Kinematic Modeling for Twin Spherical Balls Robot

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Abstract- — The goal is to build and stabilize a robot balancing on twin balls. The robot consists of six omni wheels in a special configuration standing on twin balls which gives it inverse pendulum dynamics. The robot is stabilized by rotating the wheels which makes it move in the xy-plane. First, the kinematics of omni wheels was investigated by studying different mounting configurations on platforms moving on the ground. The robot was built to verify and visualize the kinematics and special properties of omni wheels. The model is derived from energy equations and using Euler-Lagrange formulation. The energy equations are potential and kinetic energies. The obtained equations relate torque to Twin Spherical Balls Robot parameters.

Index Terms- Six omni wheels, Euler-Lagrange formulation, kinematic modeling, Twin Balls

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I. INTRODUCTION

This Twin Spherical Balls Robot System is the combination of mechanical structure, electrical and electronic components and so called the Mechatronic system. This twin balls balancing robots is tested and examined with a digital control algorithm and a Kalman filter for sensor fusion. The digital control algorithm is so called Proportional-Integral-Derivative controller (PID controller) that is investigated as path of self-balancing robot. The satiability and the performance of the control algorithm will be used on the balancing robot to provide system stability and to keep the stability based on the result of the simulation. Another vital important addition to the digital control system on the robot is the use of the complementary filter. The complementary filter is used as part of this system to provide the sensor fusion between the accelerometer and gyroscope. The digital filter provides the reliable sensor data that will be used by the robot to get the tilt angle information. The control and filter algorithms are all be written in Arduino software and implemented an Arduino board.

This is approximately the dynamics of a robot with three two-dimensional couple system. A goal can only be achieved with a strong focus on control. The aim is able to utilize the full potential of agility, which is a core feature of the robot. The prototype of Twin Spherical Balls Robot has been built with the goal of demonstrating the stable level of agility and capacity of such a driving force system [8]. The stepper-motors used in balancing robot are considered as essential component of all robot system as stepper motors are widely used in robotics and in the numerical control of machine tools to perform high precision positioning operations. Furthermore, this robot is equipped with two sets of accelerometer and gyroscope (MPU-6050) that could accurately measure the robot deflection angle and angular velocity. The complementary filtering method is used to reduce the error noise that get from the sensor fusion [9].

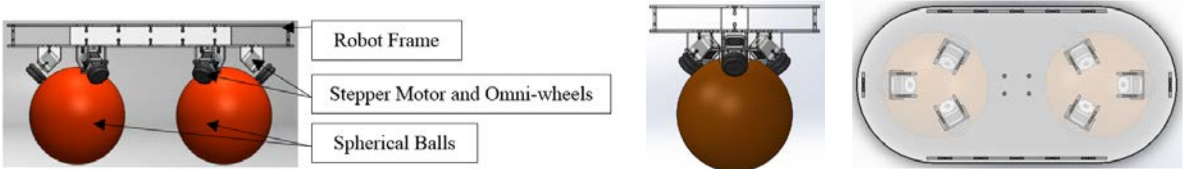
Nowadays, the transport devices in robotics are absolutely emerged and they are restricted to motion in a single direction and various steering constrains [1]. The omni-directional wheels robot was developed as BallIP in 2008 at Tohoku Gakuin University, Japan, to carry loads and is used for cooperative transportation [2][7]. So, the dynamics of wheel mobile robot motion needs to be developed to offer students a general framework for simulation analysis and model based control system design [3][4]. Rezero was developed in 2010, Switzerland [5] and re-emphasized the fast and graceful motions that can be achieved using ballbots [10].

This research (TSBs) robot aims to transport items from place to place on the upper plate of robot. This designed model is tested in real world and driving with six stepper motors in various speeds and this robot is based on the omnidirectional self-balancing or otherwise known as ballbot. It is selected two basketballs which made of rubber and this Twin Spherical Balls (TSBs) Robot system is composed of six omnidirectional wheels, the compliance of the frame connecting the twin-spheres is added to move and is appeared by the new type of balancing robot mechanism.

The robot mechanism is discussed in section 2. In the following section of this research is to obtain a kinematic model of an omni-directional wheeled vehicle based on Euler-Lagrange equation [6]. So, the coordinate system and the spherical wheel kinematic constraint of this robot is described in section 3. After that, wheels speed calculation for balls driving forces is described in section 4. These model is tested by combining PID control method and this experiment results are shown in section 5. The conclusion is described in section 6.

