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A self-balancing platform on a mobile car

Bushra Amer Tawfeeq, Maher Yahya Salloom, Ahmed Alkamachi
Mechatronics Engineering Department, Al-Khawarizmi College of Engineering, University of Baghdad, Baghdad, Iraq

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ABSTRACT

In the last years, the self-balancing platform has become one of the most common candidates to use in many applications such as flight, biomedical fields, and industry. In this paper, the physical prototype of a proposed self-balancing platform that described the self-balancing attitude in the (X-axis, Y-axis, or biaxial) under the influence of road disturbance has been introduced. In the physical prototype, the inertial measurement unit (IMU) sensor will sense the disturbance in (X-axis, Y-axis, and biaxial). With the determined error, the corresponding electronic circuit, DC servo motors, and the Arduino software, the platform overcame the tilt angle(disturbance). Optimization of the proportional-integral-derivative (PID) controllers' coefficients by the genetic algorithm method effectively affected the performance of the platform, as the platform system is stable and the platform was able to compensate for the tilt angle in (X-axis, Y-axis, and both axes) and overcome the error in a time that does not exceed four seconds. Therefore, a proposed self-balancing platform's physical prototype has a high balancing accuracy and meets operational requirements despite the platform's simple design.

Corresponding Author:

Bushra Amer Tawfeeq
Al-Khawarizmi College of Engineering, University of Baghdad
AL-Jadrriya, Baghdad, Iraq
Email: bushra.a.tawfeeq@gmail.com

1. INTRODUCTION

The parallel manipulator's design precipitated a self-balancing platform design revolution. The self-balancing platform is about using the parallel manipulator concept. Therefore, the self-balancing platform's design as several serial chains to support a single platform confirms the parallel manipulator concept's effectiveness [1]. The self-balancing platform principle is based on the short, simple, and rigid parts of the platform structure to restrict unwanted movement [2]. The most common uses of a self-balancing platform are designing it for simulation, such as a car, motorbike, ships, jets, submarines, and flight simulations. However, its applications are not limited to simulation; it can also be used for practical work in biomedical fields, the oil and gas industry, and the military [3], [4]. In designing a self-balancing platform, it is required to select a suitable material or type and proper dimensions for each part of the design (platform, motors, links, and joint) based on the design purpose and constraints facing the platform [5].

The self-balancing platform applications require an accurate response with high overall system stability. Therefore, the self-balancing platform's working principle has been categorized into three stages (sensor, controller, actuator) respectively [6], [7]. The experimental results of 2-DOF self-stabilizing showed that the platform's performance mismatch with some of the design's operational requirements due to the erroneous location of the sensor and no simulated model for the platform [8]. The mathematical system modeling calculation was derived manually to find the relationship between the servo motor's angle and the inclination of the platform [9], [10]. The Simscape environment and other modern technologies are used to design some mechanical applications, for example, inverted pendulum systems, without the need to derive the complex differential equations [11]. Despite the number of self-balancing platforms' previous physical design built by integration components (mechanical, electronic, and hydraulic) to compensate for the platform's tilt by external disturbance signal or moving on the uneven ground. However, self-balancing for biaxial inclination angle, low re-correct time, and the highest level of precision in determining the servomotor's next position are among the ones that should be worked to achieve [12]–[16].

Through practical experiments, the 2-DOF proportional-integral-derivative (PID) controller has been shown better results in the control of self-balancing robot than conventional PID control [17]. The values from the navigation parameters, the enhanced measurements from the MPU-6050 sensor, and (PD-PI) robust control are used to increases the two-wheeled self-balancing robot's stability [18]. The linear-quadratic regulator (LQR) controller also has achieved better performance over PID controllers, especially the time domain response [19]. This article will be organized: in section 2, we present the proposed design of a self-balancing platform. Section 3 results and discussion. In section 4, we conclude the study and the future works.

This study's main contribution is using low-cost materials, MPU-6050 sensor features, and PID controller functionality. Combining the above three factors has been used to build the self-balancing platform. Also, it has been used to model and control the self-balancing platform without the need to derive a complex system of mathematical differential equations.

2. CONSTRUCTION OF PHYSICAL PROTOTYPE

In terms of dynamic modeling [20], [21], a 3D model of the self-balanced platform on the mobile car was constructed and optimized by SolidWorks (SW2020) based on the design parameters and related limitations. The platform's complete system (three plates and two holders with a dimension of (45 cm length×30 cm width) at the rectangle base plate (40 cm length×40 cm width×3 cm inside) at the square middle plate, (20 cm length×20 cm width) the square top plate and each holder with (15 cm width×25 cm height). Besides, the platform attached to a reliable iron rectangle that had the advantage of having a well-balanced structure (45 cm length×60 cm width) stands on four tires, as shown in Figure 1. The physical prototype of the self-balancing platform on a mobile car has been built based on two block diagrams. Firstly, based on the conceptual control system block diagram shown in Figure 2. Secondly, based on the working principle of the block diagram is shown in Figure 3.

