SDU International Journal of Technologic Sciences
Vol. 3, No 1/Special Issue, February 2011
pp. 51-59

Computer Technology

DEVELOPMENT AND CONTROL OF A HIGH PRECISION STEWART PLATFORM

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Abstract

In this paper, development and control of a high precision 6 DOF parallel manipulator (Stewart platform) is presented. A kinematic analysis of 6-6 Stewart platform (SP) was designed and simulated in Solidworks. Also its dynamic model is developed in Matlab-Simulink environments. Platform has two main bodies (top and base plates) and six legs connecting top body to base body via universal joints. SP legs were chosen as a high-resolution direct drive motor with a 500nm design resolution from PI Company. Each motor is controlled by a simple PID control within their design resolution. Optimized PID control is designed in SIMULINK environment and embedded in a Dspace DS1103 real time controller. The trajectory and position control of SP was achieved with 500nm accuracy.

Keywords: parallel manipulator, Stewart platform, nano positioning, PID.

1. Introduction

Demand on high precision motion has been increasing in recent years. Since performance of today’s many mechanical systems requires high stiffness and accurate positioning capability, parallel manipulators have gained popularity. Their superior architecture provides better load capacity and positioning accuracy over the serial ones. Stewart Platform is a positioning system that consists of a top plate (moving platform), a base plate (fixed base), and six extensible legs connecting the top plate to the bottom plate. Stewart platform known as Stewart-Gough platform is one of the most popular parallel manipulators. It is six degrees of freedom positioning system.

Serial robots cannot perform precision positioning under heavy loads and they oscillate at high-speed under heavy loads. Therefore, in recent years, parallel robots have been widely used in several areas of industry such as medicine and defense. Some of these areas: precision laser cutting, the helicopter runway, throwing platform of missiles, surgical operations. SP is the most used parallel manipulators having 6 DOF. This platform is widely used as motion control tool due to its high robustness, high load capacity and high-precision positioning. In this study, a 6 DOF-SP is developed and manufactured for general high precision applications. Its load capacity is between 200-500 grams and repeatability is + /- 0.5 micrometer with very little friction. This prototype can serve different purposes. It can be employed in several applications easily with a little modification in the end effector. A robot

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controller will be designed to do precise positioning under different disturbances applied from outside and within effects of friction and model uncertainties.

Parallel manipulators are closed loop mechanisms and composed of parallel links between base platform and end effector with kinematic chain. On the other hand, serial robots have serial links connected to each other. Therefore, load acts to the all of the links and joints separately. The positioning errors also accumulate and result in a poor accuracy of end effector in serial robots. However positioning error of each leg in parallel robots directly affects the end effector and does not have an accumulation nature. Moreover, the robot can move the load shared in each link so its load carrying capacity is very high. The most widely used structure of a parallel robot is the Stewart platform. This platform has 6 parallel links that connect the lower and upper platform each other and it can do 6 degrees of freedom positioning. Stewart platform was invented as a flight simulator by Stewart in 1965 [1]. This platform contained three parallel linear actuators. Gough [2] had previously suggested a tire test machine similar to Stewart's model. In his system, parallel 6 actuators were used as a mechanism driven in parallel. Gough is the first person who developed, utilized and used this type of a parallel structure. Therefore, Stewart platform sometimes is named as Stewart-Gough platform in the literature. Stewart’s and Gough’s original designs are shown in Figure 1.

SP did not attract attention during the first 15 years since the first invention. Then Hunt [3] indicated the advantages of parallel robots. After 1983, researchers realized their high load carrying capacity and high positioning ability of these robots. Researchers were then started to include a detailed analysis of these structures. The widely used form of SP, where top platform is connected to base platform using 6 linear axis with universal joints, is then established [3].

