Mugla Journal of Science and Technology

DESIGN AND CONTROL OF A MOBILE STEWARD PLATFORM WITH FOUR INDEPENDENT WHEELS

Ergun Eray AKKAYA*, Faculty of Commerce, Yeditepe University, Turkey , eray.akkaya@yeditepe.edu.tr
(https://orcid.org/0000-0002-9227-1494)
Muhammet ÖZER, Department of Mechatronics Engineering, Istanbul Gelişim University, Turkey, ozermuhammet0@gmail.com
(https://orcid.org/0000-0002-1770-3592)
Kenan ŞENTÜRK, Department of Mechatronics Engineering, Istanbul Gelişim University, Turkey, ksenturk@gelisim.edu.tr
(https://orcid.org/0000-0001-8413-7570)
Volkan ÖZTÜRK, Department of Mechatronics Engineering, Istanbul Gelişim Üniversitesi, Turkey, 0volkanozturk@gmail.com
(https://orcid.org/0000-0002-8615-4080)
Ümit ALKAN, Department of Computer Engineering, Istanbul Gelişim University, Turkey, ualkan@gelisim.edu.tr
(https://orcid.org/0000-0002-0044-5494)

Received: 13.08.2021, Accepted: 28.04.2022 Research Article
*Corresponding author
DOI: 10.22531/muglajsci.982013

Abstract

For today's automated vehicles and robots' technologies in driving dynamics, the elasticity in movements has a critical role. These movements can be simulated by using some platforms which are staying on balance. It is possible to perform a few linear and angular movements according to the platform model. The purpose of this study is to provide an independent drive and keep the carrier shaft on balance while the vehicle is on the move. The steering system on the vehicle has been specialized and a balancing platform on the vehicle has been achieved to keep the balance. The vehicle in this study has four wheels and they; all have been independently designed and controlled for the requested rotation. Ackermann Steering Geometry has been used for calculations of wheel angles. In this study, the Stewart platform which has a 3x3 connection model and parallel structure has been designed. It is possible to make different linear and angular moves with this model of the platform. The steering system and platform designs have been mounted as one unit of the structure by assembling. The system can be operated manually and automatically. A mobile application has been also developed to monitor the status of the system. After all, using MATLAB simulation, its made phase space limit control of the orientations of the platform's center point relative to the x, y, and z axes has been studied.
Keywords: Stewart Platform, Independent Four-Wheel Steering System, Control Theory

DÖRT BAĞIMSIZ TEKERLEKLİ MOBİL STEWART PLATFORMUNUN TASARIMI VE KONTROLÜ

Özet

Günümüzün otomasyon ve robot teknolojilerinin sürüş dinamiğinindeki hareketlerinin esnekliği kritik role sahiptir.Bu hareketler, hareketler sırasında dengede kalan bazı platformlar kullanılarak simüle edilebilir. Bunlara ek olarak, dengeleyici platformların eğlence ve mekansal hareketler alanlarında da sıklıkla kullanıldığı görülmektedir. Platform modeline göre birkaç lineer ve açısal hareket yapmak mümkündür. Bu çalışmadaki amacımız, araç hareket halindeyken bağımsız bir tahrik sağlamak ve taşıyıcı şaftı dengede tutmaktır. Araç üzerindeki dengeyi sağlamak için direksiyon sistemi özelleştirildi ve araç üzerinde dengeleme platformu ile dengeleme başarı ile sağlandı. Bu çalışmadaki prototip araç dört tekerleğe sahiptir ve bunlar; tümü, istenen dönüş için bağımsız olarak tasarlanmış ve kontrol edilebilirdir. Tekerlek açılarının hesaplanmasında Ackermann direksiyon geometrisi kullanılmıştır. Çalışmada 3x3 bağlantı modeline ve paralel yapıya sahip olan Stewart platformu tasarlanmıştır. Platformun bu modeli ile farklı lineer ve açısal hareketler yapmak mümkündür. Direksiyon sistemi ve platform tasarımları bir araya getirilerek yapının bir birimi olarak monte edilmiştir. Sistem manuel ve otomatik olarak çalıştırılabilir. Sistemin durumunu eş zamanlı olarak izlemek için bir mobil uygulama da ilave olarak geliştirilmiştir. Son olarak, MatLab simülasyonu kullanılarak, platformun merkez noktasının x, y ve z eksenlerine göre oryantasyonlarının faz uzay limiti kontrolü yapılmıştır.
Anahtar Kelimeler: Stewart Platformu, Bağımsız Dört-Teker Sürüş Sistemi, Kontrol Teorisi

