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Modeling, Simulation and Design of Adaptive 6DOF Vehicle Stabilizer

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***Abstract*— Six Degree of Freedom (6 DOF) parallel manipulators have been utilized for many applications. In this paper, a 6 DOF manipulator is used as a robust vehicle stabilizer in order to fix the orientation of the upper platform. The paper starts with kinematic analysis of a Stewart platform. This analysis is formulated to cope with the design of vehicle stabilizer. The design and selection of mechanical components including primary joints based on comprehensive dynamic simulation. After validating simulation results of proposed design, they were implemented in to build a physical model. To improve system accuracy and performance, and to eliminate associated vibrations, a linear regression model of ground rise is embedded in the system to estimate and predict upcoming elevations. This has lowered the percentage error of platform orientation, made the system more stable.**

Keywords—Stewart Platform, Adaptive, Kinematics, Simulation, Stabilizer, linear regression, Vibration

I. Introduction

6 DOF Platforms have many applications worldwide as in [1], [2], and [3]. The objective of this research work is to utilize this mechanism in stabilizing the upper platform for any vehicle facing variations in path bumpiness. 6 DOF platforms are accurate, fast, and precise [4]. Also, the workspace is large enough to accommodate any practical path, as the top platform can rotate with angles exceeding 45° relative to the base.

II. Kinematic Analysis

The inverse kinematic analysis of a 6-DOF parallel manipulator is modeled using vector loop method as shown in Figure 1.

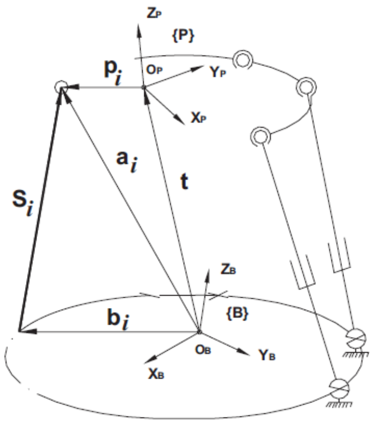

Fig 1. *6-DOF parallel manipulator vector loop [1].*

Defining the expected length of every linear actuator in Stewart platform, S_i, in the form:

$$S_i = Rp_i + t - R_b b_i \tag{1}$$

$$R = R_z * R_y * R_x \tag{2}$$

$$R_z = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 \\ \sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$R_y = \begin{bmatrix} \cos\theta_y & 0 & -sin\theta_y \\ 0 & 1 & 0 \\ sin\theta_y & 0 & \cos\theta_y \end{bmatrix} \tag{4}$$

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & sin\theta_x \\ 0 & -sin\theta_x & \cos\theta_x \end{bmatrix} \tag{5}$$

Where R is the coordinate transformation matrix as defined in (2) and (3)-(5). p_i is the upper joints coordinates reference to the center of upper platform. b_i is the lower joints coordinates reference to the center of lower platform. t is the relative distance between the centers of upper and lower platforms.

The Stewart platform assumes a fixed lower base and a free upper platform. However, a vehicle stabilizer assumes a free lower base while an ideally fixed upper platform in all degrees of freedom except along the rotation in the z axis. Thus, the inverse kinematic equation of the stabilizer would vary from the Stewart platform equation in terms of the location of the rotation matrix as shown in (6)-(7):

$$S_i = p_i + t - Rb_i \tag{6}$$

$$R = R_y * R_x \tag{7}$$

III. Model Simulation

Prior validation of proposed design is achieved by modeling the inverted Stewart platform using Simscape Multibody package. The model is shown in Figure 2.