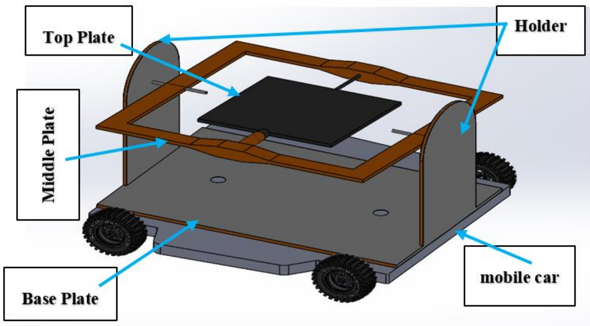


Figure 1. The CAD drawing for the proposed prototype of the 3D self-balancing platform

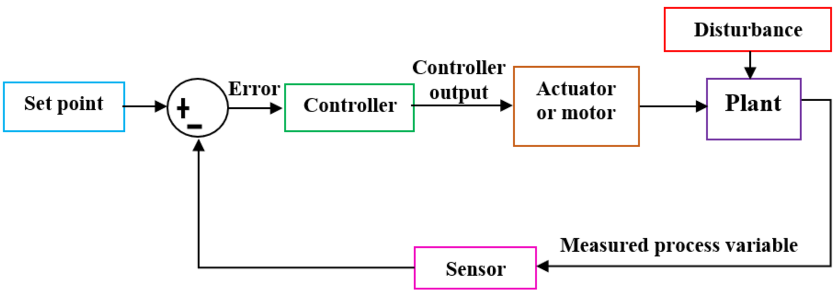


Figure 2. Conceptual control system block diagram

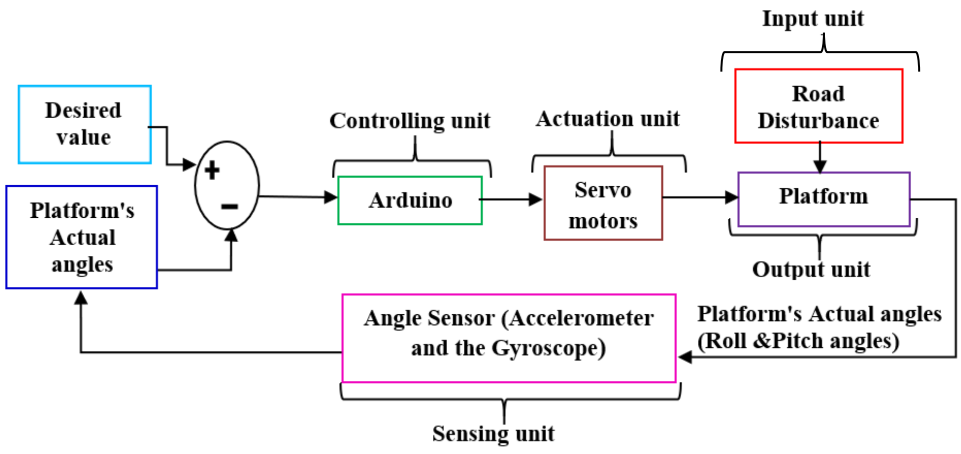


Figure 3. The block diagram of the working principle for the (physical prototype of the self-balancing platform on the mobile car)

The components that used in the physical prototype as shown in Figure 4 units are: i) input unit/(mobile car): a less expensive and more robust configuration toy mobile car with dimensions (45 cm length×40 cm width×50 cm height) has been modified to use as a transport medium for self-balancing platform into the desired position; ii) controlling unit: Arduino Mega 2560 R3 [22]; iii) actuation unit: two continuous rotation servo motors (MG995) have been used; one of the motors is for the Pitch Angle Y-axis (top plate), the other motor is for the Roll Angle X-axis (middle plate); iv) output unit: low weight Perspex GS cast acrylic glass (PMMA) [23] with a thickness of 2 mm and then cut according to the shape and dimension specified for each plate of the proposed platform by a CNC machine; and v) sensing unit: GY-521 6 axis MPU 6050 sensor has been used to measure pitch and roll angles. MPU 6050 sensor comprising a three-axis gyroscope and a three-axis accelerator [24], [25].

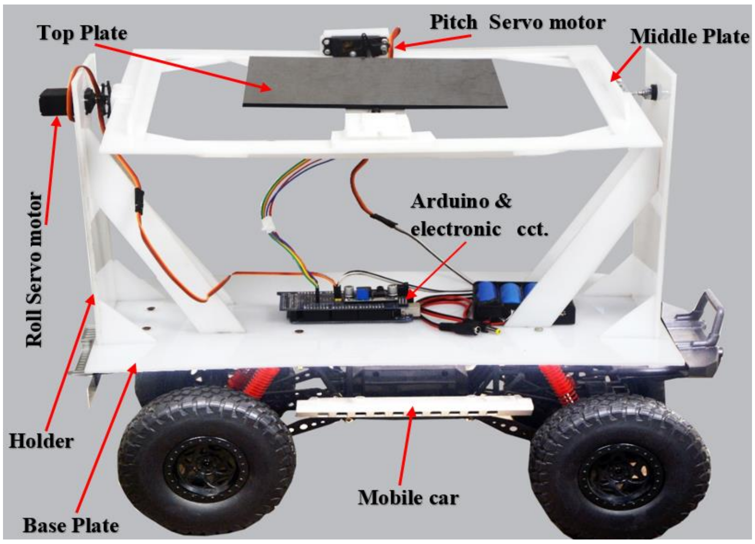


Figure 4. A physical prototype of the self-balancing platform on the mobile car

2.1. Electronic design

As shown schematic diagram of Figure 5, two servo motors were connected to Arduino Mega 2560 R3 that received input from the MPU6050 sensor [26], [27]. Also, the 3×AA battery assembled in series produced a voltage of 7.4 volts, and it was reduced to 5 volts by the voltage regulator to be distributed to servo motors, Arduino Mega 2560 R3, and MPU-6050 sensor. The schematic diagram has been drawing by Fritzing software 0.9.3b (2016).