Cite

Akkaya, E. E., Ozer, M., Senturk, K., Ozturk, V., Alkan, U., (2022). "Design and Control of A Mobile Steward Platform with Four Independent Wheels", Mugla Journal of Science and Technology, 8(1), 19-25.

1. Introduction

In the modern technology age, it is seen that many studies have been carried out for the development of mechanical systems. With the development of systems that provide mechanical movement, parallel manipulator types have also increased. Parallel manipulators provide superior precision, robustness, stiffness, and load capacity in excess of workspace generally and are used as vehicle simulators, high-precision machine tools, torque/force sensors, industrial robots and, etc. [1]. Additionally, parallel manipulators possess advantages in terms of rigidity, large load-to-weight ratio, and high acceleration [2]. Recently considerable effort was done about the parallel manipulators. Some of them are summarized in the literature as follows. Studies on parallel manipulator mechanisms have been collected in a book by Merlet [3] in a detailed way. Küçük and Bingü [4], working on linear parallel systems, developed software called SIDED for simulation and design purposes using MATLAB. In the software they developed, it is possible to simulate linear parallel systems visually on a linear skeleton model. Gosselin and Angeles [5] made a simulation tool for reverse and advanced kinematic calculations on three manipulations parallel manipulators. Ulaş [6], who developed a procedure on parallel manipulators, worked in a structure that could determine the geometric dimensions, working trajectory, and bearing strength of the parallel manipulators in his procedure. Mruthyunjava and Dasgupta [7] addressed the troubles that occurred in Stewart Platforms. Gokcen [8] designed the four-blocks mathematical model of the 3x3 and 6x3 Stewart Platform. These blocks are whole consisting of advanced kinematics, inverse kinematics, system, and dynamics. The software of the model has been prepared and its results have been mentioned by making simulations. The dynamic model of a mechanical system relates forces and torques affecting the system time-dependent to its position, speed, and acceleration. The direct dynamic model is used for system simulation when the inverse model is much more important in system control [9]. In their study, David and Clifford [10] designed a system that can make the steering angles of the wheelchairs different so that they can provide more functional movement. This system is managed with a single mechanical drive provider. Burha [11] has designed a vehicle driven from a double axle within the scope of his master's thesis. For this vehicle, Burha has created the kinematic design of a special-purpose steering system. In this context, primarily the rotational movement, the front axle parameters affecting the rotational movement and steering systems are examined and the angular wheel controls are provided according to the Ackermann Geometry. In his book, Jeza [12] has comprehensively examined vehicle steering systems and provided suggestions. He noted that it is a great advantage to reduce the turning radius of the vehicle by providing different angles of the front and rear wheels. Pflug, von Glasner, and Povel [13] provided information on the rotability of the rear axles of the vehicles. In the study, the advantages gained by controlling the hydraulic supported system electronically are mentioned. In their article, Pillar and Braun [14] mentioned about maneuverability and efforts to increase maneuverability, which is one of the parameters that significantly affect vehicle movement dynamics. They also emphasized the importance of using sensors that can detect wheel angles in vehicles. It was observed that the study provided 30% efficiency to the vehicle maneuvering movements by examining the usage areas of the system. It is stated that it will be easier to drive and park special vehicles such as garbage trucks, fire trucks, etc. in the city and agricultural vehicles.

