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Araştırma Makalesi/ Research Article

Motion Control and Analysis of Delta-type a Parallel Robot

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ABSTRACT

Parallel robots have natural advantages for many applications thanks to their high rigidity, high accuracy, low inertia of the moving parts and lightness, etc. The goal of this study has performed motion control, the kinematic and workspace analyses of a Delta-type parallel robot with 3 degrees of freedom (3-DOF). Delta-type parallel actual parameter values were used in the motion control and analyses. Forward and inverse kinematics analysis, as well as workspace analysis of the robot, were carried out. In addition, the motion control of the robot is actualized in Cartesian space. In order for the delta-type parallel robot to have zero oscillation and to have a robust structure against external disturbances, the Sliding Mode Control (SMC) method was preferred. As a result, the motion control, kinematics, and workspace analyses of the delta-type parallel robot were realized and examined.
Keywords: Delta type Parallel Robot, Kinematic and Workspace Analysis, Motion Control, SMC

Delta Tipi Bir Paralel Robotun Hareket Kontrolü ve Analizi

ÖZ

Paralel robotlar, yüksek rijitlikleri, yüksek doğrulukları, hareketli parçaların düşük ataletleri ve hafiflikleri vb. sayesinde birçok uygulama için doğal avantajlara sahiptir. Bu çalışmanın amacı, 3 serbestlik dereceli (3-DOF) Delta tipi bir paralel robotun hareket kontrolü, kinematik ve çalışma alanı analizlerini gerçekleştirmektir. Hareket kontrolü ve analizlerde delta tipi paralel robotun gerçek parametre değerleri kullanılmıştır. Robotun çalışma alanı analizinin yanı sıra ileri ve ters kinematik analizleri yapılmıştır. Ayrıca robotun hareket kontrolü kartezyen uzayda gerçekleştirilmiştir. Delta tipi paralel robotun sıfır salınım yapması ve dışarıdan gelen bozuculara karşı sağlam bir yapıya sahip olması için Kayan Kipli Kontrol (KKK) yöntemi tercih edilmiştir. Sonuç olarak delta tipi paralel robotun hareket kontrolü, kinematik ve çalışma alanı analizleri gerçekleştirilmiş ve incelenmiştir.

Anahtar Kelimeler: Delta tipi Paralel Robot, Hareket Kontrolü, Kinematik ve Çalışma Alanı Analizi, KKK

INTRODUCTION

In industrial works, robots are needed in flexible production systems, consisting of constantly changing dynamic processes. While most of the robots have open kinematic chain structure (also known as serial manipulator or anthropomorphic structures), parallel robots incorporate closed kinematic chain structures. Parallel manipulators are closed-type mechanisms, containing at least two independent kinematic loops and consisting of two platforms. The movable platform is dependent on a set of parts called the fixed platform feet at the base. As generally each leg is controlled by a separate actuator, system's degree of freedom is equal to the number of legs. As the juncture structure is non-serial, errors are not additive. They provide an advantage in terms of high-speed positioning due to having a more rigid construction. Parallel robots are closed-type parallel mechanisms created through attaching serially connected junction pieces to two platforms, one stationary and one movable, having 2 or more legs in a single axis of symmetry. Parallel delta robots are widely preferred in food, health, electricity and pharmaceutical industry due to their high-speed capacity and low footprint. Reasons for preference of parallel delta robots are their productivity, flexibility, quality, high performance period, ease of compatibility, low maintenance cost, etc. Delta robot with three degrees of freedom was developed by Clavel during 1990s. The robot moves in the three-dimensional space [1]. Clavel himself completed the kinematic and dynamic analysis of the manipulator [2]. Gosselin analyzed the workplace, namely the three-dimensional cartesian field within reaching distance from a point on the upper platform when orientated, of a parallel robot with 6 degrees of freedom [3]. Romdhane is the first researcher to address the problem of determining the workspace [4]. Workspace of these robots, having 3 degrees of freedom (DOF), is limited within an area in the three-dimensional cartesian field. The problem of determining the workspace was handled by authors, suggesting an algorithm allowing for determining certain parameters of parallel manipulators, using a genetic algorithm, in order to ensure a workspace as much approximate to the anticipated as possible [5-6]. Kosinska et al. presented a method for determining the parameters of a Delta-4 manipulator, applied to the workspace in a series of dots [7]. In another study, a new design method is presented that takes into account the desired working area and oscillation range of the ball joints of the delta robot. The rotation range of a spherical joint has been taken into account in the design approach and has proven to be effective and simple with an example [8]. Zheng carried out research on intelligent vibration suppression control of high-speed lightweight Delta robot [9]. New suggestions regarding kinematics and workspace of Delta-type parallel robots have been brought forward by Murray and yielded successful results [10-11]. Laribi et al. carried out a study involving the workspace and design analysis of a Delta-type parallel robot [12]. Maya et al. carried out a study on the workspace and bearing capacity of a new configurable delta parallel robot [13]. Riaño et al. proposed and implemented approaches based on a genetic algorithm for the optimal design of a delta parallel robot with vertical linear actuators [14]. In the study carried out by Lopez et al., forward and inverse kinematic analysis as well as the Jacobean matrix of a Delta-type parallel robot have been attained [15]. In order to improve the working performance of Delta robot, many researchers have conducted vibration suppression research [16-17]. The 4-DOF delta parallel robot has been designed to be used as a pick-and-place robot and has been examined by the mechanical interaction of this robot within its practical workspace. The authors proposed a new geometric algorithm to reduce mechanical collisions [18].

