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2 DOF HORIZONTAL PLATFORM CONTROL WITH MPU6050 AND POLOLU MICRO-MAESTRO

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RESUMEN

Los dispositivos que conocen su propia orientación respecto a la vertical y que toman acciones respecto a este conocimiento, se han vuelto cada vez más comunes, ejemplos de ellos son los drones, dispositivos móviles de una y dos ruedas, smartphones, etc., todos ellos trabajan con el mismo principio fundamental.

En este trabajo se presenta el uso del procesador inercial (IMU) MPU6050, el cual provee señales de sus acelerómetros y giroscopios internos; a estas señales se les aplica el Filtro Kalman para obtener la orientación (ángulos *X*, *Y*) de la base del sistema; los ángulos permiten que el servo-controlador Pololu Micro-Maestro realice la compensación adecuada para mantener la plataforma del sistema orientada permanentemente en forma horizontal, aun cuando la base esté inclinada. Se presenta la terminología, el diseño, las ecuaciones, algo de código y el desempeño del sistema.

Palabras Clave: Equilibrio, Inercial, Kalman, Posición Angular.

ABSTRACT

Devices that know their own orientation with respect to the vertical and take actions regarding this knowledge, have become increasingly common, examples of them are drones, mobile devices with one and two wheels, smartphones, etc., they all work with the same fundamental principle.

This paper presents the use of the MPU6050 inertial processor (IMU), which provides signals from its internal accelerometers and gyroscopes; to these signals the Kalman filter is applied to obtain the orientation (*X*, *Y* angles) of the system's base; the angles allow the Pololu Micro-Maestro servo controller to perform the appropriate compensation to keep the system platform permanently oriented horizontally, even when the base is inclined. Terminology, design, equations, some code and the system's performance is shown.

Keywords: Balance, Inertial, Kalman, Angular Position.

1. INTRODUCTION

As technology advances, more and more advanced characteristics are required in all types of equipment. One of these characteristics is the ability of the device to know its own orientation with respect to vertical. Nowadays it is very common to find orientation stabilization systems in different electronic devices like: drones, vehicles with one and two wheels, smartphone and many others; all of them are handled under the same principle.

One of the areas that have been greatly benefited by the use of inertial sensors is photography. The first image stabilizers appeared in the early 60s, these systems were able to slightly compensate for the vibration of the camera and the involuntary movements. They were based on gyroscope-controlled mechanisms, which could cancel unwanted movements by changing the position of a lens or a group of them. Another field benefited is the one related to aerial navigation with drones, which are equipped with inertial sensors that allow autonomous actions to correct disturbances of the positions and angular velocities [1]. In the field of rockets launching, the inertial processors are used to determine the exertions to which the rockets are subjected, with this information the materials and fuels more suitable for the design of the rocket are determined [2]. The use of inertial sensors in medical applications is a booming field due to the advantages that this type of sensors presents. Due to the nature of the sensors, most of medicine applications involve motion measurement in tasks such as rehabilitation and diagnosis among others [3]. Specifically, in the problem of balancing a platform, some systems resort to putting cameras for the identification of the element on a surface (commonly a ball), and thus be able to make the appropriate adjustments using the vision system to stabilize the surface. In the project Ball-on-plate a control of balance system was designed and implemented using a system of vision controlling a platform, in this study the variables of input and output were presented, as well as the disturbances [4] [5]. This article replaces the camera with an inertial sensor, which is easier to use than the vision system. This paper presents the design of a prototype that provides two degree of freedom (2 DOF) independent position control, of a platform that remains in a horizontal position, even if the system's base changes its orientation. This potentially allows for a large variety of applications.

2. PLATAFORM DESCRIPTION

Figure 1 shows picture and block diagrams of the constructed prototype; there, the functional elements of the equilibrium platform can be seen; highlights, the developed Arduino-IMU-Pololu-Servo closed loop. The platform must remain horizontal even with changes in the orientation of its base, due to movements that presented impair of its position of equilibrium.