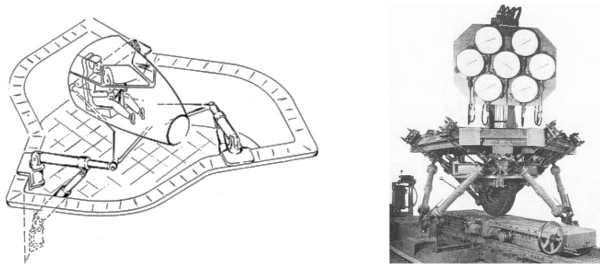

(a) (b)

Figure 1. Stewart (a) and Gough (b) original design [4].

It is a well known fact that the solution of the forward kinematics problem is easier then the inverse kinematics problem for serial robot manipulators. On the other hand, this situation is just the opposite for a parallel robot. Inverse kinematics problem of parallel robot can be expressed as follows: position vector and rotation matrix is given, and asked to find length of each link. It is relatively easy to find the link lengths because the position of the connecting points and the position and orientation of the moving platform is known. On the other hand, in the forward kinematics problem, given the link lengths, the rotation matrix and position vector of the moving platform is computed. Forward kinematic of the Stewart platform is very difficult problem since it requires the solution of many non-linear equations. There are at least 8 real solutions for SP. In the literature, solutions of the forward [5, 6, 7, 8] and the inverse [9, 10.11] kinematics has been given in detail. Parallel robot manipulators have higher load capacity and higher rigidness since all of its legs carry the load at the same time. Furthermore, there isn’t any bending stress on the legs as the load is only in the axial direction. Positioning accuracy is high because the positioning error of the platform cannot exceed the average error of the legs positions. This platform can provide nanometer-level motion performance. But it has smaller workspace and has singularities in this workspace. It should be kept in mind these disadvantages of the structure in the SP design. Short link lengths provide rigid structure and they generate small positioning errors. The large workspace requires longer links. The large base plate requires the stability. On the other hand the narrow one is needed to avoid singularities since the rotation occurs along the horizontal axis.

Specific tasks can be simulated using the dynamical model of SP. The close loop dynamic equations can be derived performing the Newton-Euler or Lagrange-Euler methods [12-20]. The forces acting on the moving platform can be observed using the dynamic model into the simulation programs.

2. The Structure of the Stewart Platform

SP system is composed of two main bodies (top and base plates), six linear motors, controller, power supply, and emergency stop circuit and interface board. The Dspace DS1103 real time controller is used to implement control algorithms. SP legs were chosen as a high-resolution direct drive motor with a 500nm design resolution from PI Company (Figure 2).

A simple emergency stop circuit was designed to protect the motors, when they move to out of the limits. Based on the signal of hall-effect sensors on each motor this circuit controls the power supply which gives the energy to the motors. A switch-mode 150W power supply with inhibit input and EMI filter is used to supply required energy. Also, an interface board was designed between controller and motors. These circuits are shown in Figure 3.

Figure 2. Direct DC motor with 500nm resolution.

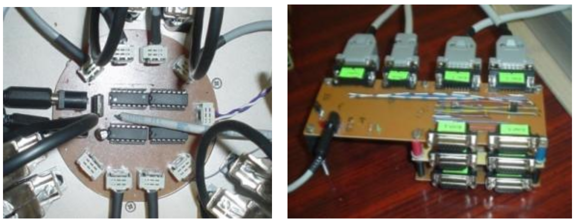


Figure 3. Emergency and interface boards.

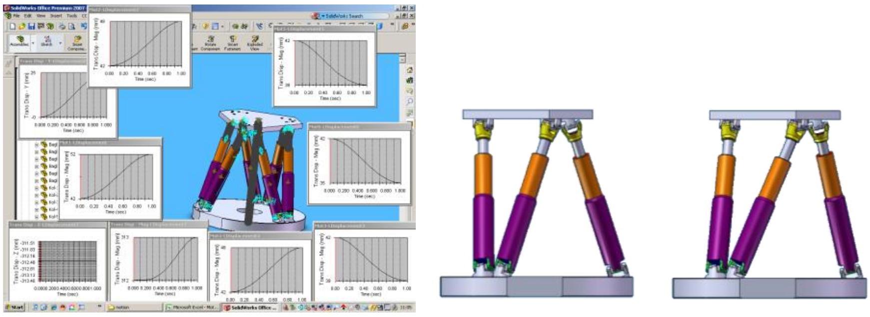
3. Design

The top and base plates were manufactured using CNC machine after having the solid model of the SP. Figure 4 illustrates the solid models obtained from SolidWorks program and the plates manufactured on CNC machine.