Préault et al. were presented new kinematics for the four degrees of freedom (DoF) robot based on the delta architecture. This new device is intended to be used as a tactile device for teleoperation applications. The robot improved based on the global parallel robot architecture was compared with the current robot in terms of kinematic behavior[19]. In another study in the literature, the delta type parallel robot was controlled with these methods in order to benefit from the adaptive and robust control advantages of adaptive control. Two adaptive methods were tried and compared on the delta type parallel robot [20].
Mitsantisuk et al. carried out a haptic system three-dimensional work space analysis, involving a Delta robot-based master and slave robot, and furthermore, achieved sensor-free force control [21]. Shen et al. are carried out a study on the kinematic sensitivity, parameter definition, and calibration of the non-symmetric parallel Delta robot [22]. Development, design and control studies of parallel robots have been researched by several researches up to date [23-26]. Boudjedir et al. were applied iterative learning control-Delta robot with non-repetitive trajectories for quadratic MIMO nonlinear systems [27].
Wu et al. worked on the disturbance observer-based trajectory tracking control of a delta-type parallel robot [28]. Ohno and Takeda researched the design of target trajectories for the detection of joint gaps in a parallel robot based on motor torque measurement [29]. The goal of this study has performed motion control, the kinematical and workspace analyses of a Delta type parallel robot with 3 degrees of freedom (3-DOF). Delta-type parallel actual parameter values were used in the motion control and analyses. Forward and inverse kinematics analysis, as well as workspace analysis of the robot, were carried out. In addition, the motion control of the robot is actualized in Cartesian space. In order for the delta-type parallel robot to have zero oscillation and to have a robust structure against external disturbances, the Sliding Mode Control (SMC) method was preferred. As a result, the motion control, kinematics, and workspace analyses of the delta-type parallel robot were realized and examined.

MATERIAL and METHOD

System Overview and Analyses

Parallel robots are closed-type parallel mechanisms created through attaching serially connected junction pieces to two platforms, one stationary and one movable, having 2 or more legs in a single axis of symmetry. In this section, kinematic and workspace analyzes of the system were done. Physical parameter values of the Delta type Parallel robot are provided on Table 1.