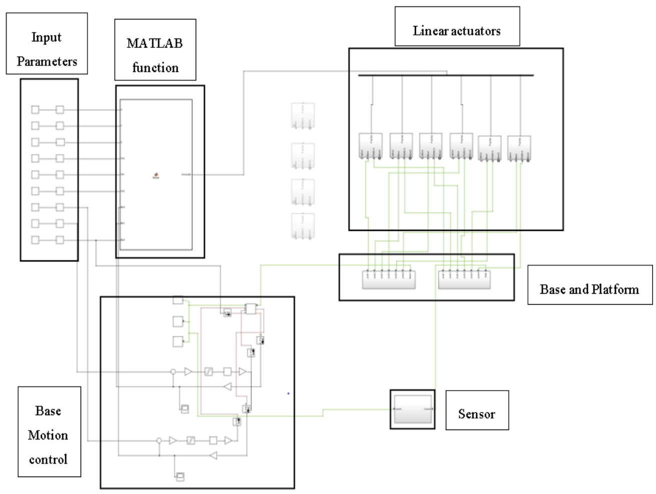

Fig 2. *Simulated model of vehicle stabilizer*

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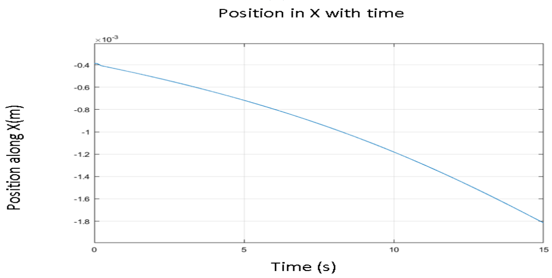
Initially, the manipulator was tested as a Stewart platform to verify the design and the choice of joints. Then, the fixed constraints on the lower base were altered to rotational joints, and the position and orientation of the top platform was monitored. The controller used in the simulation was a proportional-derivative controller. A test case to for the position of platform while base is rotating about the x-axis is shown in Figures 3 and 4. The percentage error was about 0.35%, 3.75%, and 0.2% in the x, y, and z axes, respectively.

(a)



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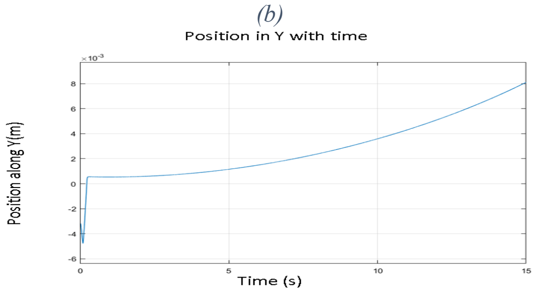

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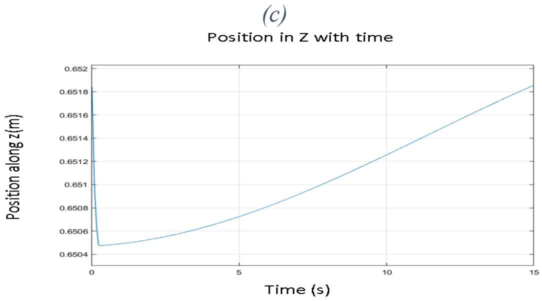

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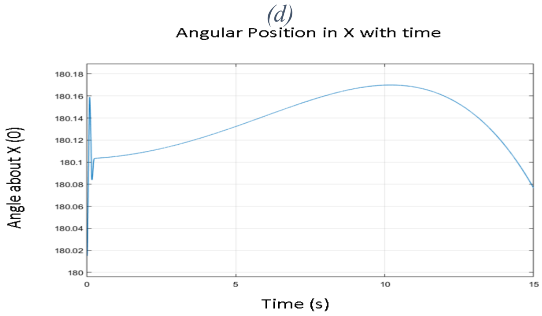

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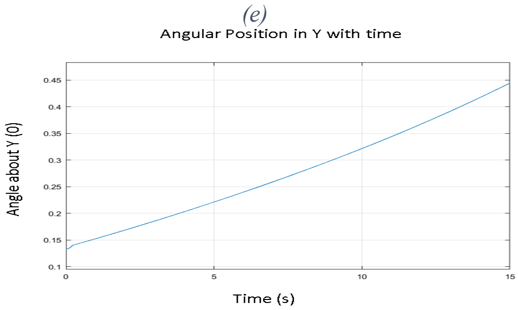

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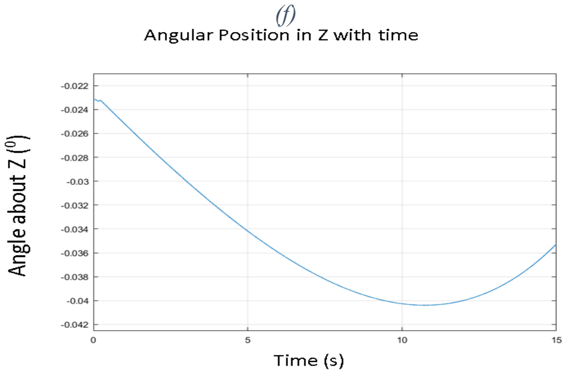