In the present study, a unique design was made and "Independent Wheel System and Steering Gear System (IWSSGS)" was used. In IWSSGS, the wheels are designed to be able to move in all directions at the desired angle independently or to move circularly around the imaginary turning center (O) at the desired speed in Figure 1.

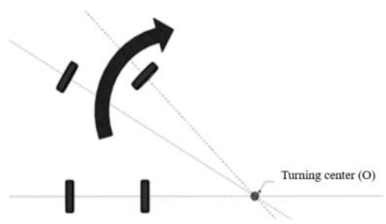

Figure 1. Rotation of the vehicle around O center

Maneuverability is an important feature for a vehicle. It is also an important feature whether the wheel angles are independent and controllable or not. In calculating the steering angles, the speed factor of the wheels should be calculated precisely in order to prevent unwanted jolts of the vehicle while turning and to increase maneuverability. The Ackermann Principle is the most known and basic method which helps understanding the kinematics of the steering system. The vehicle's wheel rotation flexibility, vehicle size, driver and steering configurations closely affect maneuverability.

According to the designed wheel system, a DC motor with a reducer is used in the structure of each wheel to provide a transport and movement system. Servo motors are used to make the wheel system move back and forth or to the left and right. While turning, the vehicle's wheel and steering angles are calculated single-centered according to Ackermann Geometry. Thus, the steering of the vehicle has been made more functional and the turning radius has been minimized. If this system is adapted to cars, the system's individual functions can be used to facilitate parking. In this study, the 3x3 Stewart Platform model is used. According to this model, six pistons operate in relation to the crank mechanism structure. Servo motors integrated into their structure change the rotational motion to linear motion. Linear and angular movements can be controlled by switching to different control modes with the Stewart Platform. Angular controls of the system are triggered by using the balance function of the Stewart Platform placed on the vehicle. The platform integrated on the vehicle is constantly in balance according to the angle sensor data used on the system. The main objective of the prototype developed here is to enable a vehicle to move freely and keep the platform on it in balance during this motion. In the prototype vehicle within the scope of this study, all wheels provide rotation in the desired direction independently.

The remainder of this paper is organized as follows. In the following section, the theoretical background is given. Then, the methodology is mentioned. In the last section, conclusions of this paper are given.

2. Theoretical Background

The idea of parallel manipulator flight training simulations was suggested by Stewart in 1965 and was named after the system designed [15]. This system consists of six arms and twelve joints.

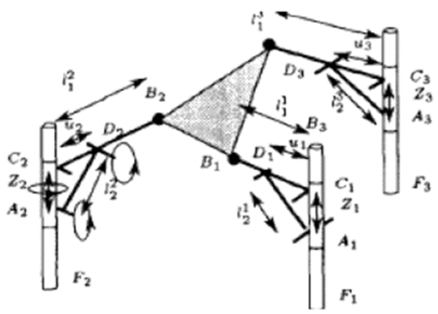

Figure 2. First Platform model suggested by Stewart [15]

With his work in designing this system, Stewart has revealed that all the spatial points in the orbit can be reached while the system is running. However, joints remain fixed at the desired angle when the system is not working [16]. There are some advantages and disadvantages when parallel, serial, and hybrid model mechanisms are compared (see Table 1).

Table 1. : Comparison table for parallel, series and hybrid mechanisms.

Parallel Mechanisms	Series Mechanisms	Hybrid Mechanisms
There are multiple links between the start and the end.	It consists of consecutive joints.	It has a special bond structure according to the need. Serial and parallel methods are used together.
Working space is limited.	Working space is very huge.	Working space can be shaped according to the purpose.
Powerful	Weak	There is a balance of power according to the design structure.
Slow	Fast	The speed of the system depends on the design.
Complex kinematic equations are used.	Simple kinematic equations are used.	Complex kinematic equations are used.
From the beginning, errors become the average error towards the tip manipulator.	From the beginning the errors turn into batch errors towards the tip manipulator.	From the beginning, errors are calculated with equations according to the serial and parallel design parts of the system towards the end manipulator.