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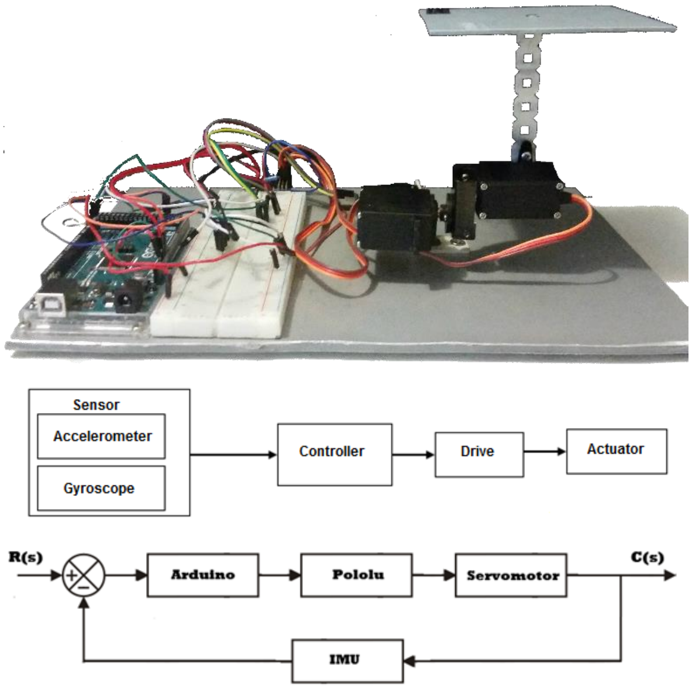

Figure 1. Platform prototype.

The prototype consists of a position control system of two degrees of freedom, which is composed of two servomotors that are coupled in such a way that one can move on the *X*-axis and the other on the *Y*-axis; servomotors are controlled by the Micro-Maestro, a second-generation USB servo-driver, the smallest of Pololu, which governs by pulses every servomotor to move the angle that reads the inertial sensor MPU6050; this sensor is responsible for obtaining the orientation angles of the base, both on the *X*-axis and on the *Y*-axis; the communication of the driver Pololu and the sensor was made by Arduino, which is the brain used in the entire system. In Figure 2, the connections necessary for the platform to work are shown.

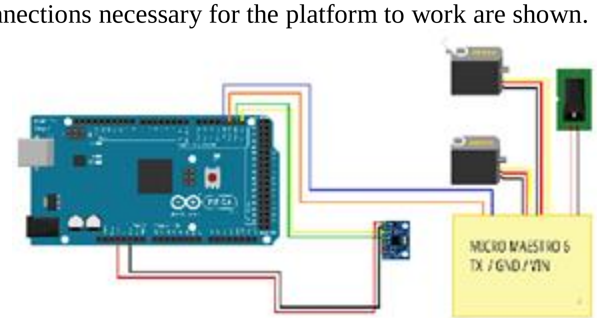

Figure 2. Plant connections.

2.1 MPU6050 Sensor

One of the most important parts in the design of the prototype is the proper selection of sensors and actuators. The selection of these components inevitably imposes restrictions on the performance that the platform can achieve.

In the choice of the actuators it was relevant to maintain a compromise between the speed of the motor and the torque that it can give. Sufficient speed must be ensured to react to system disturbances. In the same way the actuators must give sufficient torque to hold and mobilize the body of the platform. Due to the above, two servomotors model MG995 were selected. These motors work with a voltage of (4.8 V to 7.2 V). They have an operation speed of 0.16 S/60º (6V). The maximum torque provided is 15 Kgf•cm [6].

The Inertial Measuring Unit (IMU) is an electronic device that allows to measure angular velocity and orientation in its most basic conformation. An IMU is used to obtain angles that describe the position changes on a given surface. To obtain the tilt angle of the system, an IMU is required that contains a three-axis accelerometer and a gyroscope of at least one axis.

Commercial IMU are sold with different types of interfaces (I^2C, SPI), even models can be found that provide only voltage, which requires an analog-digital conversion to process the information obtained [7]. An IMU of the InvenSense brand of six degrees of freedom is selected for this prototype. This IMU is formed by a three-axis accelerometer and a three-axis gyroscope.