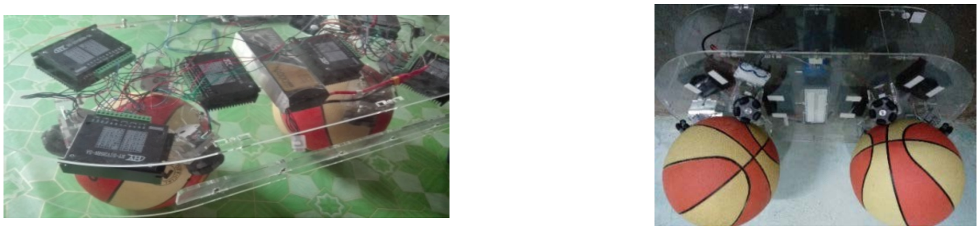
II. DESIGN OF TWIN SPHERICAL BALLS (TSBS) Robot

The new design of balls-wheel omnidirectional mobile (TSBs) robot has the total net weight is 7kg and it contains the net weight of robot frame which made of acrylics plate and the weight of electronics devices, lipo battery 10000 mAh and omniwheels. This arrangement allows the wheel to be always contact with the ball at any given time. The measurements of the robot are 780mm in length, 382mm width and 380mm in height including the ball with the total mass of approximately 7kg. The designated 3D-CAD model of robot is shown in Fig. 1. The fully assembled prototype system of TSBs robot which six stepper motors attached with omnidirectional wheels and all requirement electronics devices for TSBs robot is shown in Fig. 2. The main body of the Twin Spherical Balls Robot (TSBs) consists of a platform that has two stores. The first store includes the circuit board, 10000mAh (14.8V) 4 cells battery, the six devices TB6600 stepper motor drivers those weight are 1.2kg, IMU sensor etc. The IMU sensor is proposed in tracking and controlling the ball movement and it is based on Arduino Uno microcontroller that was used for tilt sensing and controlling respectively. The PID tuning for TSBs Robots is shown in Fig.3.



(a) Front View (b) Side View (c)Top View

Figure.1. Design for TSBs Robot



(a) Normal Condition (b) Reverse Condition

Figure.2. Actual for TSBs Robot with electronic devices

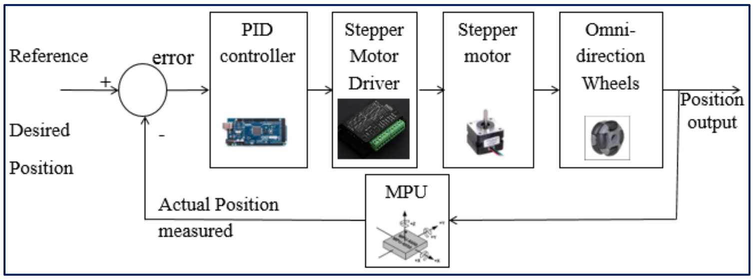


Figure.3. PID control system for TSBs Robot

III. COORDINATE SYSTEM OF KINEMATIC MODEL

In order to describe the position of the robot in its environment, two different coordinate systems (frames) need to be defined.