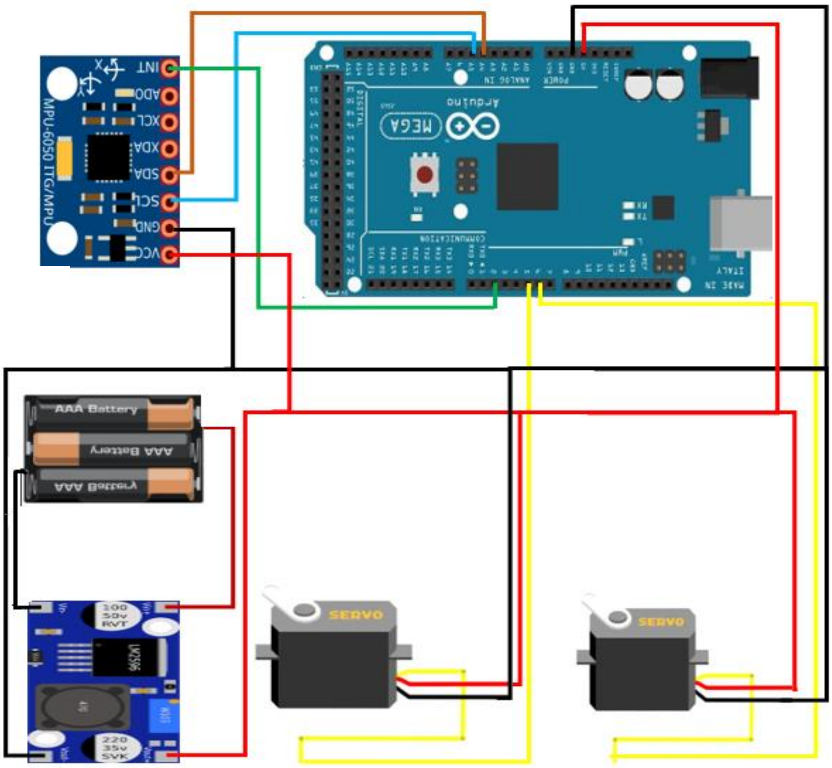


Figure 5. Schematic diagram

2.2. System flow chart

Arduino IDE 1.8.13 has been utilized to write system code (using C++ language) [28]. Then code has been uploaded to the Arduino Mega 2560 R3 board from a computer/window directly through a universal serial bus (USB) cable [29], [30]. The code uses the MPU-6050 sensor's feature and the PID controller functionality to control the servo motors' speed and direction. This controlling used for compensating the tilt of the platform under road disturbances. The system flowchart is shown in Figure 6.

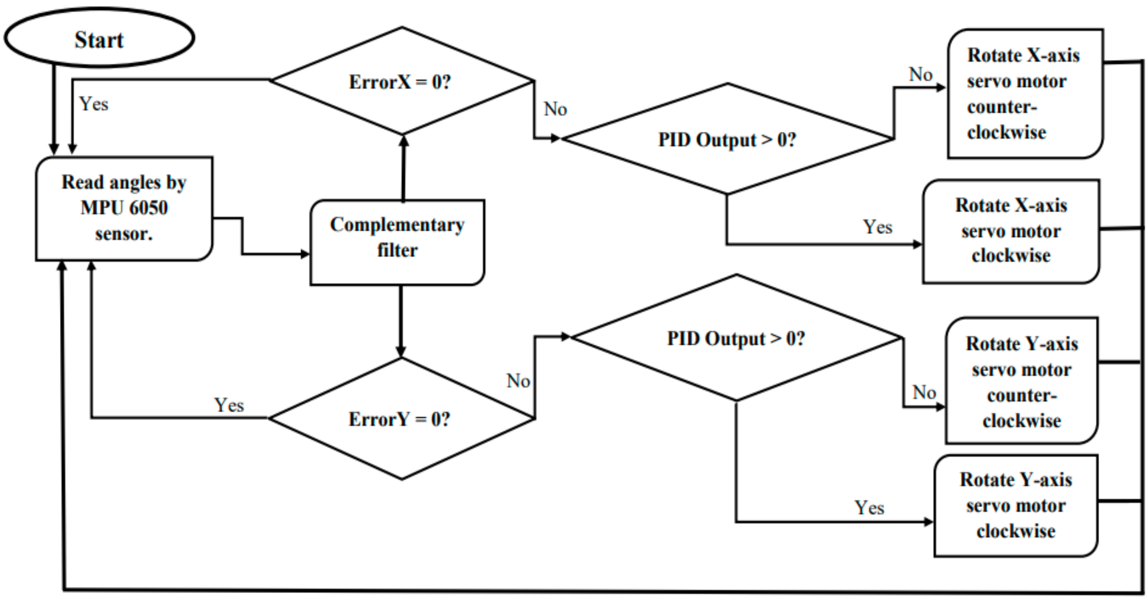


Figure 6. System flowchart

The filter used in this project (self-balancing platform on a mobile car) is the complementary filter. By using the complementary filter, the pitch and roll can be found according to the (1), (2) [31], [32]:

$$\mathrm{XAngle} = \underbrace{(\mathrm{XAngle_{old}} + \mathrm{gyroX} * \mathrm{dt}) * 0.98}_{\text{High pass filter}} + \underbrace{\mathrm{accXAngle} * 0.02}_{\text{Low pass filter}} \tag{1}$$

$$\mathrm{YAngle} = \underbrace{(\mathrm{YAngle_{old}} + \mathrm{gyroY} * \mathrm{dt}) * 0.98}_{\text{High pass filter}} + \underbrace{\mathrm{accYAngle} * 0.02}_{\text{Low pass filter}} \tag{2}$$

where XAngle and YAngle are the (Roll angle ϴ) and (Pitch angle ϕ), respectively. The XAngle_old and YAngle_old are the previous roll and pitch values, respectively. The gyroAngleX and gyroAngleY are the roll and pitch found using the gyroscope readings, respectively. The accXAngle and accYAngle are the roll and pitch found using the accelerometer readings, respectively.