The integrated circuit MPU6050 contains an accelerometer and a gyroscope MEMS in a single package of three degrees of freedom each one. It has a 16-bit resolution, which means it divides the dynamic range into 65536 fractions; these apply for each *X*, *Y*, and *Z* axis as with the angular velocity. The sensor is ideal for designing robotic control, vibration measurement, inertial measurement systems (IMU), fall detector, distance and speed sensor, and many other things The MPU6050 contains a gyroscope, an accelerometer, and a temperature sensor; in Table 1, the operation ranges of the IMU sensor are shown. This IMU works under the protocol of serial communication I^2C, it feeds with a voltage of 3.3 Volts and their dimensions are small [8][9][10].

Table 1. IMU operation scale.

Range scale Gyroscope (°/seg).	Gyroscope sensibility	Range scale Acelerometer (g).	Acelerometer sensibility
±250	131	±2	16384
±500	65.5	±4	8192
±1000	32.8	±8	4096
±2000	16.4	±16	2048

2.2 Driver Pololu Micro-Master

To achieve the balance of the system, it is necessary to govern the actuators starting from the signals obtained by the inertial sensor, which will generate an angular reference, which is used to make the angle compensation in the platform actuated by the servomotors.

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The Micro Maestro is a highly versatile servo-controller and contains a general purpose I/O plate in a highly compact package (0.85"×.20"). It supports three control methods: USB for direct connection to a computer, TTL serial for use with integrated systems and, finally, internal scripts for standalone applications without host controller. The channels can be configured as servo outputs for use with radio control servos (RC) or electronic speed controls (ESC), such as digital outputs, or as analog inputs. The servo-pulses are extremely accurate and high-resolution, have a jitter of less than 200 *ns*, which makes these servo-controllers suitable for high performance applications such as robotics and animatronics; the built-in speed and acceleration control for each channel make it easier to achieve fluid and impeccable movements without requiring the control source to constantly calculate and transmit intermediate position updates to the Micro Maestro. Servomotors are elements driven by the Pololu driver by means of pulse width modulation (PWM).
From the outset, two different strategies are posed for control: angular position control or angular velocity control.

3. INCLINATION ANGLES

The first step in estimating the angle of inclination at the base of the platform is to achieve the serial communication with the IMU. The MPU6050 sensor operates under the I^2C communication protocol, it allows to maintain communication with the devices, using only two connections. The routines that allow initializing the IMU are executed with the parameters set out in Section 3.1.

3.1 IMU Calibration

The calibration process of the IMU is to store 100 readings of each axis of the accelerometer in a given time, then calculates its average. At the same time, 100 readings are obtained from one of the gyroscope axes and the average is obtained in the same way. The values obtained at the end of this procedure correspond to the offset of the IMU. The time between each of the readings is 10 *ms*. This procedure is performed only once when the platform is turned on.
It makes use of the three axes of the accelerometer (X, Y, Z) and one of the axes of the gyroscope (X). The angle that is calculated is the one obtained by rotating on the X-axis of the IMU.

3.2 Accelerometer

Taking into account that the only force that acts on the sensor is the force of gravity (9.8 m/s²), then the values obtained in the components of the accelerometer correspond to the gravity and the angles of the resulting will be the inclination of the plane of the sensor (Figure 3) since gravity is always vertical
To understand it better, it is assumed that on the plane X-Z and the MPU6050 tilts a θ angle, this angle is calculated in Equations (1) and (2).

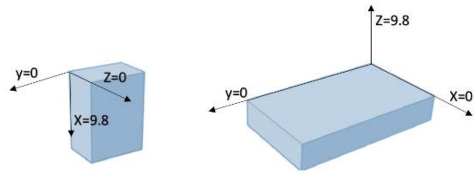

Figura 3. Accelerometer components.

$$AnguloY = \operatorname{atan}\left(\frac{-x}{\sqrt{y^2+z^2}}\right) \quad (1)$$

$$AnguloX = \operatorname{atan}\left(\frac{y}{\sqrt{x^2+z^2}}\right) \quad (2)$$

Where x, y and z are the acceleration´s vector components, which correspond to the movement of the accelerometer in each direction.
$AnguloX$ is the inclination presented by the accelerometer in the x axis.
$AnguloY$ is the inclination presented by the accelerometer in the y axis.