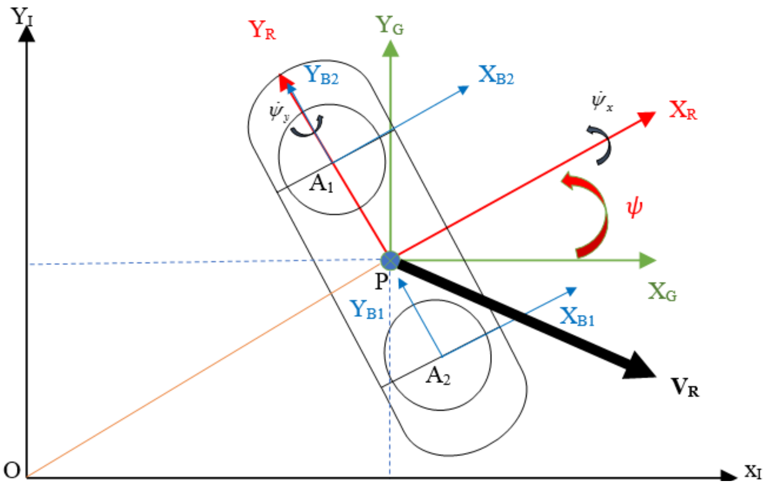


Figure 4. The global reference frame and the robot local reference frame

At first, the inertial coordinate system is considered and the coordinated system is a global frame which is fixed in tee environment or plane in which the TSB moves in. Moreover, this frame is considered as the global reference frame from the same origin and is denoted as $[X_I, Y_I]$. Next, the robot coordinate system is considered to specify the position of the robot the mid-point P on the axis between the balls as it position reference point [6]. This coordinate system is a local frame attached to the TSB and that it moves in this frame denoted as $[X_R, Y_R]$. The two coordinate frames for robot is illustrated in Fig.4. The point is the global reference frame is specified by coordinate X and Y, and the angular difference between the global and local reference is given by the assign of ψ. It can describe the pose of the vector with these three elements. The use of the subscript I to clarify the basis of this pose as the global reference frame as shown in Fig.4The robot position and orientation in the Inertia Frame can be defined as by Eq.(1). Using in the calculation of the dynamics movement of global reference frame and the robot local reference frame parameters is defined in Table l.

Table 1. Required Parameters of Coordinated System

Symbol	Parameter
X_I	Inertia of global frame with respect to the X axis
Y_I	Inertia of global frame with respect to the Y axis
X_{B1}	First Ball of chassis frame with respect to the X axis
Y_{B1}	First Ball of chassis frame with respect to the Y axis
X_{B2}	Second Ball of chassis frame with respect to the X axis
Y_{B2}	Second Ball of chassis frame with respect to the Y axis
X_G	Global reference frame of robot body with respect to the X axis
Y_G	Global reference frame of robot body with respect to the Y axis
A_1	First Ball center's point
A_2	Second Ball center's point
Ψ	Rotation angle of Z axis
$\dot{\psi}_x$	Angular velocity of ψ with respect to X axis
$\dot{\psi}_y$	Angular velocity of ψ with respect to X axis
P	Halfway between the two spherical balls

$$\xi I=\begin{pmatrix} x \\ y \\ \psi \end{pmatrix} \tag{1}$$

To describe the robot motion in terms of component motions, it will be necessary to map motion along the axes of the global reference frame of motion along the axis of the robot's local reference frame. Of course, the mapping is a function of the current pose of the robot. This mapping is accomplished using the orthogonal rotation and inverse orthogonal rotation matrixes are described by Eq.(2). and Eq.(3).

$$R(\psi)=\begin{bmatrix}\cos\psi & \sin\psi & 0\\ -\sin\psi & \cos\psi & 0\\ 1 & 1 & 0\end{bmatrix} \qquad (2)$$

$$R(\psi)^{-1}=\begin{bmatrix}\cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 1 & 1 & 0\end{bmatrix} \qquad (3)$$

The matrix can be used to motion in the global reference frame [X_I, Y_I] to motion in terms of the local reference frame [X_R, Y_R]. The operation is denoted by $\psi\left(\dot{\xi}I\right)$ because the computation of this operation depends on the value of ψ. Given some velocity $\left(\dot{x}\ \psi\dot{y}\ \right)$ in the global reference frame and it can compute the components of motion along this robot's local axis X_R and Y_R.

Firstly, the contribution of each wheels spinning speed to the translation speed at P in the direction of $+X_R$ is considered. If one wheel spins while the other wheel controbutes notion and is stationary, since P is halfway between the two wheels, then it will move instantaneously with the half the speed: $\dot{X}_{B1}\omega=\frac{1}{2}r\cos\dot{\psi}_{B}{}_{B1}$ and $\dot{X}_{B2}\omega=\frac{1}{2}r\cos\dot{\psi}_{B}{}_{B2}$. Second, there is lateral motion. The contribution of each wheels spinning speed to the translation speed at P in the direction of $+Y_R$ is considered. If one wheel spins while the other wheel controbutes notion and is stationary, since P is halfway between the two wheels, then it will move instantaneously with the half the speed: $\dot{Y}_{B1}\omega=\frac{1}{2}r\sin\dot{\psi}_{B}{}_{B1}$ and $\dot{Y}_{B2}\omega=\frac{1}{2}r\sin\dot{\psi}_{B}{}_{B2}$. Third, the rotational component $\dot{\psi}_R$ of $\dot{\xi}_R$ must be computed. The relation velocity $\dot{\psi}_{B1}$ at P can be computed because the wheel is instantaneously moving along the arc of a circle of radius 2l: $\dot{\psi}_{B1}=\frac{r\omega_{B}\ B1}{2l}$. The same calculation applies to the left wheel, with the exception that forward spin results in clockwise rotation at point P: $\dot{\psi}_{B2}=\frac{r\omega_{B}\ B2}{2l}$. In this case, due to specific angle of the robot, motion along X_R equal to $\dot{y}$ and motion along Y_R equal to $-\dot{x}$.