2.3. PID controller tuning

A genetic algorithm (GA) is a global algorithm base on Darwin's theory of evolution. Genetic algorithm is one of the PID controller optimization methods, especially if the PID controller interconnected system is a DC motor [33]. Accordingly, the genetic algorithm often provides a reasonable balance between the PID controller coefficient's accurate values and better PID response regarding the rise time and the settling time. GA consists of four main stages (initial generation, cost function, selection techniques, crossover, and mutation [34], [35].

For this project, two PID controllers have been used. One PID controller for pitch angle (top plate) and the other for roll angle (middle plate). To obtain the experimental results, the two PID controllers' parameters were tuned using the GA and cost function (ITAE) [36], as shown in Table 1.

Table 1. Genetic algorithm parameters

GA Parameters	Value/Method
Variable boundaries [Kp Ki Kd]	For Roll angle PID controller Lower [0,0,0], Upper [150,350,1] For Pitch angle PID controller Lower [0,0,0], Upper [100,200,1]
Maximum number of Population	60
Size generations	100
Fitness value	Cost function/Integral of time multiplied by absolute error (ITAE)
Selection method	Normalized Geometric Selection
Crossover Method	Arithmetic Crossover
Mutation method	Uniform Mutation
Iteration	78

3. RESULTS AND DISCUSSION

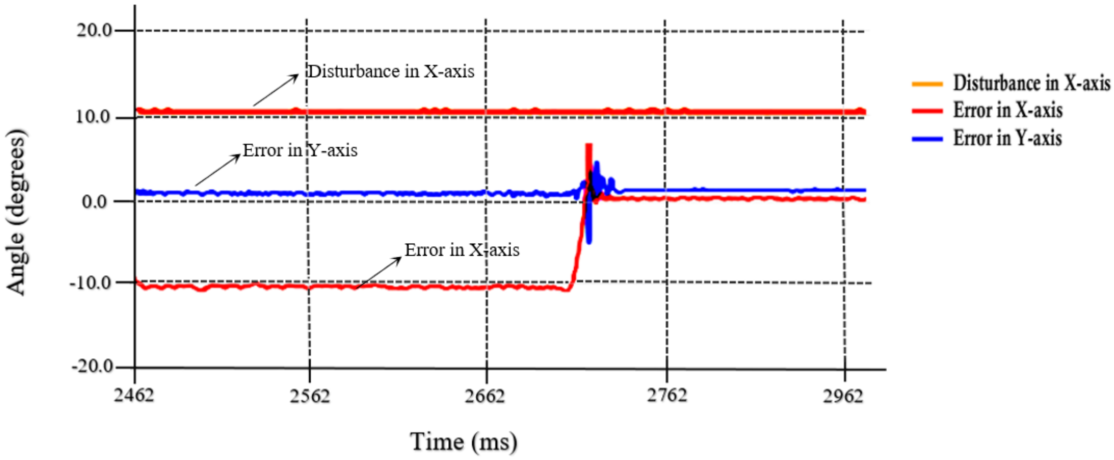
The platform prototype's self-balancing performance has been studied under the influence of disturbance scenarios. Where four road disturbance scenarios (X-axis, Y-axis, and biaxial) have been used. The platform's self-balancing performance is shown in below four cases.

3.1. Case one: Self-balancing attitude in the physical prototype under the influence of road disturbances scenario in the X-axis

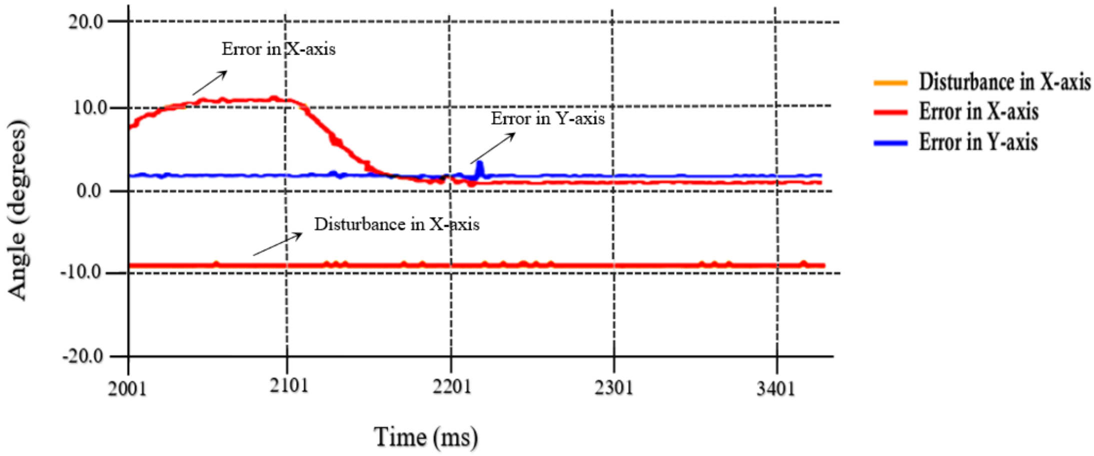
The platform's self-balancing behavior as a result of the platform being subjected to disturbances in the X-axis is shown in Figures 7(a) and 7(b), respectively. Disturbances in the X-axis are (tilt angle 10° on +X-axis and -10° on -X-axis). Furthermore, the realistic self-balancing of a platform under the tilt angle (10° on +X-axis and -10° on -X-axis) are shown in Figures 8(a) and 8(b), respectively.

3.2. Case two: Self-balancing attitude in the physical prototype under the influence of road disturbances scenario in the Y-axis

The platform's self-balancing behavior as a result of the platform being subjected to disturbances in the Y-axis is shown in Figures 9(a) and 9(b), respectively. Disturbances in the Y-axis are (tilt angle 10° on +Y-axis and -10° on -Y-axis). Furthermore, the realistic self-balancing of a platform under the tilt angle (10° on +Y-axis and -10° on -Y-axis) are shown in Figures 10(a) and 10(b), respectively.