Figure 4. The solid models obtained from SolidWorks program and the plates manufactured on CNC machine.

3.1 Motion Analysis

Before manufacturing the system, different motion scenarios of SP were examined by using SolidWork motion software. The accuracy of the forward kinematics equations obtained analytically is compared with the Solid Motion results. This software provides a platform for verifying the analytical expressions. Dynamics equations of SP are developed and compared with Solid Motion results after verifying the kinematics equations. Some motion scenarios are determined first then both analytical and numerical results are compared. Figure 5-a shows interface of the software for SP. As an example, as shown in Figure 5-b-c, the top plate is moved from zero position to +25 mm.



(a) (b) zero (c) 25 *mm*

Figure 5. (a) Solidworks Motion software gui for analysis, Motion of the top platform from zero (a) to 25mm (b) in x direction.

Figure 6 shows trajectory of each leg as the top plate moves from zero position to 25 mm.

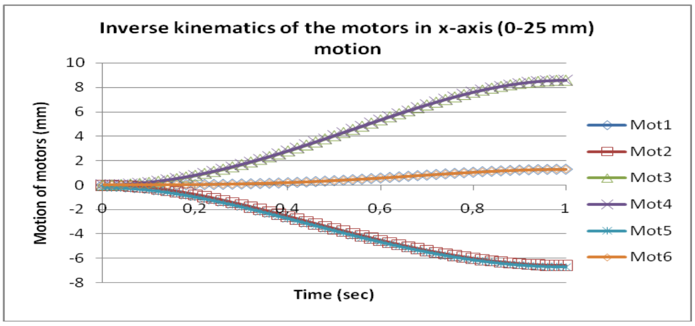


Figure 6. Inverse kinematic solution of the SP and trajectories of the legs from zero to 25mm in x direction

4. Control

Trajectory planning is needed for computing motion commands which is applied to the motors. Trajectory planning includes position and orientation of the top plate along the x-y-z axes. For each simulation time, the leg lengths are computed using the inverse kinematics given by equation 1.

$$L = \left\| \left(R * p\_t + p \right) - p\_b \right\| - l\_n \tag{1}$$

Where,

L……: leg lengths

R……: rotation matrix

p_t….: connection positions on top plate

p…….:position of the top plate with respect to base plate

p_b….: connection positions on base plate

l_n…..: nominal length of the legs

Equation 1 was implemented in Simulink and it is shown in Figure 8.