Fig 3. *Translation and rotational movement of top platform with respect to the 3 axes respectively*

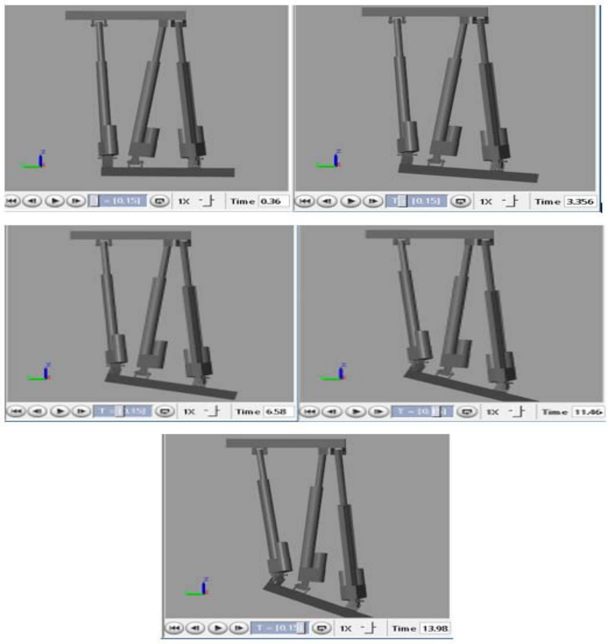


Fig 4. *Position of top platform as the base rotates 30° about X axis*

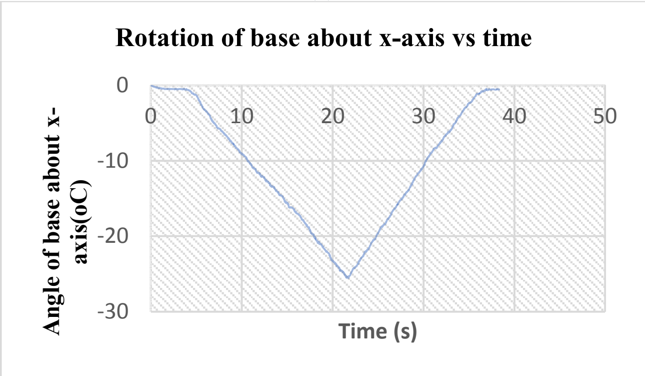
IV. PHYSICAL PROTOTYPE

The main prototype consisted of six extendable legs (linear actuators) connected to the base and platform with universal joints as shown in Figure 5.

Fig 5. *Final design of vehicle stabilizer*

Each motor is connected to a full bridge motor driver that gets the signal from a microprocessor. Two 6-DOF inertial measurement unit (IMU) sensors are used. One of them is connected to the base while the other is connected to the top platform. The readings of the base sensor are fed to the microprocessor as the rotation matrix to find the required length of the linear actuators. A PD controller is used to ensure that each linear actuator reaches the required position.

(a)



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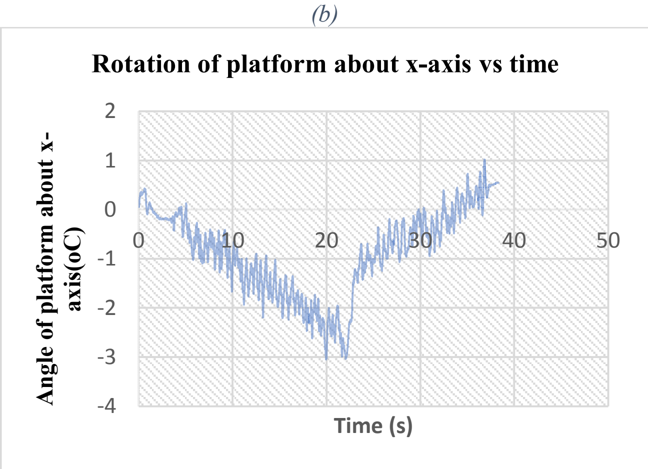


Fig 6. *Rotation of (a) base and (b) platform w.r.t X-axis*

Figure 6(a) shows the input ramp signal due to a pathway bump. As shown in Figure 6(b), the maximum angle reached is about 3° (12%) even though the angle that the base is rotated about is 25°. The negative sign comes from the orientation of the sensor. The top platform undergoes 1° vibration along the rotation. This results in an undesirable jerky behavior.