3. Methodology

Kinematic calculations according to Stewart's 3x3 model were used in this study. The description of spatial movement changes of the model is done as well. The system consists of two platforms which both have geometrical shapes as equilateral triangles. One of the platforms is fixed (lower platform) and the other platform (upper) performs spatial movements responding to the objectives. Platforms are connected to each other by arms of varying length using an inverse kinematic analyzer with hemispherical joints named as for lower and for upper platforms. The number of connections between the platforms is three for each and they are equal. The total number of arms is six (i = 1,2,3, and j = 1,2,3).

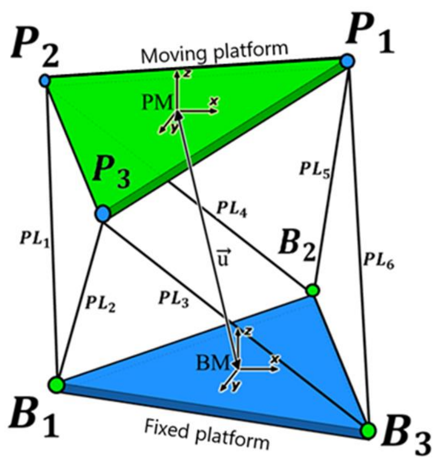

Figure 3. Axis arrangement and translation vector of the platform which is used in this study.

In Figure 3, the blue part is a fixed platform represented by BM and green part located above is movable platform represented by PM. The coordinate systems for the same platforms can be given as BM (x, y, z) and PM (x, y, z) respectively. The position vectors of the connection points for the BM (x, y, z) coordinate system (the lower plate) is expressed by b_i (i = 1..3) and similarly, for PM (x, y, z) coordinate system (the top plate), the position vectors of the connection points are expressed as p_j (j = 1..3). Therefore the vector of piston PL_i can be obtained by Equation (1),

$$\overrightarrow{PL_i} = {}^{B}R_P.\overrightarrow{p_j} + \vec{u} - \overrightarrow{b_i} \quad (1)$$

where $\vec{u}$ is a translation vector.

The tilting motion of the upper plate in three axes relative to the lower plate is expressed by the ${}^{B}R_p$ transformation matrix. The orientation of rigid bodies in three-dimensional space is expressed by using the Euler angle. In expressing the motions in three axes for the Euler angle the terms elevation, roll and azimuth are used frequently which also represent the rotational movements performed in the direction of x, y, z axes respectively. Based on this, we can define the rotations around the x, y, z axes with the angles e, r, a respectively. If these angles are applied to the system, the transformation matrix ${}^{B}R_p$ becomes as given in Equation (2) ;

$${}^{B}R_P = \begin{bmatrix} \cos(a)\cos(r) & \cos(a)\sin(r)\sin(e) - \sin(a)\cos(e) & \cos(a)\sin(r)\cos(e) + \sin(a)\sin(e) \\ \sin(a)\cos(r) & \sin(a)\sin(r)\sin(e) + \cos(a)\cos(e) & \sin(a)\sin(r)\cos(e) - \cos(a)\sin(e) \\ -\sin(r) & \cos(r)\sin(e) & \cos(e)\sin(e) \end{bmatrix} \quad (2)$$

Therefore PL_i is obtained as given in Equation (3).

$$PL_i = \sqrt{\overrightarrow{PL_i} \cdot \overrightarrow{PL_i}} \quad (3)$$

Equation (3) expresses the length of the i^{th} piston. The lengths for all pistons are calculated by performing these operations. The values that meet the condition $PL_{min} < PL_i < PL_{max}$ are taken into the solution set. In the Stewart Platform Mechanism, according to the change in length *(PL_i) of* the i^{th} piston, the angles formed with respect to the n_{bi} vector perpendicular to the fixed plate and n_{pj} vector perpendicular to the moving plate are respectively θ_{bi} and θ_{pj} that are angles of a fixed platform and movable platform in a given order. Therefore, we can find the angle between joint and fixed part θ_{bi} by using Equation (4);

$$\theta_{bi} = \cos^{-1}\frac{\overrightarrow{PL_i}.\overrightarrow{n_{bi}}}{PL_i} \quad (4)$$