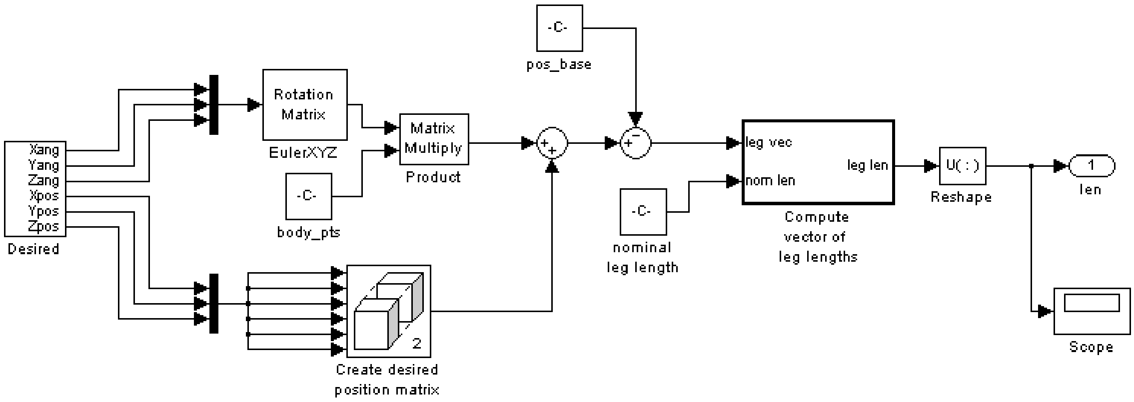
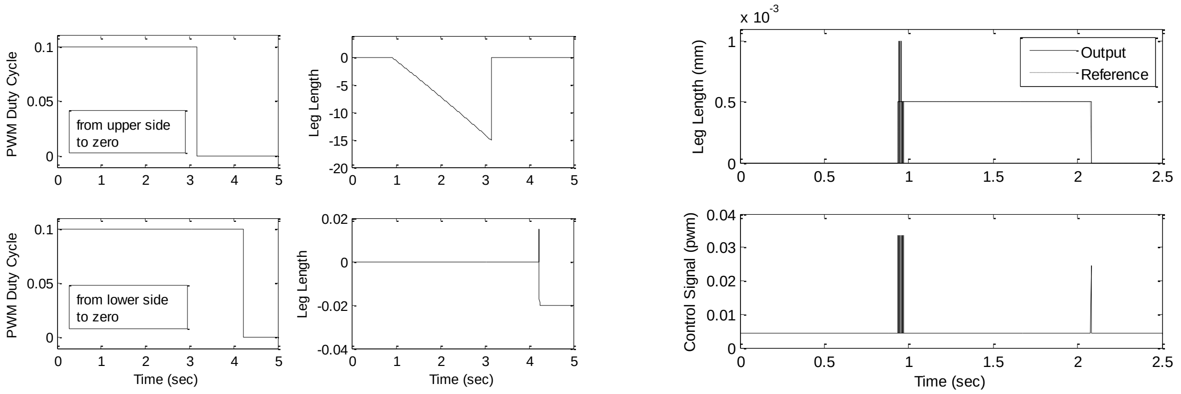


Figure 7. Path planning and inverse kinematic solution model.

The position of each motor is controlled after computing each leg lengths. Motors have incremental encoders therefore first they must be brought their zero or home position. When SP system is energized, an index search algorithm looks what the position of the each leg is. Movements to the home position for possible two situations (from upper and lower sides to zero) are shown in Figure 8-a. The figure also illustrates the real time response of a motor.



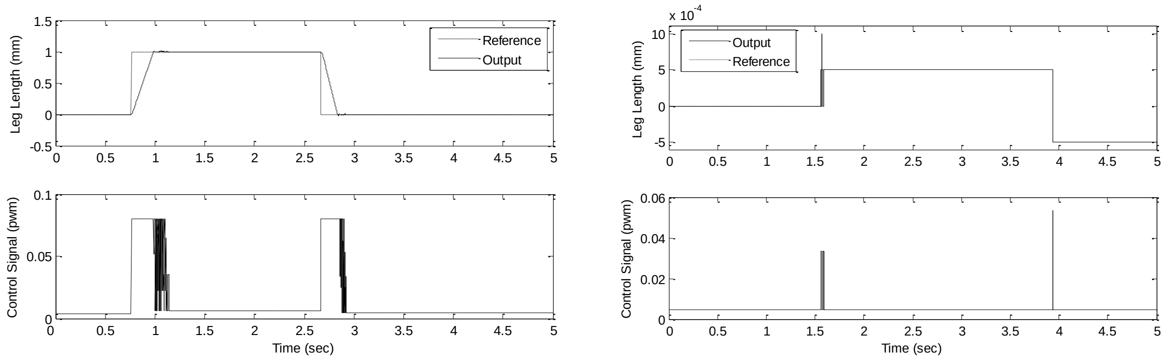
(a) (b)

Figure 8. (a) Initialization routine, (b) 500nm step response of one leg of SP.

A controller is needed for top platform to go desired position and orientation from the initial position. It will generate required forces for each motor. A PID (proportional-integrator-derivative) controller (Equation 2) is used in this study.