3.3 Gyroscope

The gyroscope delivers an angular velocity with reference to the pivot axis (Figure 4). If the angular velocity is integrated, an angle is obtained; as a consequence the angles of inclination from the angular velocities of each axis can be estimated. See Equations (3) and (4).

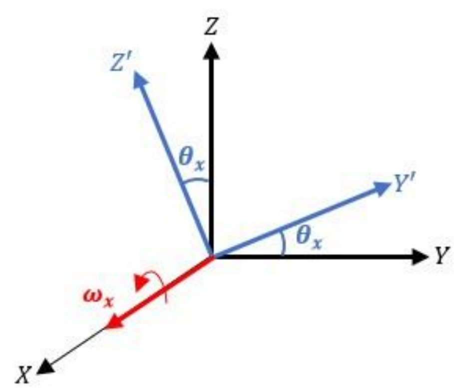

Figure 4. Reference to rotation axis.

$$\theta_x = \theta_{x0} + \omega_x \Delta t \quad (3)$$
$$\theta_y = \theta_{y0} + \omega_y \Delta t \quad (4)$$

Where θ_x is the spin angle of the sensor in the x axis.
ω_x is the angular speed of the sensor spinning in the x axis.
Δt is the period of time.
The same is true for the y axis, equation (4).

3.4 Kalman Filter

A gyroscope provides a stable and noiseless measurement of angular velocity. It is known that if the angular velocity is acknowledged, the position can be identified; this is possible through the integration operation. The problem of making a numerical integration of the value provided by the gyroscope, is that it causes that, as the time progresses, the estimated reading of the gyroscope contains a deviation of the real value, product of the numerical approximation. Similarly, although an accelerometer allows to know directly the angle of inclination, the reading provided is highly noisy and sensitive to imperceptible vibrations that do not allow to obtain a stable reading [10].

Due to the above considerations, a Kalman filter is used to obtain an estimated reading of the tilt angle of the platform in the presence of noise [11].

The Kalman filter is an optimal recursive data processing algorithm, which is based on a system's state space model for estimating future status and future output by making optimal filtering of the output signal [12]. The Kalman filter estimates the states in optimal form so as to minimize the index of the mean quadratic error [13-15].

The Kalman equations only depend on a previous sample and the present sample which allows a considerable saving of memory when being implemented in a digital system and its easy programming makes it very attractive because it is based on a recursive method [16].

The Kalman requires the dynamic system being represented in state-space form, as shown in equations (5) and (6).

$$X_k = A_{k-1}X_{k-1} + B_{k-1}u_{k-1} + w_{k-1} \quad (5)$$
$$Y_k = C_kX_k + v_k \quad (6)$$

Where X_k are the states, Y_k is the system's output, k is the sample. w_k y v_k are white noise signals with Q_k and R_k variance respectively.

P_k is the covariance of error estimator of the system's states, equation (7).

$$P_k = A_kP_{k-1}A_k^T + Q_k \quad (7)$$

The correction equations of Kalman filter can be seen in equations (8)-(10).

$$K_k = P_kC^T(CP_kC^T + R_k)^{-1} \quad (8)$$
$$X_k = X_k + K_k(Y_k - CX_k) \quad (9)$$
$$P_k = (I - K_kC)P_k \quad (10)$$

Where I is the identity matrix, X_k is the last estimated state, K_k is the Kalman gain, P_k is the actualization of the covariance of error.

The Kalman algorithm is conveniently developed in a library for Arduino and it is applied in the following code section.

```
if ((AnguloY < -90 && kalAnguloY > 90) || (AnguloY > 90
&& kalAnguloY < -90)) {
    kalmanY.setAngle(AnguloY);
    compAnguloY = AnguloY;
    kalAnguloY = AnguloY;
    gyroAnguloY = AnguloY;
  } else
    kalAnguloY = kalmanY.getAngle(AnguloY, gyroYrate, dt);
// Calculo del ángulo utilizando filtro Kalman
  if (abs(kalAnguloY) > 90)
    gyroXrate = -gyroXrate; //Velocidad de inversión, por lo
//que se ajusta a la lectura restringida del acelerómetro
  kalAnguloX = kalmanX.getAngle(AnguloX, gyroXrate, dt);
// Calculo del ángulo utilizando filtro Kalman
#endif
```

So, the Kalman library for Arduino is used to carry out the required calculations.