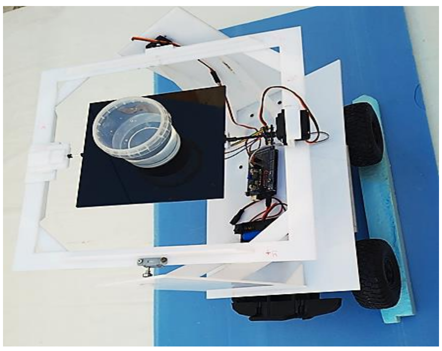


(a)

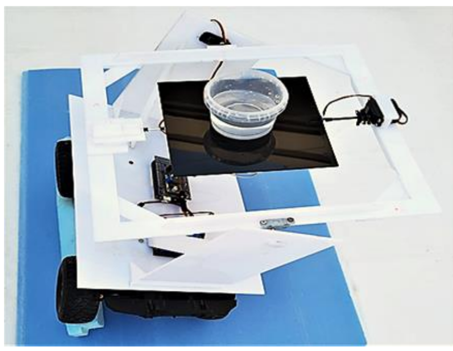


(b)

Figure 7. Self-balancing behavior in the middle plate of the physical prototype car (a) under tilt angle 10° on the positive X-axis and (b) under tilt angle -10° on the negative X-axis



(a)



(b)

Figure 8. Self-balancing of the (platform on the mobile car) structure (a) under tilt angle 10° on the positive X-axis and (b) under tilt angle -10° on the negative X-axis

3.3. Case Three: Self-balancing attitude in the physical prototype under the influence of road disturbances scenario in the biaxial (contradictory tilt angles in X-axis and Y-axis)

The platform's self-balancing behavior as a result of the platform being subjected to biaxial disturbances is shown in Figures 11(a) and 11(b), respectively. Biaxial disturbances are (tilt angle 10° on

+X-axis and -10° on -Y-axis) and (tilt angle -10° on -X-axis and 10° on +Y-axis). The realistic self-balancing of a platform under (tilt angle 10° on the +X-axis and -10° on the -Y-axis) is shown in Figure 12(a). Moreover, the realistic self-balancing of a platform under tilt angle (-10° on -X-axis and 10° on +Y-axis) is shown in Figure 12(b).

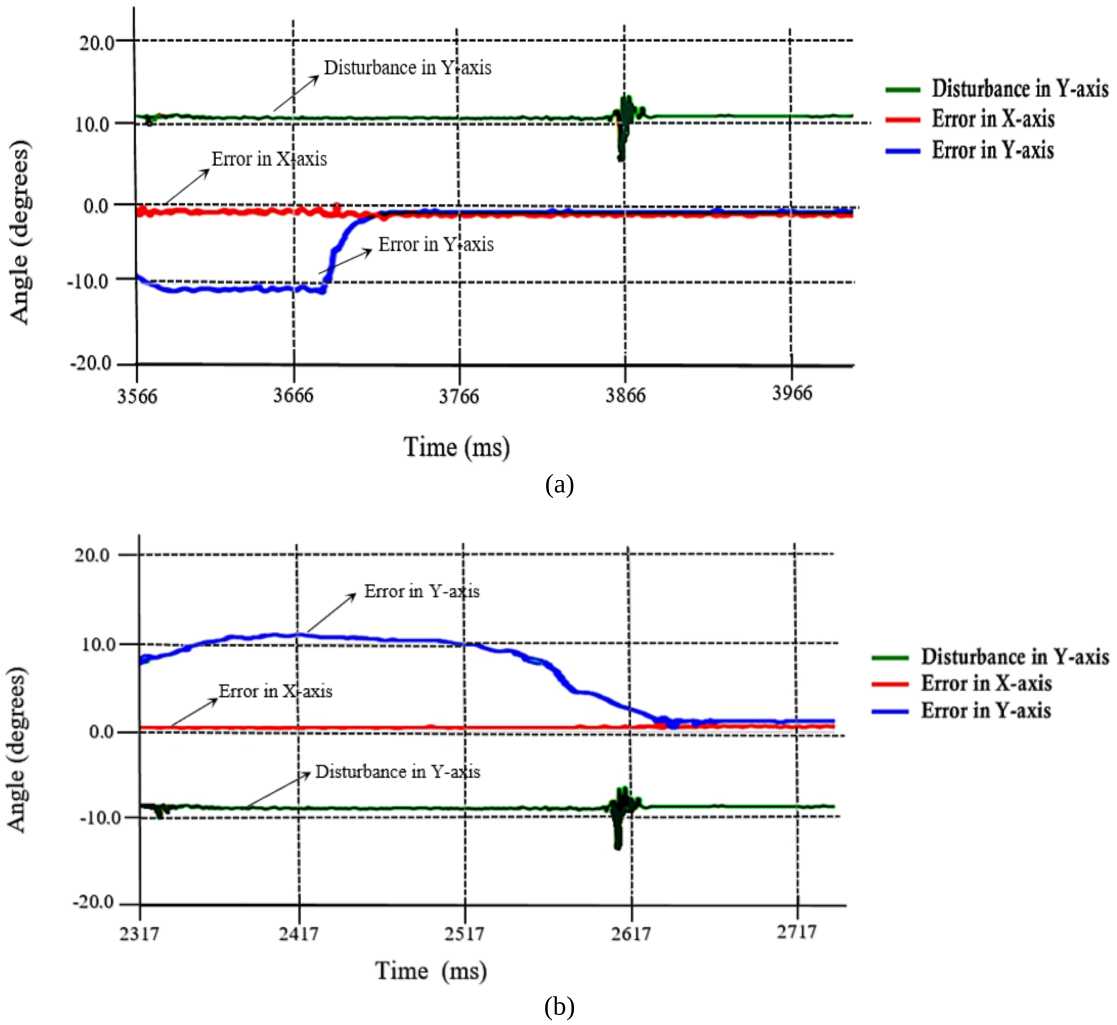


Figure 9. Self-balancing behavior in the top plate of the physical prototype (a) under tilt angle 10° on the positive Y-axis and (b) under tilt angle -10° on the negative Y-axis