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{d}{dt} e(t) \qquad (2)$$

Firstly, the motor on each leg was controlled and its controllability is verified separately. Then, all motors were controlled together. In order to test the precise moving ability, several experiments were performed with PID controller. Some real time responses of the motor are shown here. Real time 500nm, 1mm and 0/500/-500 nm step response and control signal of the motor is shown in Figure 8-b. Figure 9-a and 9-b, respectively.



(a) (b)

Figure 9. (a) 1mm and (b) 0/500/-500 nm step response of one leg of SP.

The main model of the controller designed in Simulink and embedded in the dspace ds1103 is shown in Figure 10. The model contains some subsystems such as leg trajectory, encoder, initial, PID, pwm and sign. These subsystems performs the inverse kinematic solution, the measurements of the leg lengths, the initialization routine, the PID position controller and produces output signals pwm and sign, respectively.

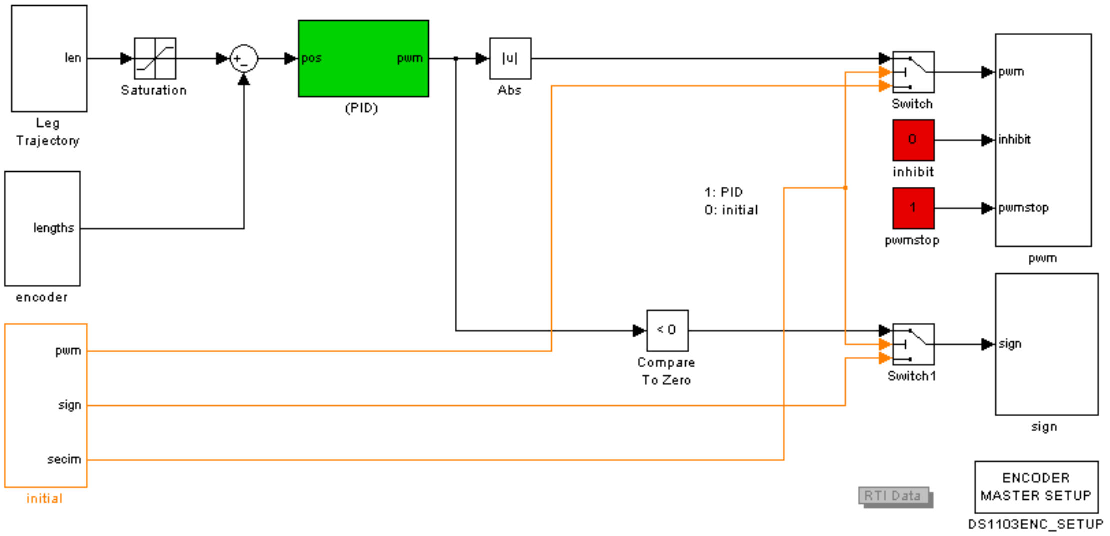
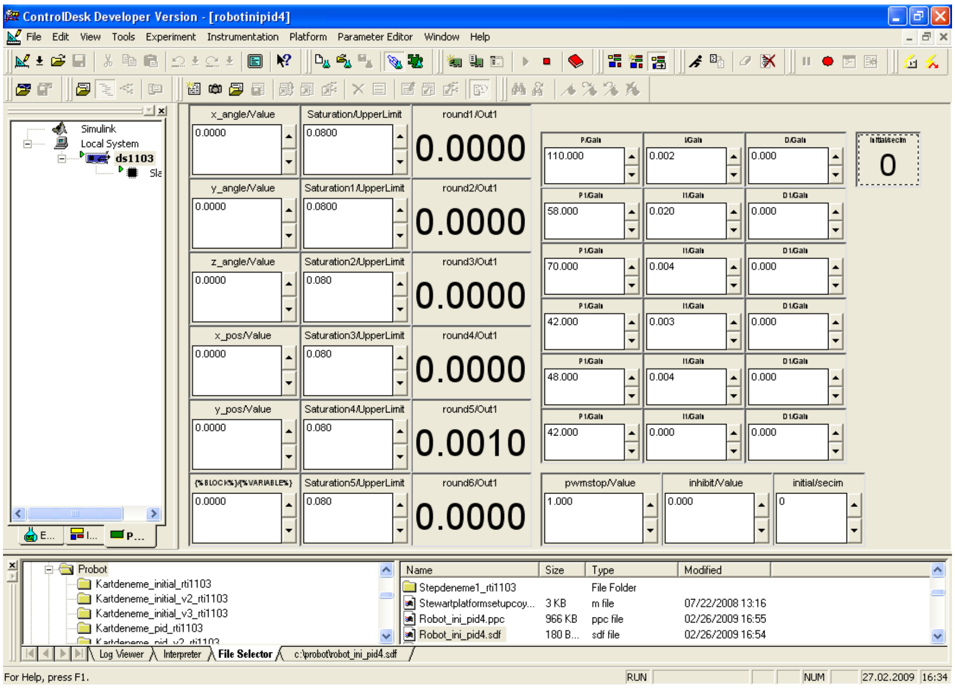


