# Simulation of the Dynamic Model of a 3-Axis Stabilized Satellite

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***Abstract*— In this study, the rotations around all three axes are performed practically by designing a small prototype for the (3-Axis Stabilized Satellite). The prototype shown in this research placed in space by using suitable mechanism. The panels is neglected for the design to be lighter in weight and offer more space for the designed prototype to rotate around the three axes (Pitch, Yaw and Roll). Instead of solar power, Dc power supply is used. The actuators are DC geared motor with a jack that slides in and out. The length of the jack rod is modified to adequate the design and for the roll axis the rod is removed. The computer and a (DASYLab Application Software) are used with (DAQpersonal3001) hardware to drive the motors. The motors that have high current rating interfaced with the (DAQpersonal3001) hardware using interface circuits that comprises Transistors and relays as main components. The interface circuit separates the low command signal generated from the (DAQpersonal3001) to the base of the transistors and the power that operates the actuators of the design. The linear type potentiometer used as an angle sensors to measure the degree of rotation around the three axes. Several maneuvers performed to test the system and several relations drawn between the angle in degrees and the time spent for each rotation. The results in average show that the relation between the angle and time spent for each rotation in this study is linear relation.**

***Keywords-component; formatting; style; styling; insert (key words)***

## I. INTRODUCTION

An important problem of the artificial Satellites technology is the precise control of the Satellites orientation in a known reference frame. The Satellite attitude is referenced to Earth-Fixed reference frame in order to obtain angle data from angular velocity in a body fixed frames. The attitude controller of the Satellite must have the ability to correct the attitude of Satellite if the attitude gets errors due to the external forces acting on the Satellite. Then the Satellite needs an attitude determination control system ADCS. This attitude control system has the ability to determine the current attitude, error attitude and finally the correction of Satellite attitude. The attitude can be determined by sensors such as sun sensor, and it can be controlled by actuators such as thrusters [1, 2].

The most general motion of a rigid body with a fixed point is a rotation about a fixed axis. Angle (θ) is rotation angle around the (X-axis). The rotation around Y axis, is a rotation angle ($\phi$) which is the ($y_{o)}$ axis and lastly the rotation around ($Z_o$) axis and it is denoted by ($\psi$), Euler's angle transformation can be presented by using (Roll, Pitch, and Yaw) angles. These angles help to determine the attitude of the Satellite relative to the Orbit frame. The Pitch angle $(\theta)$ is a rotation around X axis, the Yaw angle $(\phi)$ is a rotation angle around $Y_o$-axis, and the Roll angle is a rotation angle ($\psi$) about the ($Z_o$-axis). The main problem with Euler angles is the existence of singularities. If the rotations are written in terms of rotation matrices, the general rotation matrix will be:

$$R = R_1(\theta).R_2(\phi).R_3(\psi) \tag{1}$$

In which:
(R) Is a general rotation matrix.
($R_1$) is the rotation matrix around X axis with angle of rotation ($\theta$) Pitch.
($R_{2)}$ is the rotation matrix around Y axis with angle of rotation ($\phi$) Yaw.
($R_3$) is the rotation matrix around Z axis with angle of rotation ($\psi$) Roll. It's clear from **Figure (1)** the (X, Y, and Z) coordinates is before rotation. But after rotation by an angle ($\theta$) the new coordinates are ($\overline{X},\overline{Y},\overline{Z}$). It is clear that after rotation (x= $\bar{x}$). By using the rules used in coordinate transformation section the following equations can be written.

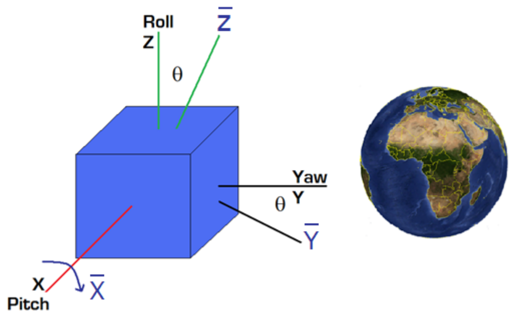

Figure (1): Rotation of Satellite about the Pitch axis by an $\theta$

The general rotation matrix can be written as follows:

$$R(\theta,\phi,\psi)=\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (2)$$

In which:

