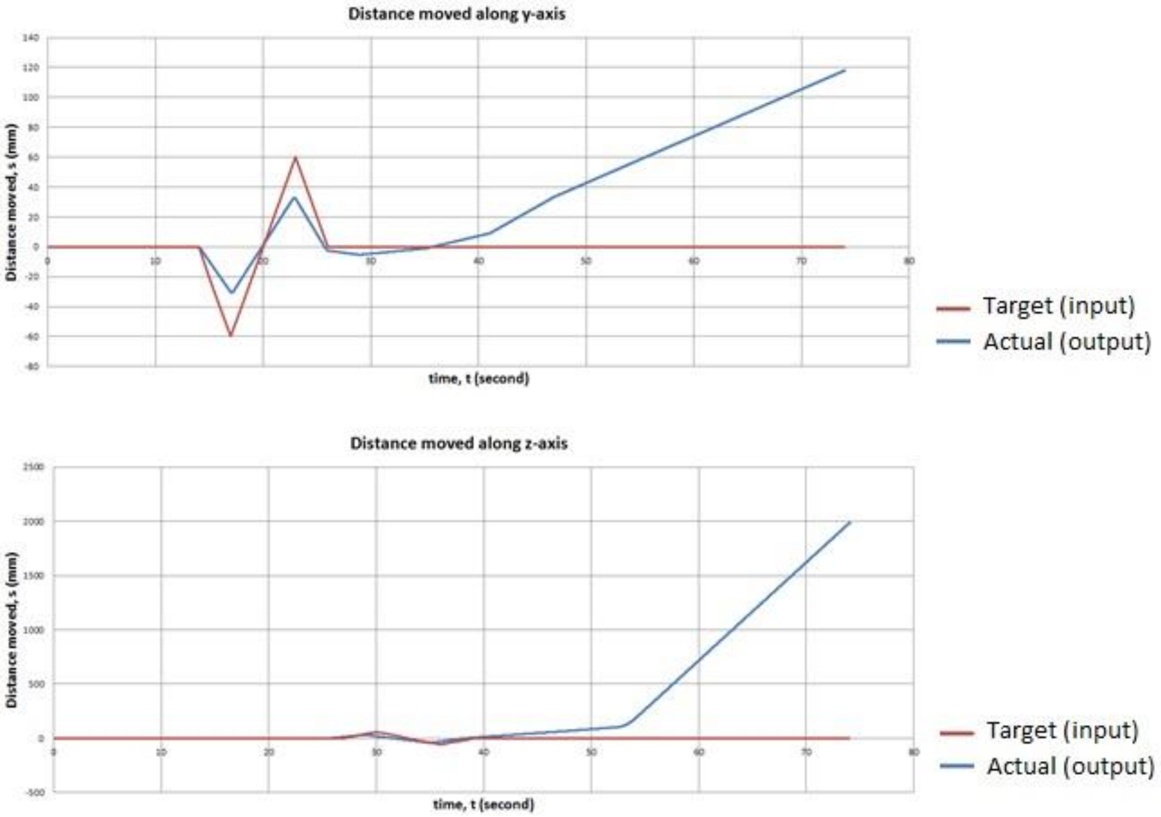


Figure 5: Experiment data for positions

Conclusions and recommendations

The kinematics equation has successfully been formulated. The prototype of 6-DOF motion platform for bicycle simulator was successfully designed and built. The prototype was able to function well, although it is not perfect and there are some defects that must be improved. The accuracy of the prototype was tested. Results were satisfying but there are still many further improvements to be developed.

A design feasibility programming was also successfully created in order to find out a feasible design before fabricating the prototype. This is an important procedure to determine the dimensions required for the desired movements. The program provides a number of conveniences in the design stage for a 6 DOF moving platform. It has been successfully implemented in this project and helped to determine a feasible design.

Through this project, many unexpected mistakes and errors occurred. A great deal of experience was gained from this project. This is to prevent similar mistakes from happening again in the second prototype, which will be in full scale, Reducing the risk of mistakes during the designing and building stage for the next prototype is vital. Besides that, the dynamics of the 6 degree of freedom platform will be further calculated for the next prototype. A graphical environment will also be added to the display on the screen.

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