3.5 Matlab Analysis

To study the behavior of control strategies, experiments were conducted using Matlab feeding it with the readings of the accelerometer and the gyroscope. To do this, measurements of the sensor are taken while it is resting, stored in an Excel file and processed with Matlab, saving the measurements as variables in the Workspace.

Graphs of the sensors' measurements at rest in function of time were obtained (Figure 5); there can be appreciated the oscillation that each sensor produce.

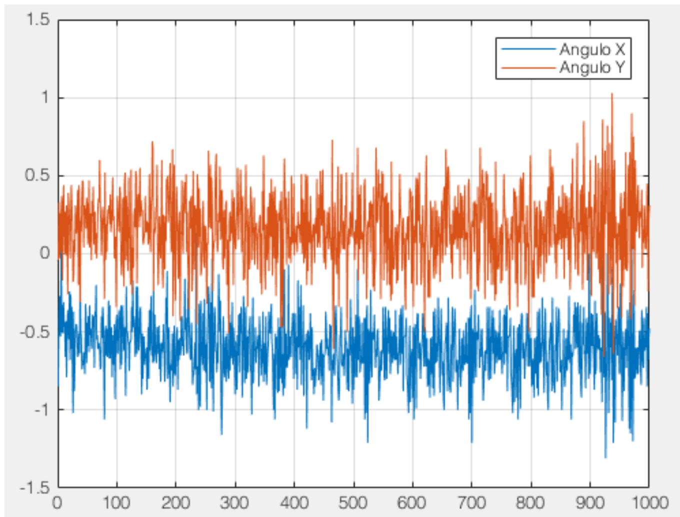

Figure 5. Sensor measurements at rest.

The average and the typical deviation of these samples taken in both sensors are calculated, these are shown in Table 2.

Table 2. Measurements of the Angle X and Angle Y.

	Average	Typical Deviation
Angle X	$\hat{X} = -0.61°$	$\sigma = \pm 0.1994°$
Angle Y	$\hat{X} = 0.17°$	$\sigma = \pm 0.2423°$

To implement the angular position control, the angle obtained from the signal of the accelerometers is required by calculating the arc-tangent; equations (1) and (2), but as they has been analyzed in the preceding paragraphs, the accelerometer is very sensitive to external forces and quite noisy, it is necessary to correct the measurement with the Kalman filter using the gyroscope that also needs to be conditioned, that implies a discrete integration that will cause a deviation of the measurement of the gyroscope angle. The position of the servomotors can be assigned in a closed control loop through the measurement of the angular velocity given by the sensor.

4. SYSTEM EVALUATION

The two degrees of freedom of the system *X* and *Y* are clearly observed in Figure 6, where the two actuators connected are appreciated.

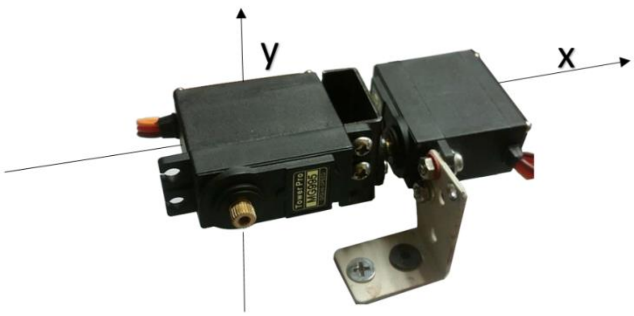

Figure 6. 2 DOF System.

The system was evaluated by moving the base on the two *X* and *Y* axes. The IMU sensor is located at the base of the system and at the moment of moving it on each of its axes, the reaction exerted on each actuator is observed depending on the axis being moved. The servomotors move in sequences that change their position depending on the inclination that the sensor presents.

The system input will be the set angle obtained from the sensor *R(s)* and fed to the servomotors and the output will be the instantaneous angular position of the servomotor *C(s)*, as shown in Figure 7.