$A_{11}= Cos(\theta o Cos(\psi o$

$A_{12}= Cos(\theta)\, Sin(\psi)$

$A_{13}= -Sin(\theta)$

$A_{21}= -Cos(\phi)\, Sin(\psi)+Sin(\phi)\, Sin(\theta)\, Cos(\psi)$

$A_{22}= Cos(\phi)\, Cos(\psi)+Sin(\phi)\, Sin(\theta)\, Sin(\psi)$

$A_{23}= Sin(\phi)\, Cos(\theta)$

$A_{31}= Sin(\phi)\, Sin(\psi)+Cos(\phi)\, Sin(\theta)\, Cos(\psi)$

$A_{32}= -Sin(\phi)\, Cos(\psi)+Cos(\phi)\, Sin(\theta)\, Sin(\psi)$

$A_{33}= Cos(\phi)\, Cos(\theta)$

With known coordinates (x, y, and z) new coordinates after rotation ( $\bar{X},\bar{Y},\bar{Z}$ ) can be found by multiplying the known coordinate with the general rotation matrix [3].

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R(\phi,\theta,\psi).\begin{bmatrix} \bar{X} \\ \bar{Y} \\ \bar{Z} \end{bmatrix} \quad (3)$$

The only important thing here is the rotation sequence not the name of angles, because the rotation matrix changes when the rotation sequence is changed. According to reference [13], one can formulate another 6- direction cosine matrix of another type such as (313, 212, 131, 232, 121, and 323). In order to simplify the expression of the rotation matrix it's simpler to express it in this form:

$$R=\begin{bmatrix} r_{xx} & r_{xy} & r_{xz} \\ r_{yx} & r_{yy} & r_{yz} \\ r_{zx} & r_{zy} & r_{zz} \end{bmatrix} \quad (4)$$

By full direction cosine matrix, Euler angles can be found from the last row and the first column of the matrix:

$$\theta=-\arcsin(\, r_{zx}\,) \quad (5)$$

$$\phi=a\tan 2(r_{zy},r_{zz}) \quad (6)$$

$$\psi=a\tan 2(r_{yx},r_{xx}) \quad (7)$$

The above three angles are called Euler angles (Yaw, Pitch, Roll). Which is represents the rotations of a Satellite in three dimensional coordinates. When using Euler's angles to simulate ADAC systems, singularities are often arise in the trigonometry. To bypass these singularities, the ADAC Model uses quaternion notation instead of Euler angles for the analysis [3, 4,5,6,1, 7, 8, 9 and10].

## II. ATTITUDE DETERMINATION AND CONTROL HARDWARE

Attitude determination and control subsystem (ADCS) plays an important role in the design steps of a Satellite. The data taken from the sensors of the Satellite helps to determine the location of the Satellite. Figure (2) shows block diagram for an attitude control system (ACS). It's clear that Satellite attitude is affected by two types disturbance torques, first external torques such as (Aerodynamics, Magnetic, Gravity gradient, solar radiation, thrust misalignment) and second is internal torque such as (mechanisms, fuel movement, astronaut movement, flexible appendages, general mass movement[9].

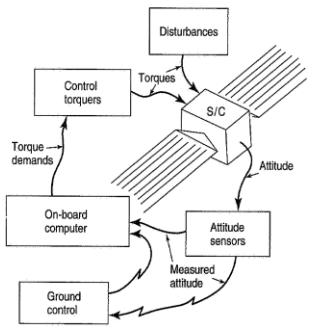


Figure (2) : Block diagram for an attitude control system

Attitude sensors senses the disturbance torques and collects data then passes it to onboard computer and ground control. The processed information will be used to determine the torques that should be applied to the Satellite [2, 9, and15].

## III. SIMULATION OF A 3-AXIS DYNAMIC MODEL

To simulate the dynamic model of a 3-axis stabilized Satellite practically, a prototype is designed. The electrical part consists of (actuators, sensors and drives). The drive or insulation circuit is for the DC permanent magnet motor that controls the direction of rotation and receives the control signals from the computer which represents the ground control of the Satellite. The (DASYLab) and (DAQpersonal3001) Hardware used to complete the control system. [16, 17].One of the goals of this work is to use a linear potentiometer as an angle sensor for the designed dynamic simulation of the (3-Axis Stabilized Satellite). The plot of the relation of the voltage output and the wiper position is shown in Figure (3).

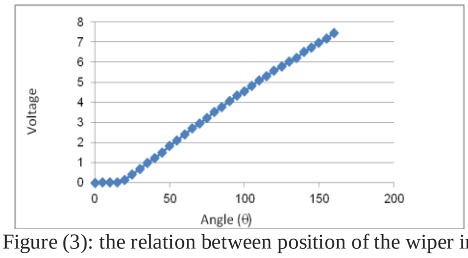


Figure (3): the relation between position of the wiper in angle and the output voltage.