Figure 10. Simulink model of the controller

An interface created through the DSPACE software is shown in Figure 11. All system information can be entered through this interface. It contains variables that can be used in the development phase. Reference input values can be easily entered through the interface.



x_angle/Value: 0.0000
Saturation/UpperLimit: 0.0800
round1/Out1: 0.0000

y_angle/Value: 0.0000
Saturation1/UpperLimit: 0.0800
round2/Out1: 0.0000

z_angle/Value: 0.0000
Saturation2/UpperLimit: 0.080
round3/Out1: 0.0000

x_pos/Value: 0.0000
Saturation3/UpperLimit: 0.080
round4/Out1: 0.0000

y_pos/Value: 0.0000
Saturation4/UpperLimit: 0.080
round5/Out1: 0.0010

{%BLOCK%}/{%VARIABLE%}: 0.0000
Saturation5/UpperLimit: 0.080
round6/Out1: 0.0000

P/Gain	I/Gain	D/Gain
110.000	0.002	0.000

P1/Gain	I1/Gain	D1/Gain
58.000	0.020	0.000
70.000	0.004	0.000
42.000	0.003	0.000
48.000	0.004	0.000
42.000	0.000	0.000

initial/secim: 0

pwmstop/Value: 1.000
inhibit/Value: 0.000
initial/secim: 0

Probot
Kartdeneme_initial_rti1103
Kartdeneme_initial_v2_rti1103
Kartdeneme_initial_v3_rti1103
Kartdeneme_pid_rti1103
Kartdeneme_pid_v2_rti1103

Name	Size	Type	Modified
Stepdeneme1_rti1103		File Folder	
Stewartplatformsetupcoy...	3 KB	m file	07/22/2008 13:16
Robot_ini_pid4.ppc	966 KB	ppc file	02/26/2009 16:55
Robot_ini_pid4.sdf	180 B...	sdf file	02/26/2009 16:54

Log Viewer | Interpreter | **File Selector** | c:\probot\robot_ini_pid4.sdf

For Help, press F1. RUN NUM 27.02.2009 16:34

Figure 11. Control Desk GUI for data acquisition and parameter update

Several trajectory experiments were performed to optimize the PID parameters and some of them are shown in Figure 12 and 13. In this figure, the top platform is moved with sinus and cosine along the x and y directions, respectively. Real time leg length errors are shown in figures and maximum errors are labeled on the subfigures. In the Figure 13, 1mm step response along x direction is shown.