$$\dot{\xi}I=\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\psi}\end{bmatrix}=R(\psi)^{-1}=\xi I \qquad (4)$$

$$\dot{\xi}I=R(\psi)^{-1}\begin{bmatrix}\left(\frac{r\omega_{B}\dot{}_{B1}}{2}+\frac{r\ \omega_{B}\dot{}_{B2}}{\underset{\psi}{2}}\right)\cos\\ \left(\frac{r\omega_{B}\dot{}_{B1}}{2}+\frac{r\ \omega_{B}\dot{}_{B2}}{2}\right)\sin\psi\\ \frac{r\omega_{B}\dot{}_{B1}}{2l}-\frac{r\ \omega_{B}\dot{}_{B1}}{2l}\end{bmatrix} \qquad (5)$$

$$\dot{\xi}_I=R(\psi)^{-1}\begin{bmatrix}\cos\psi & 0 & 0\\ 0 & \sin\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\left(\frac{r_B\dot{\omega}_{B1}}{2}+\frac{r_B\dot{\omega}_{B2}}{2}\right)\cos\psi\\ \left(\frac{r_B\dot{\omega}_{B1}}{2}+\frac{r_B\dot{\omega}_{B2}}{2}\right)\sin\psi\\ \frac{r_B\dot{\omega}_{B1}}{2l}-\frac{r_B\dot{\omega}_{B1}}{2l}\end{bmatrix} \quad (6)$$

$$\dot{\xi}_I=R(\psi)^{-1}\begin{bmatrix}\cos\psi & 0 & 0\\ 0 & \sin\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\left(\dot{\omega}_{B1}+\dot{\omega}_{B2}\right)\cos\psi\\ \left(\dot{\omega}_{B1}+\dot{\omega}_{B2}\right)\sin\psi\\ \frac{r_B\dot{\omega}_{B1}}{2l}-\frac{r_B\dot{\omega}_{B1}}{2l}\end{bmatrix}\frac{r_B}{2} \quad (7)$$

$$\dot{\xi}_I=\frac{r_B}{2}R(\psi)^{-1}\begin{bmatrix}\cos\psi & 0 & 0\\ 0 & \sin\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 1\\ 1 & 1\\ \frac{1}{l} & \frac{-1}{l}\end{bmatrix}\begin{bmatrix}\dot{\omega}_{B1}\\ \dot{\omega}_{B2}\end{bmatrix} \quad (8)$$

$$\dot{\xi}_I=\frac{r_B}{2}R(\psi)^{-1}\begin{bmatrix}\cos\psi & 0 & 0\\ 0 & \sin\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 1\\ 1 & 1\\ \frac{1}{l} & \frac{-1}{l}\end{bmatrix}\begin{bmatrix}\dot{\omega}_{B1}\\ \dot{\omega}_{B2}\end{bmatrix} \quad (9)$$

$$\dot{\xi}_I=\frac{r_B}{2}R(\psi)^{-1}\begin{bmatrix}\cos\psi & 0 & 0\\ 0 & \sin\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\cos\psi & \cos\psi\\ \sin\psi & \sin\psi\\ \frac{1}{l} & \frac{-1}{l}\end{bmatrix}\begin{bmatrix}\dot{\omega}_{B1}\\ \dot{\omega}_{B2}\end{bmatrix} \quad (10)$$

$$\dot{\xi}_R=V_R=\begin{bmatrix}\dot{x}_I & \dot{y}_I & \dot{\psi}_I\end{bmatrix}^T=R(\psi)\dot{\xi}_I \quad (11)$$

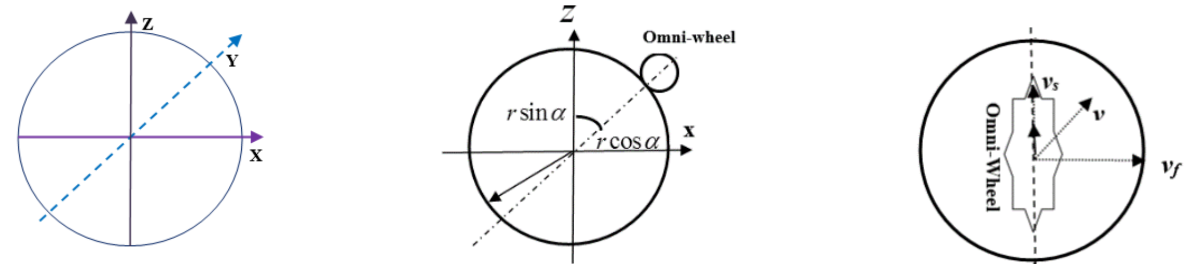
$$\dot{\omega}_{B1}=\begin{bmatrix}\dot{\omega}_1 & \dot{\omega}_2 & \dot{\omega}_3\end{bmatrix}^T \quad (12)$$