Also, for determining the angle between piston and movable platform θ_{pi} by using equation (5);

$$\theta_{pj} = \cos^{-1}\frac{\overrightarrow{PL_i}.{}^{B}R_P.\vec{n}_{pj}}{PL_i} \quad (5)$$

All the calculations related to this study were performed by using the equations described above.

A design in 3x3 models has been considered and output based on piston logic has been taken for the balance platform and after the necessary mathematical calculations, drawings were made by using the SolidWorks software program. A 3D printing machine was used to print the parts which are assembled afterward. Servo motors are used to provide piston movement, and a product has been manufactured with a machine technique similar to a crank mechanism. In order to ensure balancing the six mechanisms are attached to the floor and the upper table that needs to be balanced with ball joints. The x-y data taken from the gyroscope card were recognized by the Arduino card to the relevant mechanism and an additional stable result was obtained. The carrier body was first designed, and a body installed on the wheel was made to ensure the free movement of the vehicle. During the design of the body, the middle part of it was preferred for the Stewart platform, which was previously finished, in order to prevent the vehicle tipping problem due to the deviation of the center of gravity. Hull and Stewart platform tests have been done and software optimization has been made until the most stable result is achieved. It is planned to make a stable wheel rotation thanks to the feedback from the servo motors which provide direct support for the wheel to be mounted on the body. Afterward, the servo inter-wheel fastener part was drawn on SolidWorks and printed on a 3D printer. Tests were carried out and Ackermann geometry was applied on 4 wheels after the assembly process. The wheel system created was mounted and the battery and card system were placed in the center of gravity of the body. The necessary software connection was established by using the Arduino card. Bluetooth communication is used for remote control and data control via Android. The control user interface in the Android application is given [17] in Figure 4.

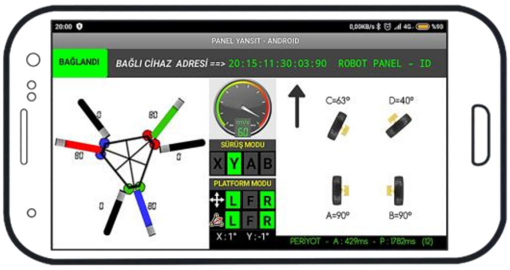

Figure 4. The user interface developed for prototype control.

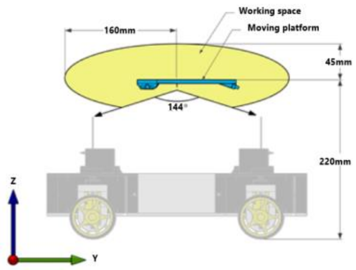

Figure 5. Working space of the platform (side view).

The working modes of the prototype were simply described below.

Mode 0: The damping of angular movements relative to the angle sensor is the mode that provides real-time balance for the Stewart platform mechanism's top plate. As soon as the system starts up, it works with this mode as default. x and y slope values are read at the lower part of the platform with a fixed angle sensor and gyroscope sensor operating according to the principle of maintaining angular balance. It keeps the platform in balance by making angular movements against these values. The system performs this movement in 40 ms periods and continuously updates the platform angle. When mode 0 status is active, the balance mode is activated. In inclined positions, the device automatically stabilizes the top plate. In this case, the top plate becomes parallel to the floor on which the vehicle is located. It can be seen in Figure 6.