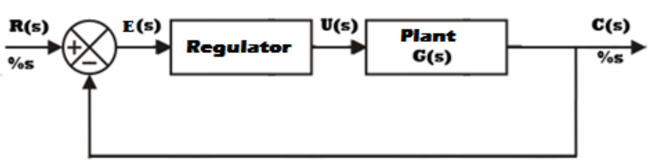

Figure 7. Diagram of System blocks.

With the variables in Matlab, graphs can be obtained to verify that the signal of the sensors perfectly provides the set point for the rotation of the servomotors.

The processing of the signals obtained from the axes (*X* and *Y*) of the inertial sensor (IMU) was filtered by the Kalman filter to generate a smoother and more stable response.

The results obtained are shown in Figures 8 and 9. It can be noted that in both graphs, both the *X* and *Y* (Blue) Angle has an erratic (noisy) nature, which after being corrected by the Kalman filter, the Angle with Filter (Yellow), appears more softened; finally the Position of the Servo, which is instantaneous, appears in Red and is observed to follow the set point in Yellow.

Thus, it is clearly appreciated the change of position that the servomotors present with reference to the inertial sensor (IMU) and with the filtering of the signal, one can see an improvement in the equilibrium of the platform.

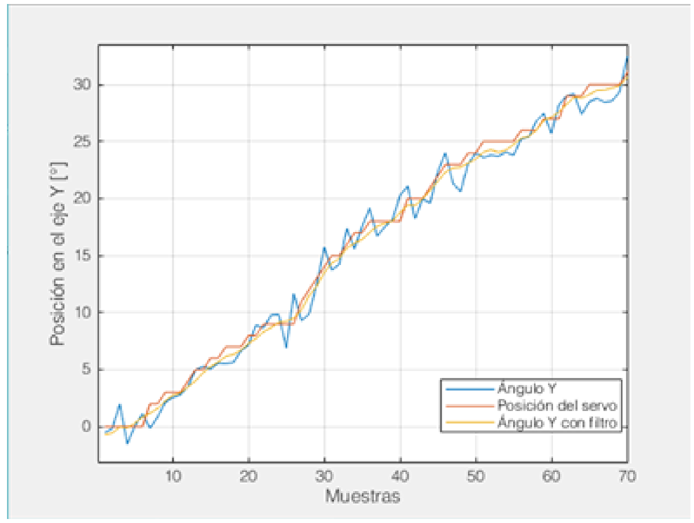

Figure 8. Actuator response in Y-axis.

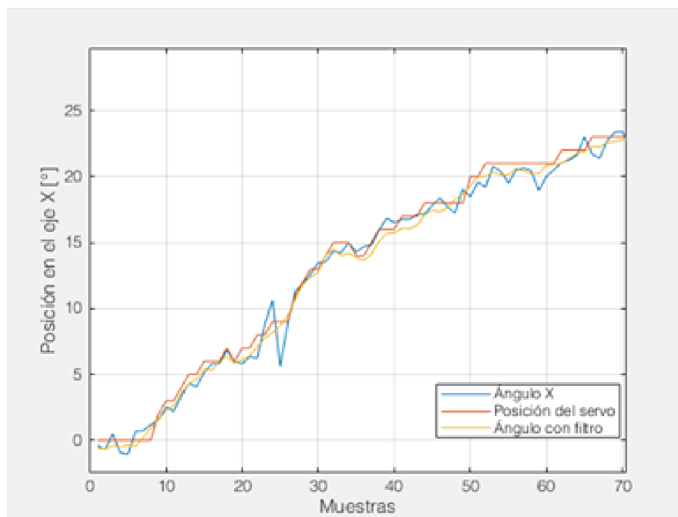

Figure 9. Actuator response in X-axis.

5. CONCLUSIONS

This article described a prototype that performs the position control of a system by means of several processors and their software libraries and the evaluation of the system to observe their behavior in real time. It involved applying the knowledge of the physics of the movement, from the mechanical design, to the programming of the equations involving the variables obtained from the sensors to achieve the control of orientation. Its main contribution lies in the proper integration of the elements of the prototype, both hardware and software to achieve the proper functioning of a low-cost system with a broader variety of applications.

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