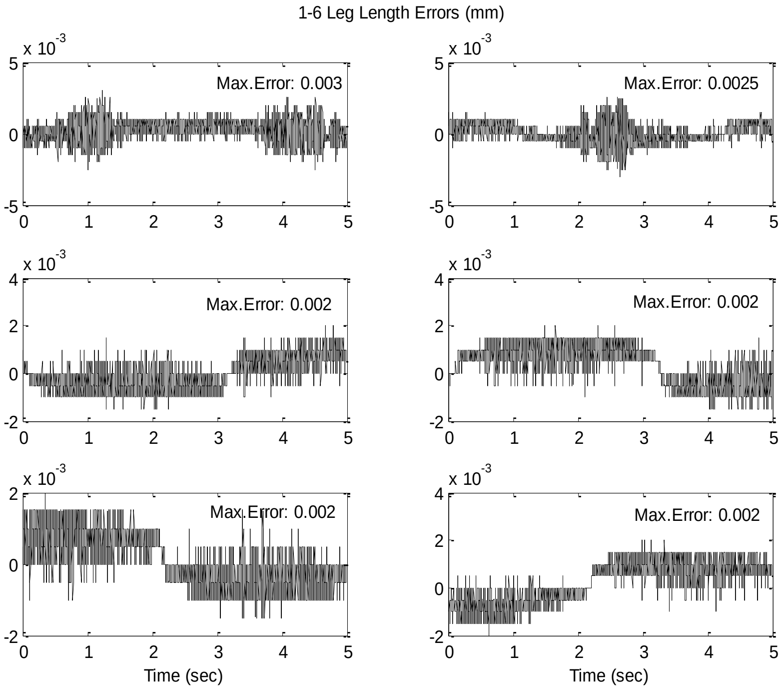


Figure 12. Trajectory control of SP.

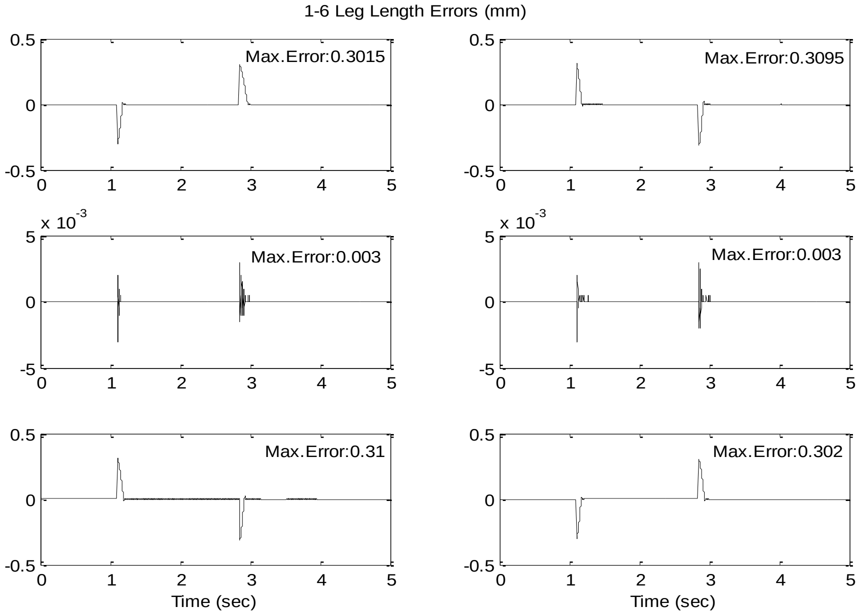


Figure 13. Position control of the SP.

5. Conclusion

In this study, a high precision 6 DOF parallel manipulator is developed and controlled by a PID controller which is designed in SIMULINK environment and embedded in a Dspace DS1103 real time controller. The zero steady-state error is obtained for step inputs. The top plate of manipulator is positioned to the desired target with an error less than 0.5µm. When the top plate is positioned within the wider workspace, the performance of the PID controller is getting worse due to the non-linear structure of the system. Additionally, the PID controller may lose its control ability under non-linear loads. Therefore, different algorithms can be developed for dealing with the non-linear loads and disturbances. Some major drawbacks of PID controller can be described as follows: (i) the rounding errors cause vibration on the legs under high precision. The state variables can be filtered in order to overcome this problem, (ii) the PID parameters are obtained by trial and error, the best PID parameters can be determined using the dynamic model of the system for the wide range, (iii) the workspace can be divided into several regions and the optimized PID parameters can be obtained for each region.

Acknowledgements

This work is supported by The Scientific and Technological Research Council of Turkey (TUBITAK) under the Grant No. 107M148.

One of the authors (S.K.) acknowledges the financial support of TÜBİTAK-BİDEB.

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