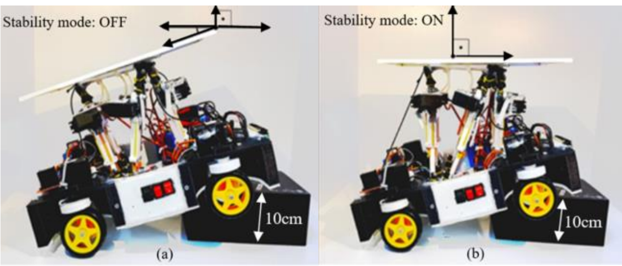

Figure 6. Stability mode (Mode 0) off (a) and on (b) with the status of the upper platform.

Mode 1: It is the mode that is affected by the angle of deviation with respect to the z-axis when viewed from the top, considering the O point as the center. Angular movement deviates ± 47 degrees. Besides, in order to make the system more functional while this mode is active, the platform is automatically turned towards the steering direction of the vehicle. Here, steering angle values are added and applied.

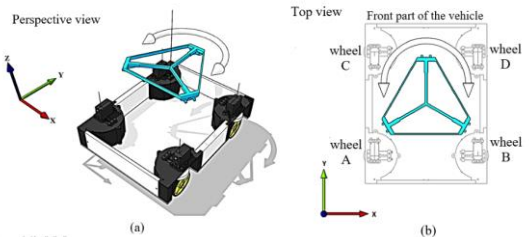

Figure 7. The direction of the angular movement of Mode 1 (a) perspective and (b) top view.

Mode 2: It is the mode used to make a linear motion on the y-axis (± 8cm can move linearly).

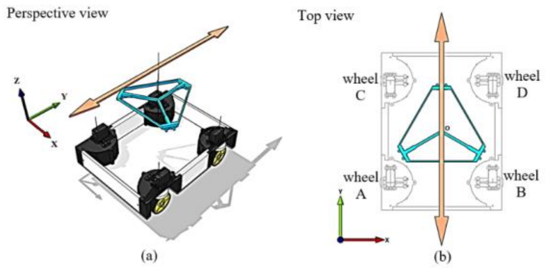

Figure 8. The direction of a linear motion with Mode 2 (a) perspective and (b) top view.

Mode 3: Y-axis provides a straight motion (± 8cm movement restricted) on the axis at 60 degrees angle deviation, occurring counter clockwise when viewed from the vertical axis.

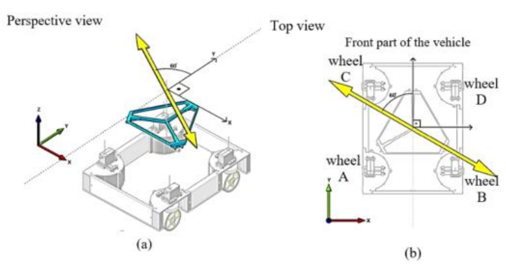

Figure 9. The direction of a linear motion with Mode 3 (a) perspective and (b) top view.

Mode 4: When viewed from the vertical axis, it provides a straight movement on the line in the case of 60 degrees angle deviation clockwise relative to the y-axis (there is a ± 8cm movement restriction).

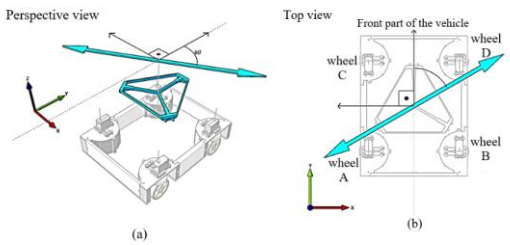

Figure 10. The direction of a linear motion with Mode 4 (a) perspective and (b) top view.

Mode 5: Dolphin movement is provided in the same direction set with Mode 2. It is the mode used to make angular motion (can reach a slope of ± 18 degrees).

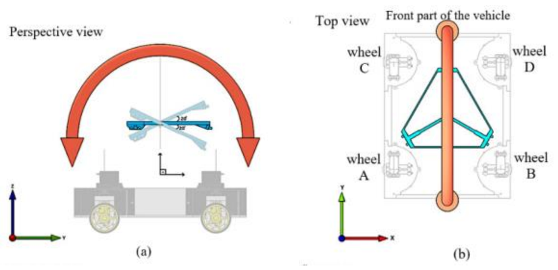

Figure 11. The direction of a linear motion with Mode 5 (a) perspective and (b) top view.