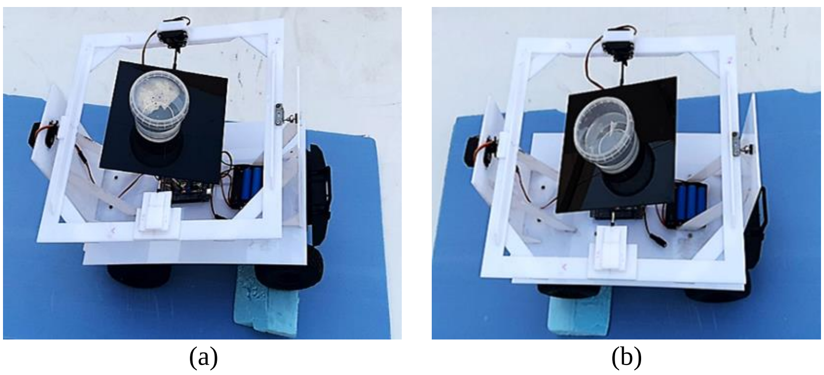
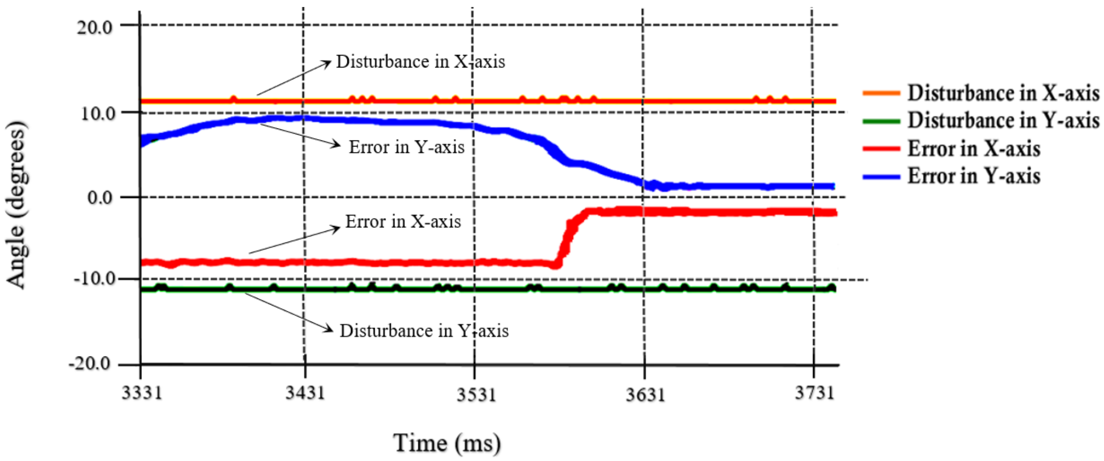
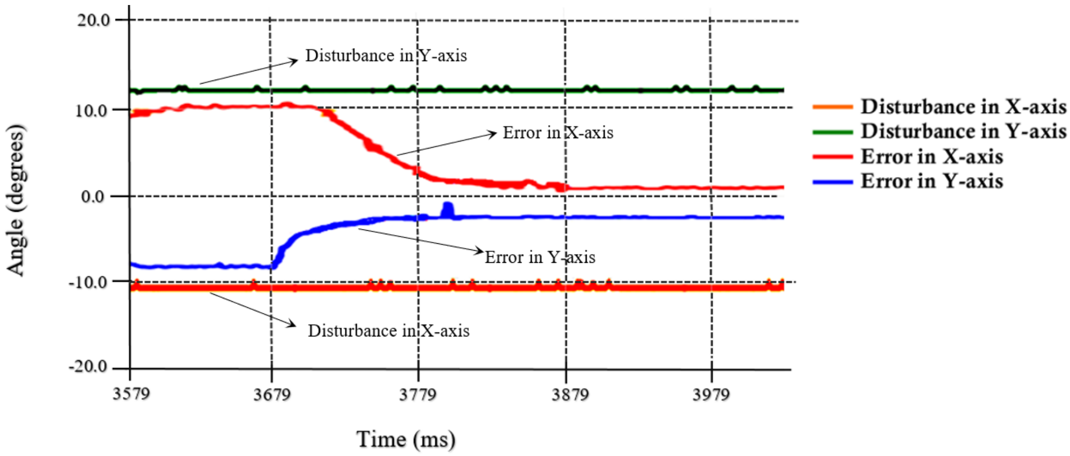


Figure 10. Self-balancing of the (platform on the mobile car) structure (a) under tilt angle 10° on the positive Y-axis and (b) under tilt angle -10° on the negative Y-axis

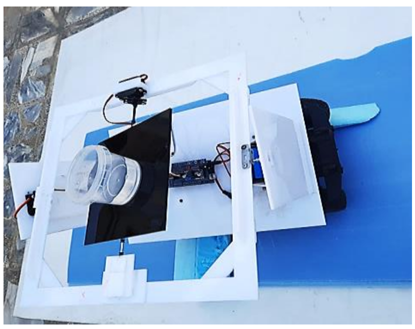


(a)