Clearly, the relation is not linear for the first four records of the wiper position. It means that voltage output is too small, and the voltmeter device reads very little voltage value (near to zero). But for the rest recordings, the relation is linear. To control one of the motors that is responsible to rotate the designed prototype using (DASYLab) and (DAQ personal3001) Data acquisition hardware. Taking into account that the motor is DC permanent magnet motor and its rating is (12 VDC up to 36 VDC). It is like the motors used to rotate the dish of DVB'S receivers. So that the high rating power must be separated from the low rating power, and for this reason interface circuits were connected to operate the motors that act as an actuator. Figure (4) shows the direction of current flow in forward rotation.

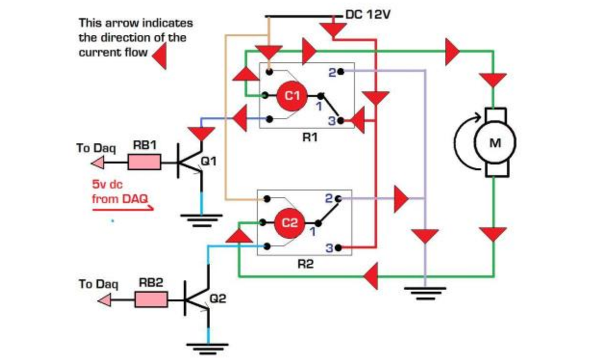


Figure (4): Forward rotation of the PMDC motor, the red arrow indicates the direction of current flow in the circuit.

In the same way when there is no control signal going from DAQpersonal3001 to the base of transistor Q1, and a 5v control signal is applied to the base of transistor Q2 the coil of R2 will energize, later the position of the switch of R2 will change from NC to NO, and current will flow in reverse direction and makes the motor rotate in reverse direction. Figure (5) shows the process of reverse direction.

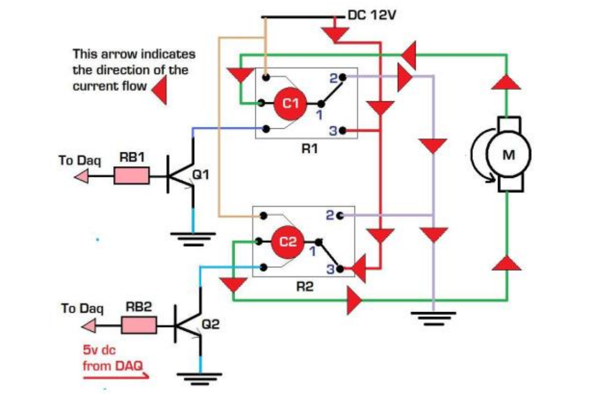


Figure (5): Reverse rotation of the PMDC motor, the red arrow shows the direction of current flow in the circuit.

Figure (6) circuit diagram is used in this work to control three motors that rotate the simulated 3-axis stabilized Satellite prototype in three dimensionally:

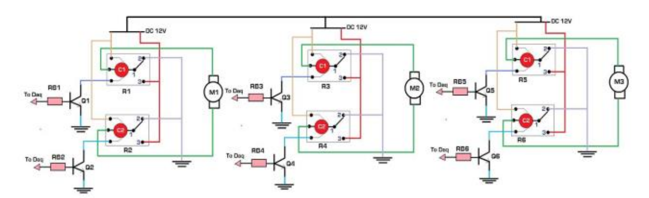

Figure (6): bidirectional control of three PMDC motors.

Figure (7) shown the mechanical part of this study is designed to have 3 dimensions of rotation (Pitch, Yaw and Roll). As like the 3-axis stabilized satellites, the simulated prototype is box shaped and the body of the box is made of aluminum to be light in weight.


Figure (7): Three Axis-Stabilized Satellite prototype.

The mechanical design simulates the (3 Axis stabilized Satellite) in the space. the system has 3 Degrees of rotation (X, Y, Z), also called (Pitch, Yaw, Roll) the axis is marked with number (1) in Figure (3.24) gives the rotation around the X (Pitch) axis, the axis that is marked with (2) and (3) give the rotation around the Y (Yaw) and Z (Roll) respectively.