Mode 6: Dolphin movement is provided in the same direction set with Mode 3. It is the mode used to make an angular motion (can reach a slope of ± 18 degrees).

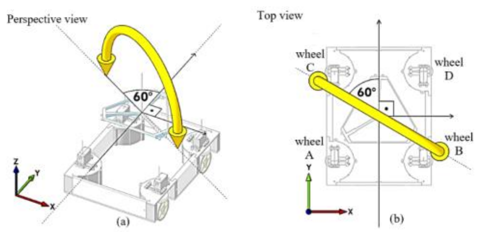

Figure 12. The direction of a linear motion with Mode 6 (a) perspective and (b) top view.

Mode 7: Dolphin movement is provided in the direction set with Mode 4. It is the mode used to make an angular motion (can reach a slope of ± 18 degrees).

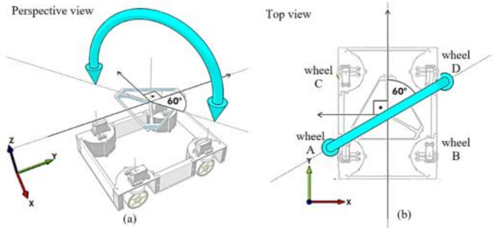

Fig 13. The direction of a linear motion with mode 7 (a) perspective and (b) top view.

4. Simulation Control

It has been made phase space limit control of the orientations of the platform's center point relative to the x, y, and z axes by using Matlab software.

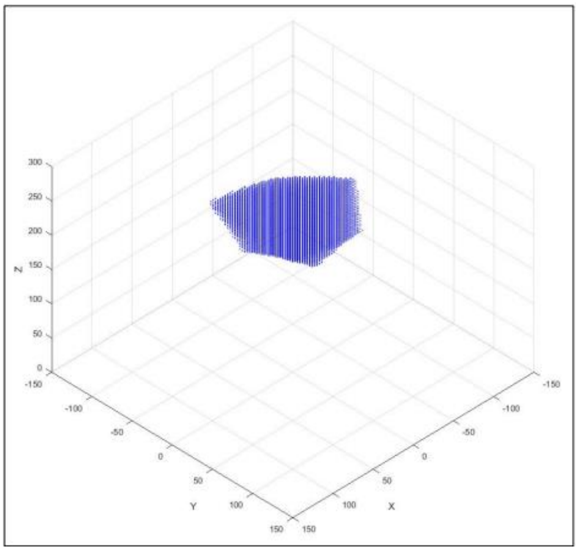

Figure 14. Platform's phase space perspective point cloud using Matlab program. (according to 2mm point spacing)

When the workspace is examined planarly, the platform in the system whose prototype is developed there are some contractions in the movements of the movable upper platform towards the border parts are seen. This happens due to the limitations of linear motor systems on the platform.

Table 2. Linear endpoints of the working space for the x, y, and z axes

Axis	Lower Limit	Upper Limit
X	-52 ± 0.5 mm	38 ± 0.5 mm
Y	-40 ± 0.5 mm	40 ± 0.5 mm
Z	-45 ± 0.5 mm	23 ± 0.5 mm

As can be seen in Table 2. Z-axis is the minimum upper limit due to the shape of the platform. This makes the system more stabilized and lets the platform be loaded with external weights.