V. Linear Regression

In the previous stage, it was shown that the stabilizer only senses the rotation of the base after it rotates. However, it was suspected that this is leading to the jerky effect, so artificial intelligence was introduced into the system to predict the future position of the base before it rotates. Reference [2] suggested the use of dynamic neural network. However, due to its complexity, linear regression was used. The experiment was done several times and the data of rotation was taken to train the algorithm. The model of the algorithm in this case was a hyper-plane in the sixth dimension. The algorithm would take the current position, the current speed, and four previous values of speed. The mathematical model of the algorithm was of the form:

$$y' = XW \tag{8}$$

Where y' is the predicted angle, X is the input vector, and W is the parameter vector [2]. The vector W was found by training the algorithm using 4200 data point, and the model was tested on 1800 data point. The criterion of training was minimum squared error [3] which is in the form:

$$E = \sum (y_i' - y_i)^2 \tag{9}$$

$$E = \sum (XW - y_i)^2 \tag{10}$$

In order to find the minimum E, the equation is differentiated and equated to zero.

$$X'XW = X'y \tag{11}$$

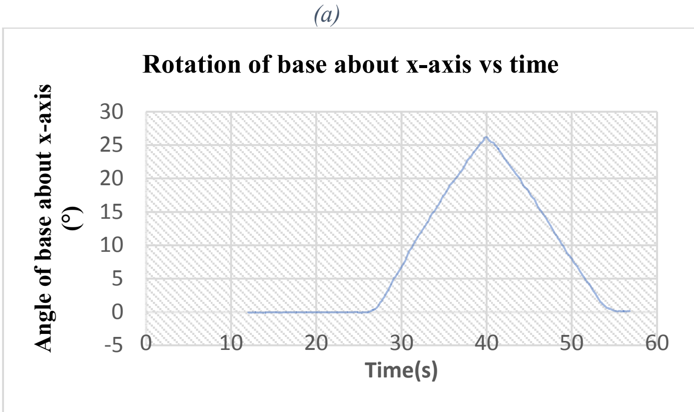
$$W = (X'X)^{-1}X'y \tag{12}$$

Thus, the W calculated from (12) would yield the minimum squared error and is the one used in the prototype. Using the coefficient of determination (R^2) formula to test the algorithm:

$$R^2 = 1 - \frac{\sum (y_i' - y_i)^2}{\sum (y_{mean} - y_i)^2} \tag{13}$$

The coefficient of determination was about 0.998. When the system was analyzed with the linear regression algorithm, the vibration decreased from about 1° to about 0.5° and the maximum angle reached was about 1° (excluding the outlier) yielding a percentage error of about 4% compared to the previous 12%.

(a)



(b)

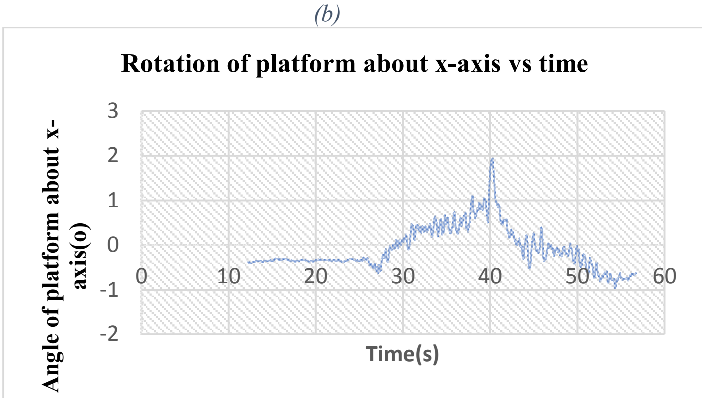


Fig 7. *Rotation of (a) base and (b) platform w.r.t X-axis*

VI. Conclusion

The inverted 6-DOF parallel manipulator is utilized as vehicle stabilizer, where the upper platform orientation is designed to be stabilized at zero degrees at different base orientations due to variation in pathway elevations. Initially, the model was tested in Simulink environment to validate its capabilities to stabilize the system at practically large angles. The real prototype required more advanced controller to accommodate the nonparametric variables in real testing environment. In order to improve the controller, linear regression model was implemented to achieve more robust performance of the stabilizer. The maximum error reached decreased from 12% to about 4% and the level of vibration amplitude has decreased from about 1^o to about 0.5^o. .

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