$$\dot{\omega}_{B2}=\begin{bmatrix}\dot{\omega}_4 & \dot{\omega}_5 & \dot{\omega}_6\end{bmatrix}^T \quad (13)$$

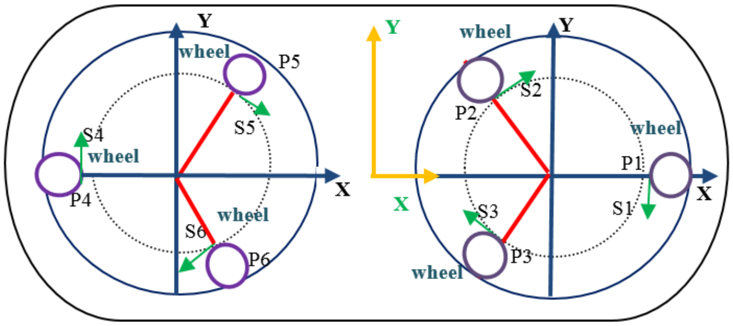
The robot velocity in global coordinates is defined as the Eq.11. The angular velocity of the omniwheels and peripheral velocities of the first ball's wheels and second all's wheels are defined as Eq. 12 and Eq.13, and they are assigned as $\dot{\omega}_{B1}$ and $\dot{\omega}_{B2}$

IV. WHEEL SPEED CALCULATION FOR BALLS DRIVING FORCES

The robot body consisted of an electronics circuit including sensor and ball drive with six stepping motor and the omnidirectional wheels.



(a) Local area axis (b) Balls and wheel from side (c) Relative velocity between Ball and wheel



(d) Balls and wheels from top

Figure. 5. Defined Axis and relationship of balls and omnidirectional wheels

The local coordinate frame with its origin each ball center is shown in Fig.5(a). Robot axis are fixed on the robot body. The z axis is along the vertical line passing through the ball center and the robot center of mass, and the x and y axes perpendicular of the z axis. The wheel speed is getting the balls angular velocity ω is derived by the contact point between the omni-wheel i and the balls be P_i and whose position vector is P_1, P_2, P_3, P_4, P_5 and P_6. The orientation S_i , zenith angle α and velocity v_i at position P_i corresponding to each ball's angular velocity ω is obtained at following Eq.12 and Eq.13. This is independent of the number of wheel for more stable support multiple ball contact with three omni-wheels for each ball. This wheels arranged on each ball are shown in Fig.5(d).

V. EXPERIMENTAL RESULTS

Kalman and complementary filters are used comparatively to get the required data from MPU 6050 sensor. The sensor gives gyro and accelerometer data. In this journal, the acceleration is considered as feedback to the controller. Therefore, accelerations of X and Y axes are calculated. Although Kalman filter is good at estimating future state, the complementary is better for this work as shown in Fig.7 and Fig.5.8. The experimental results for balancing for robot are shown in Fig.8. and Fig.9. In real-time, the robot can't move on the balls because the steppers can't drive the balls. Therefore, the testings in real-time are conducted with making the inclinations of the robot frame without moving the robot on the balls, and collecting the speeds and directions of the six steppers controlling via two PID controllers for X and Y data from MPU 6050 sensor. The following results are obtained from real time system data. The body angle (XY plane) was varied manually and the speed values generated by the controller are recorded. These results are then plotted as shown in Fig.8 and Fig.9.