5. Conclusion

This work aimed to develop a prototype on which the upper platform is always in balance when it is moving freely. The movable platform built on the prototype was kept in full balance by applying the Stewart Platform model. The prototype's component was made on PCB filament using a 3D printer. It has four servo motors and one electric motor. The platform in a 3x3 connection format with six degrees of freedom was designed and placed on the chassis. The platform consists of a fixed bottom plate, a movable top plate, and six pistons. The wheel system and platform mechanism presented in this work have been controlled by using special modes and the control arm. All the wheels of the prototype were customized and controlled independently. Wheels' angles were calculated by using Ackermann Geometry. Wheel and platform control algorithms have been designed according to the objectives, and C programming language-based code has been written. This code was installed on the Arduino microcontroller board, which is the brain of the system. Using the server-based mobile application development environment App Inventor 2, a graphics-based mobile application was developed to monitor the prototype system status. Bluetooth 2.0 protocol has been used to provide communication between the mobile application and the prototype device. In the mobile application, information such as piston positions, wheel angles, vehicle movement direction, wheel-platform modes, slope, and speed of the system status are shown. As a result, the flexibility and driving ease for car driving were achieved on the prototype vehicle designed in this study. Furthermore, the prototype's platform limits are controlled by using the matlab program.

6. References

[1] Cagdas, B.," Kinematic and Dynamic Analysis of Spatial Six Degree of Freedom Parallel Structure Manipulator", Master dissertation, 2003.Retrieved from:https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp.

[2] Shao, Z.-F., Tang, X., Wang, L., "Dynamics Verification Experiment of the Stewart Parallel Manipulator", *International Journal of Advanced Robotic Systems*, 12, , 1-10,2015.

[3] Merlet, J.P., *Parallel Robots*, Springer , Netherland, 2006.

[4] Kurtoğlu, A., *Robot Tekniği,* Papatya,Istanbul ,2011.

[5] Gosselin, C. and Angeles, J. "Singularity analysis of closed-loop kinematic chains", *IEEE Transactions on Robotics and Automation*, 6(3) , 281-290, 1990.

[6] Ulas, B., "Design of the Stewart Platform", Master dissertation, 2009. Retrieved from: https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp.

[7] Dasgupta, B., Mruthyunjava, T.S., "The Stewart Platform manipulator: a review", *Mechanism and Machine Theory*, 35(1), 15-40,2000.

[8] Gokcen, H.M., "Control of a Stewart mechanism using direct kinematic solution", Master dissertation, 1992. Retrieved from: https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp.

[9] Lopes, A.M. and Almeida, F., *Dynamic Model of a 6-dof Parallel Manipulator Using the Generalized Momentum Approach*, Parallel Manipulators, towards New Applications, intechOpen, 2008.

[10] David, M.B. and Clifford, E.B. , "A steering linkage for short wheelbase vehicles: Design and evaluation in a wheelchair power base - A technical note", *Journal of rehabilitation research and development*, 36(1) , 42-47,1999.

[11] Burha, M., "Kinematic design of a multi-axle steering for a three-axle special purpose vehicle", Master dissertation, 2010.Retrieved from: https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp

[12] Jazar, R.N., *Vehicle Dynamics: Theory and Applications*, Sprinher, Boston, 2008.

[13] Pflug, H., von Glasner, E., and Povel, R., "Commercial Vehicles with Intelligent Rear Axle Steering Systems," SAE Technical Paper 962185, 1996.

[14] Pillar, D. and Braun, E., "All-Wheel Steering System for Heavy Truck Applications," SAE Technical Paper 952680, 1995

[15] Stewart D., "A Platform with Six Degrees of Freedom". *Proceedings of the Institution of Mechanical Engineers*. Vol.180, No.1, 371-386, 1965.

[16] Anlı, E., "Positional Kinematics Analysis of the 6-3 Stewart Platform Mechanism Using Heuristic Algorithms", Master dissertation, 2005.Retrieved from: https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp.

[17] Ozer, M., "Implementation of Hybrid Vehicle Prototype with Upper Plate Balancer Stewart Platform and Angular Controlled Wheels", Master dissertation, 2019.Retrieved from: https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp.

[18] Ozturk, V. "Applying the platform with 6 dof level by designing it on to a linear motor system and enhance its software, Master dissertation, 2019. Retrieved from:
https://tez.yok.gov.tr/UlusalTezMerkezi/tezSorguSonucYeni.jsp