Table 1. The Physical Parameters of a Delta type Parallel robot

Parameters	Values	Symbols
La	450	mm
Lb	250	mm
R	225	mm
r	100	mm

Kinematic Analyses

Forward and Inverse Kinematic

Kinematic analysis is carried out in order that the position of the movable platform or the angles ensuring a certain position of the movable platform are determined based on the angles of the driven elements. Since driven elements in a delta robot are connected to the platform with swivel joints, the parameter determining the positions of such elements is the angle with the stationary element. The analysis in which position of the movable platform is calculated based on the angles of the driven elements is called "Forward Kinematic"; while the other is called "Inverse Kinematic". The Delta-type parallel robot is shown in Figure 1. In general, parallel robot is a closed-loop manipulator, which is rather inconvenient for kinematic calculation. The movable platform remains connected to the base platform, and the direction around the vertical axis on the base plate is zero at all times. As shown on Figure 2, it is stationary, movable platforms are circular with radius of R, and r. Junction points of stationary platform to stationary poles are S1, S2 and S3. X, y, and z coordinates of these points are provided in Equation 1. Motors used in the movable and stationary platform have been placed with the angle of 1200. Geometrical parameters of the Delta-type parallel robot are shown on Figure 3.

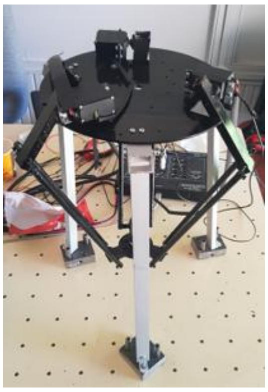
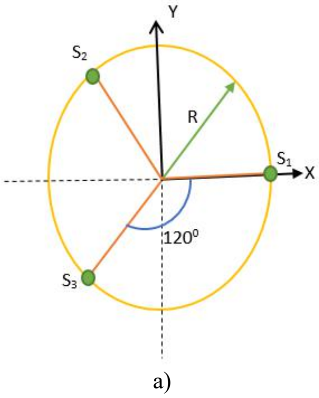


Figure 1. The Delta-type parallel robot



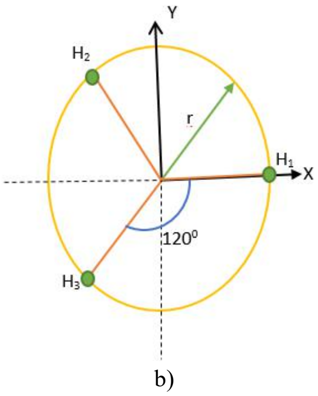


Figure 2. Stationary and movable platform of the Delta-type parallel robot

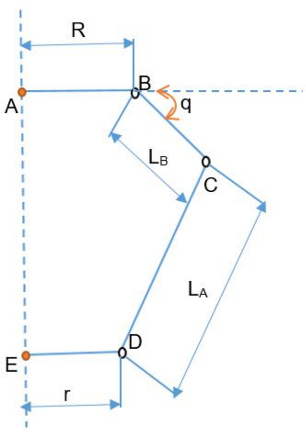


Figure 3. Geometrical parameters of the Delta-type parallel robot

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} R & -\frac{R}{2} & -\frac{R}{2} \\ 0 & \frac{R\sqrt{3}}{2} & -\frac{R\sqrt{3}}{2} \\ 0 & 0 & 0 \end{bmatrix} \quad (1)$$

Junction points of the movable platform to parallelograms are H1, H2 and H3 points. X, y, and z coordinates of these points are provided in Equation 2.

$$\begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} = \begin{bmatrix} r & -\frac{r}{2} & -\frac{r}{2} \\ 0 & \frac{r\sqrt{3}}{2} & -\frac{r\sqrt{3}}{2} \\ 0 & 0 & 0 \end{bmatrix} \quad (2)$$

Forward kinematic equations, calculating the XYZ cartesian space of the robot's junction lead position in junction variable values through the use of such angles, were calculated as follows.

$$x_i = (R + L_A cos\theta_i)cos\alpha_i \quad (3)$$

$$y_i = (R + L_A cos\theta_i)sin\alpha_i \quad (4)$$

$$z_i = L_A sin\theta_i \quad (5)$$

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = {L_B}^2 \quad (6)$$

Geometrical parameters of the delta robot are L_A, L_B, r, R and θ_i as defined on Figure 3, and the variables are the junction angles defining the *i* = *1,2,3…* configuration. According to the aforementioned equations, there are three unknowns (*x,y,z*). Therefore, three equations have been attained by replacing such unknowns with *'i'* values.