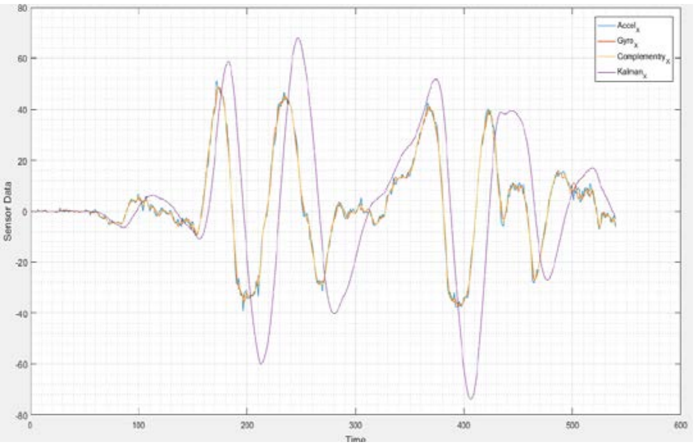


Figure 6. Kalman vs. Complementary Filters for X Axis

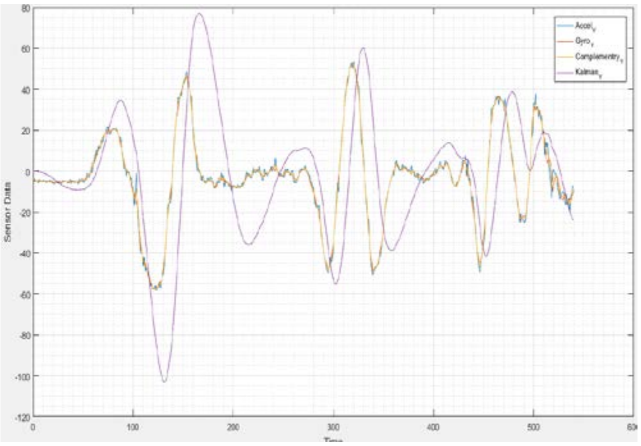


Figure 7. Kalman vs. Complementary Filters for Y Axis

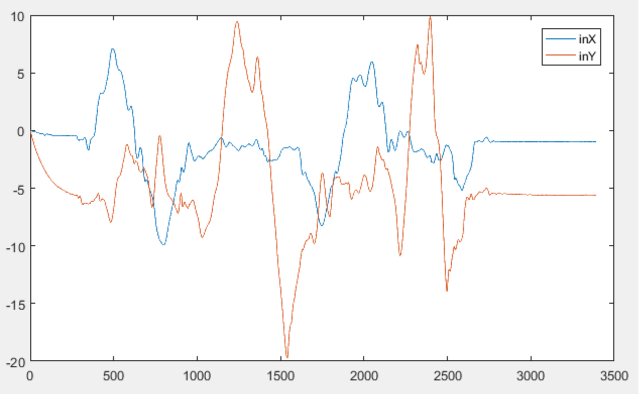


Figure 8. Filtered Sensor Data for X and Y Axes

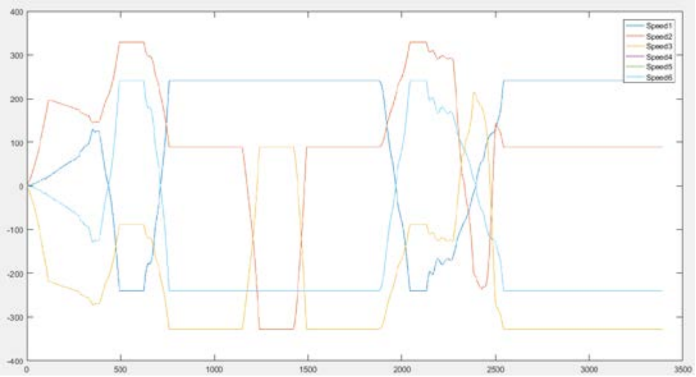


Figure 9. Speeds of Six Steppers for X and Y Axes

VI. CONCLUSION

This is the designating of the kinematic model for TSBs Robot, so required a planar mathematical model was derived using Euler-Lagrange formulation. For balancing the TSBs Robot using PID controller with combination feedback of MPU 6050 sensor. A balancing controller was designed to stabilize the double spherical wheeled dynamically stable mobile robot. The ballbot represents a new class of wheeled mobile robots capable of agile, omni-directional motion. Although the controller is talking precise corrective actions, it was observed that the system stabilizes about a plane with assistance, but fails to stabilize without assistance. The solution would be to use a set of six motor drivers with current control for both (1/8) micro-stepping as well as specific torque control.

FURTHER EXTENSION

For the further extension of the two wheeled balancing robots. Adding encoders to the robot to allow it to measure and control its speed is needed because it will prevent the falling over with maximum speed. There is need to designation to control algorithm for robot with model predictive control (MPC) or linear quadratic control (LQR) to get smart the robot balancing in time of operation. By using the brushless DC geared motors to get better torques instead of steppers.

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