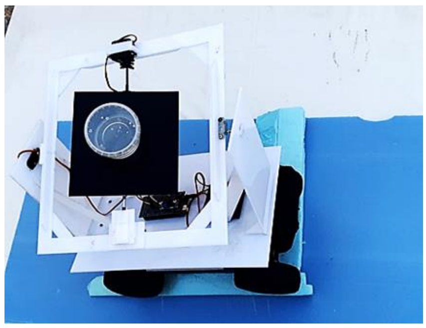


(b)

Figure 11. Self-balancing behavior the physical prototype (a) under tilt angle 10° on the positive X-axis and -10° on the negative Y-axis and (b) tilt angle -10° on the negative X-axis and 10° on the positive Y-axis



(a)



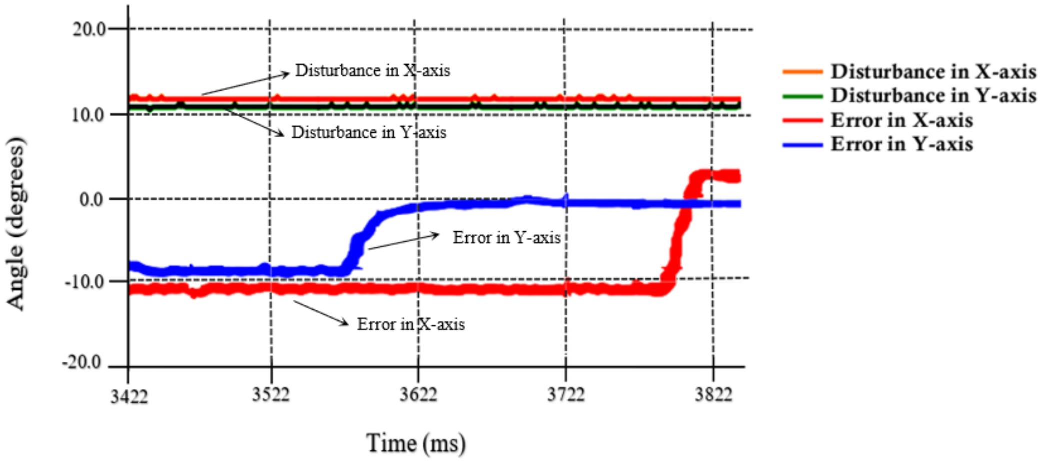
(b)

Figure 12. Self-balancing of the (platform on the mobile car) structure (a) under tilt angle (10° on the positive X-axis and -10° on the negative Y-axis) and (b) under tilt angle (-10° on the negative X-axis and 10° on the positive Y-axis)

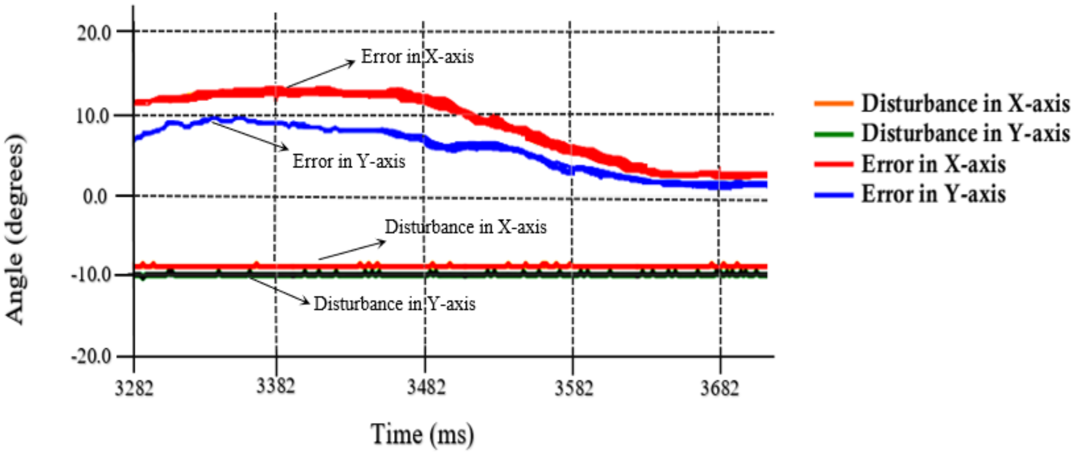
3.4. Case Four: Self-balancing attitude in the physical prototype under the influence of road disturbances scenario in the biaxial (similar tilt angles in X-axis and Y-axis)

The platform's self-balancing behavior as a result of the platform being subjected to biaxial disturbances is shown in Figures 13(a) and 13(b), respectively. Biaxial disturbances are (tilt angle 10° on

+X-axis and 10° on the +Y-axis) and (tilt angle -10° on the -X-axis and -10° on -Y-axis). The realistic self-balancing of a platform under tilt angle (10° on the +X-axis and 10° on the +Y-axis) is shown in Figure 14(a). Moreover, the realistic self-balancing of a platform under tilt angle (-10° on -X-axis and -10° on -Y-axis) is shown in Figure 14(b).



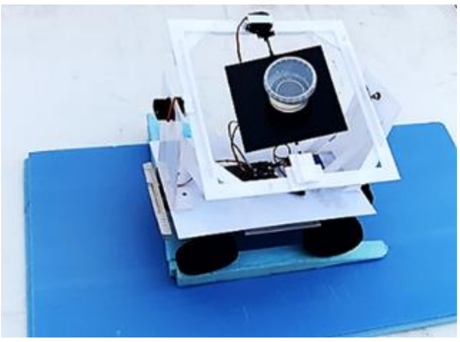
(a)



(b)

Figure 13. Self-balancing behavior the physical prototype (a) under tilt angle 10° on the positive X-axis and 10° on the positive Y-axis and (b) tilt angle -10° on the negative X-axis and -10° on the negative Y-axis

(a)



(b)

Figure 14. Self-balancing of the (platform on the mobile car) structure (a) under tilt angle 10° on the positive X-axis and 10° on the positive Y-axis) and (b) (tilt angle -10° on the negative X-axis and -10° on the negative Y-axis)

The analysis of the experimental results explained in detail in the previous three cases showed that correct location, exact calibration, and complementary filter were among the factors that helped the inertial measurement unit (IMU) sensor accurately measure the tilt angle (disturbance) that the platform has been exposed on any axis. Furthermore, accurate measurements of the tilt angle contributed to achieving the self-balancing of the platform because the angle calculations that appear in the error curve depend on the correct measurements of the tilt angle. Hence, the angle in the error curve (in all cases) will determine the value and direction of the angle that the servo motor would rotate the respective plate to balance and overcome the tilt angle(disturbance).