$$(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 = {L_B}^2 \quad (7)$$

$$(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 = {L_B}^2 \quad (8)$$

$$(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 = {L_B}^2 \quad (9)$$

When the equations above are solved in turn and certain limitations were applied for ease of operation, the following equations were attained.

$$x_0 = \frac{a_1 z_0 + b_1}{d} \quad (10)$$

$$y_0 = \frac{a_2 z_0 + b_2}{d} \quad (11)$$

$$z_0 = \frac{-b \pm \sqrt{\Delta}}{2a} \quad (12)$$

In general, there are two possible solutions; which are the two possible configurations for the given junction angles from the movable platform to the base. Equation 13 was obtained upon use of an epitomic resultant vector value.

$$\overrightarrow{S_1 O} + \overrightarrow{OP} + \overrightarrow{PH_1} = \overrightarrow{S_1 H_1} = L \quad (13)$$

Inverse kinematic problem is caused by determining the q_i (i =1,2,3) angle values in cases of characteristic point or the end effector (TCP-Tool Center Point) positions based on general coordinates: x_p, y_p, z_p

$$a_i + b_i cos\theta_i + c_i sin\theta_i = 0 \quad (14)$$

$$a_i = ((R-r)cosa_i - x)^2 + ((R-r)sina_i - y)^2 + z^2 - {L_2}^2 + {L_1}^2 \quad (15)$$

$$b_i = 2\big((R-r)cosa_i - x\big)L_1 cosa_i + 2\big((R-r)sina_i - x\big)L_1 sina_i \quad (16)$$

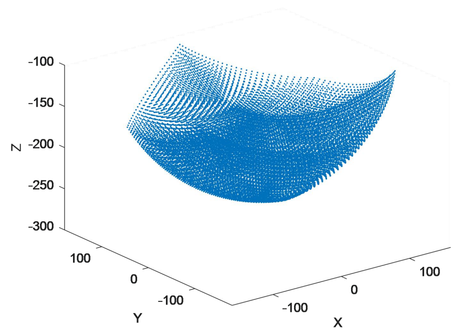
$$c_i = 2zL_1 \quad (17)$$

$$\theta_i = 2arctan\frac{-c_i \pm \sqrt{c_i^2(a_i^2-b_i^2)}}{(a_i-b_i)} \quad (18)$$

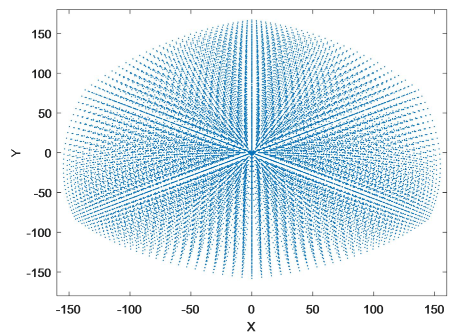
The equations provided above are the general equations intended for inverse kinematic analysis of the system.

Workspace Analyses

One of the most significant subjects in designing processes of parallel robots is determining the workspace. This can be even more critical for parallel robots, as they will, at times, have a highly limited workspace. In recent years, various numerical methods have been developed for determining the workspace of parallel robots. The following figures show the three-dimensional robot workspace. The views of a) Three-dimensional workspace, b) XY, c) XZ, d) YZ dimensions are shown in Figure 4.



a)



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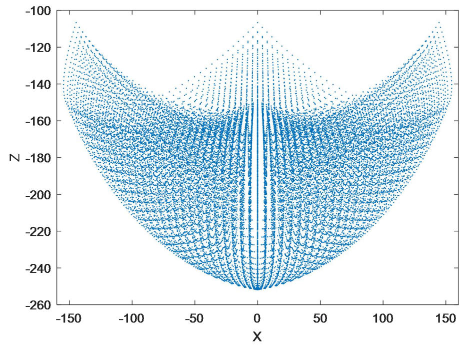

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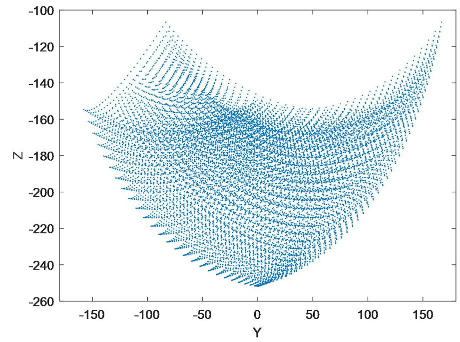

d)

Figure 4. Workspace of Delta type Parallel Robot

Motion Controller Design

The Sliding Mode Control (SMC) control method was used in motion control. This method was utilized in different works in the literature [30-36]. The goal of the control method is that the output value of the robot follows the reference value. The controller was tried to minimize the error. The block diagram of the SMC method is illustrated in Figure 5.

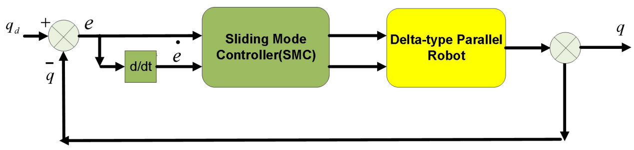

Figure 5. Control structure of the SMC method.

Error and time derivative of the error are given in Eq. (19) and Eq. (20), respectively.

$$e(t) = q_d(t) - q(t) \quad (19)$$

$$\dot{e}(t) = \dot{q}_d(t) - \dot{q}(t) \quad (20)$$

In the above equation, q_d denotes the desired joint trajectory and q shows the real trajectory. The first and second-degree derivatives were used for the Eq. (19).

$$S = \dot{e} - \lambda e \quad (21)$$

$$\dot{S} = \ddot{e} - \lambda \dot{e} \quad (22)$$

where, S represents the sliding surface and λ is a positive defined symmetric matrix, u control signal is given in Eq. 23. Saturation function is used to solve the chattering problem and ϕ shows the thickness of the boundary layer.

$$u = -k \times sign(s)$$

$$sat(s/\phi) = \begin{cases} \dfrac{s}{\phi} & if \left|\dfrac{s}{\phi}\right| \le 1 \\ sign(s/\phi) & if \left|\dfrac{s}{\phi}\right| > 1 \end{cases} \tag{23}$$

where, k is the constant parameter and *sign* is a signal function and s functions as a switch.

$$u = k * sat(s) \tag{24}$$

The selected function expression is given in equation 25 in order to perform stability analysis according to the Lyapunov function. The derivative of this expression must be less than zero. Therefore, s should be negative (equation 26).

$$V = \frac{1}{2}s^2 \tag{25}$$

$$\dot{V} = \dot{s}s < 0 \tag{26}$$

RESULT and DISCUSSION

In this section, motion control simulation studies were carried out in Cartesian space and the results of the method are given graphically. Location-based control is achieved by converting a robot control problem into various motion control problems and each motor in the robot with position tracking control. Motion control with zero oscillations at the start and end positions of the road is often targeted to maintain zero swing values when picking and placing operations are performed. The sliding mode control method has been preferred for the delta type parallel robot to have zero oscillation and to have a robust structure against the externally impacting disruptors.

The robot was controlled by inverse kinematic equations. Control variables are the position values of X, Y, and Z. Simulation run time was taken as 8 seconds. Figure 6 shows the position-time responses of X, Y, and Z in the simulation environment in accordance with the desired reference input. Figure 7 illustrates the position-time error responses of X, Y, and Z. The results seem to be consistent as seen in Figure 6. Considering Figure 7, it is seen that the control method's positioning errors of the delta type parallel robot are effectively reduced to near zero as expected.

CONCLUSION

A study on kinematic and workspace analyses of a Delta type parallel robot with three degrees of freedom was made and motion control of the robot was performed. The robot's forward and inverse kinematic analyses and the robot's workspace analysis were performed. In addition, the robot's motion control was done using the Sliding Mode Control (SMC) method in Cartesian space. The crackling problem is solved by using the saturation function in the SMC control method. Therefore, the method has become simple and applicable. Given the motion control simulation results, it shows that the method provides good positioning accuracy. As a result, motion control, kinematic and work area analyzes of the delta type parallel robot has been made and examined.