Experimental results indicated to firstly, in all cases of disturbance scenarios that were exposed to the physical model of the platform, the platform was able to compensate for the angle that it was exposed to (whether in the X-axis or Y-axis or both axis (biaxial) and setting error to zero in a time not exceeding 4 seconds. Secondly, the platform system during self-balancing remained stable with negligible vibrations and overshoot because vibrations and overshoot were eliminated by fine-tuning the PID controllers' coefficients. Thirdly, the servo motors produced torque that enough to rotate the respective plate (middle plate, or top plate, or both plates at the same time) and carrying weight in the middle of the top plate during balance the tilt angles in (X-axis, or Y-axis, or biaxial). Optimized PID Controllers' parameters values that gave the best response in terms of maximum peak overshoot and response time are shown in Table 2. Also, experimental data has been exported from Arduino to MATLAB to get key values, as shown in Table 3.

Table 2. Optimized PID controllers' parameters of physical prototype

	Roll angle	Pitch angle
P	150	100
I	230	184
D	1	1

Table 3. Key values of experimental results

Rise time	645 ms
Overshoot	16% when tilted in one axis, 18% when tilted in two axes
Settling time	889 ms
Steady state error	0.57° to 1.8°

4. CONCLUSION

Most self-balancing platforms use a design that addresses and balances in case the (disturbance or tilt) in each axis singly. Also, most self-balancing platforms depend on deriving a complicated system of mathematical differential equations to find the relationship between the motor's rotation angle and the platform's tilt angle. Therefore, the primary aim of this work is to design, model, and control a self-balancing platform on the mobile car as a physical design that achieves self–balancing in (X-axis, Y-axis, or both axis (biaxial)) under the influence of road disturbances without the need to derive a complex system of mathematical differential equations.

In this work, the proposed platform is based on the parallel manipulator concept and designed as three plates (base, middle and top) on a mobile car. One of the plates is for the pitch motion (top), the second for the roll motion (middle), and the third (base) as a robust outer plate to keep the first two plates in place. Additionally, two plates on each side (right and left) have been added to attach the base plate with a middle plate. The proposed platform is controlled using the proportional-integral-derivative (PID) controller to maintain the platform balance and compensate for road disturbances (tilt angle). Several road disturbances scenarios were designed in the X-axis, Y-axis, or both axis (biaxial) to examine the effectiveness of the PID controllers to compensate for any road disturbances (tilt angle). The experimental results showed the platform's physical design compensates for any road disturbances (tilt angle) in the X-axis, Y-axis, or both axis (biaxial) during the platform carrying a load (175 g) less than 4 seconds. Finally, it was concluded that a proposed self-balancing platform on a mobile car has high accuracy in self-balancing and meets operational requirements despite the platform's simple design.

Future work includes changing the disturbance profile of (X-axis, Y-axis, or biaxial) into diverse values of tilt angles (between each angle and another a period of time) on the positive and negative side of the axis. It is also possible to add new elements to the platform's dynamic modelling design to study the self-balancing performance in six DOF. Finally, developing a system to control the movement of a mobile car so that it can control its movement, for example, by drones to remote, winding areas for transport materials or liquids and others.

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BIOGRAPHIES OF AUTHORS

Bushra Amer Tawfeeq was born in Baghdad in 1988. She graduated from the Mechatronics engineering department at the University of Mosul, Iraq, in 2010. From 2011-2019, she has been with the computer technology engineering department in Al-Bani university college, Baghdad, Iraq, where she is acting as a laboratory head. She has received the M.Sc. degree in Mechatronics engineering from Baghdad University, Iraq, in 2022. Her research interests include embedded systems, modeling, control, and robotics. She can be contacted at email: bushra.a.tawfeeq@gmail.com.

Maher Yahya Salloom was born 1962. He has a BSc. in Mechanical Engineering 1984 from the University of Baghdad, and a MSc. in Applied mechanics 1999 from the University of Baghdad. Ph.D. in Applied Mechanics from University Science Malaysia, (USM) 2011. Currently, he works as an Assist Prof. Dr. in the Department of Mechatronics engineering in University of Baghdad. Maher does research in mechanical engineering, hydraulic and pneumatic control systems, automation systems, robotics, machine design, CAD/CAM systems, advanced manufacturing systems materials engineering, and aerospace engineering. Their current project is 'Hydraulic Control systems (fluid Power). He can be contacted at email: drmahir@kecbu.uobaghdad.edu.iq.

Ahmed Alkamachi received the B.Sc. degree in electrical engineering from Baghdad University, Iraq, in 2000, and the M.Sc. degree in electrical engineering/computer and control division from Baghdad University, Iraq, 2003. He also received a Ph.D. degree in control engineering from Gaziantep University-Turkey. He is currently working as an Assist Prof. Dr. in Mechatronic engineering dept. in Al-Kawarizmi college of engineering in University of Baghdad since2004. His current research interests span robust control, adaptive control, UAV, and robotics. He can be contacted at email: ahmed78@kecbu.uobaghdad.edu.iq.