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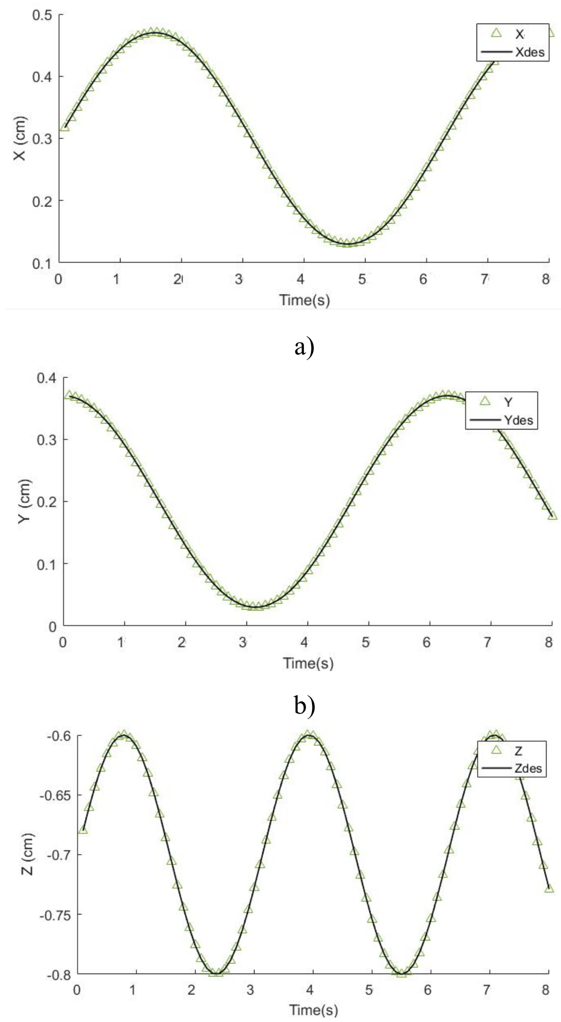
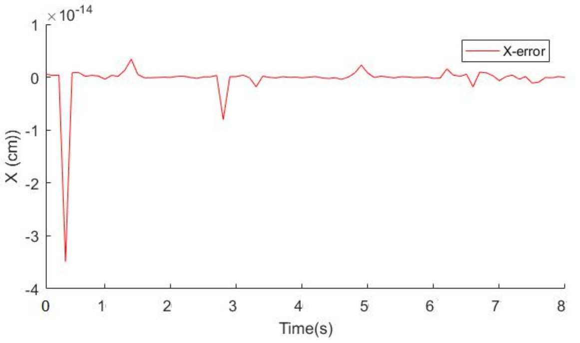
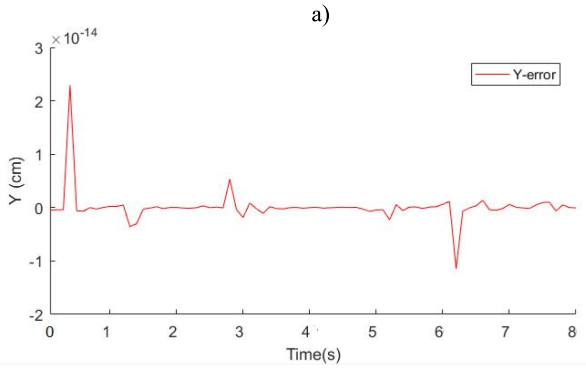


a) b) c)

Figure 6. Positions of (a) X, (b) Y, (c) and Z obtained by the reference values



a)



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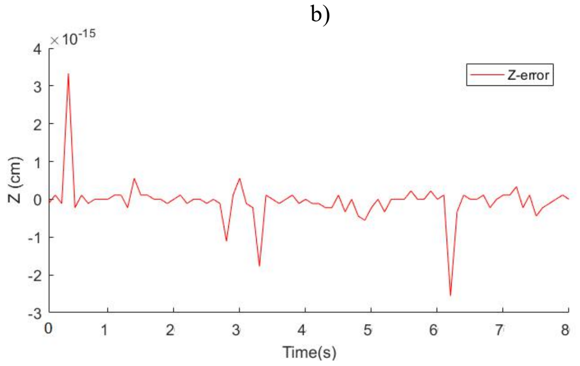

c)

Figure 7. Position error values (a) X, (b) Y, (c) Z

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