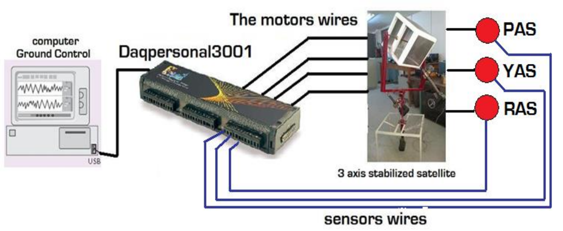


Figure (8) the connection between the computers, DAQpersonal3001and three axis stabilized Satellite.

The sensors in Figure (8) denoted by (PAS, YAS and RAS).This simulated 3-axis Satellite is responsible for showing how the Satellite rotates in the space and can be controlled according to the desired angle of rotation, this project has been done using DASYLab and DAQpersonal3001.

The controller has the ability to run the motors if the software is completed with the DASYLab, the sensors wiper element must be connected to the axis of rotation, for the three rotations about X, Y and Z three angle sensors needed. These angle sensors will measure the rotation angle of the designed 3 axis while rotating, mechanically Satellite is made from aluminum to be Lightweight and in addition the supporting parts are made from iron to be strong and withstand all types of forces. Two of motors use this technique (Pitch and Yaw Motors) but for the Roll rotation the linear motion removed and the axis of rotation connected on the rotational part only to get the rotation around Roll axis. This neglecting of linear motion makes the speed of rotation around the Roll axis faster as compared with the other two axes.

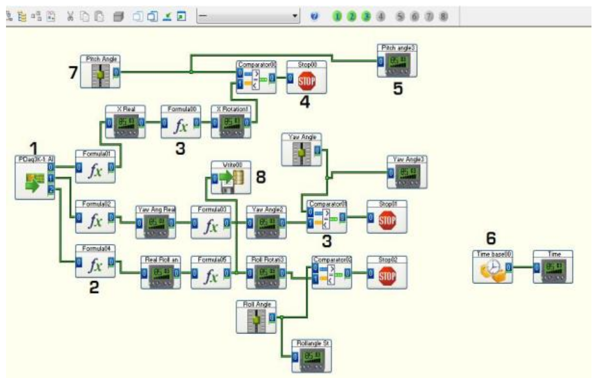

Figure (9) the modules used to generate angle data, to limit the rotation and also stopping the rotation.

In Figure (9) the first module that is marked with (1) is the analog input module with three input channels. Three input channels are the sensor's output, or sensors data that must be changed to angle by calibrating the data, once the sensor is activated its data will appear in the analogue input module channel, and this data will be voltage output from the angle sensor according to the wiper position. This data should be converted to angle by using the formula interpreter module marked with (2). This module has the ability to calculate any formula with one variable named (N {0}) this means the input channel number zero, the straight-line equation that is found before can be calculated with this module:

$$f(x) = ax + b \qquad (8)$$

(X) is N {0} and (b) is a constant, with some calculation from the calibration data for the relation between the voltage out from the potentiometer and the position of the wiper in angles a perfect straight-line equation for our data is:

$$f(IN(0)) = ((19.24) * IN(0)) + (13.8) \qquad (9)$$

So after writing the equation the data out from the module will be angle of rotation. The digital meter after the function module (1) is used to show the angle drawn by the sensor, after this digital module there is another formula interpreter module marked with (3), this module is used to round the angle value in order to be ready for comparison, to restrict the rotation around the three axes by giving the angle value from our program. This will be done by comparing the sensor data and the desired angle data value which is provided by a slider module marked with number (7). So, by comparing these two values the rotations will start and stop according to the inserted desired angle, the rounding of the sensor data should be performed before the comparison because the sensor data and the slider data never be equal if the sensor data is not rounded, the comparison performed by a comparator module, both outputs from the second formula interpreter and the slide should be connected to the two input channels of the comparator and in comparator setting we should change the comparison condition to (channel 1= channel 2) mode then also change the output value to (10 VDC) when this condition is true, and zero when the condition is false.

For this study, logic high action is used, and the action of stopping measurement, it means that when the input of the stop module is high, the measurement must stop, then after setting the desired angle of rotation, we can start the workplace, and the motor will run until the sensor data equals to the desired angle of rotation then the motor will stop. This is done for all the three sensors, in the slider setting the scale setting changed, for the minimum Value (set zero) and for the max. Value (set 360) besides the resolution is 360, then the slider changes from zero to 360 each step is 1, in addition the unit of the data can be changed, to a (Deg.).

The time base module marked with (6) is used to generate the period of rotation in seconds. And the digital meter module is used to display this time. The software in current formation is hard to deal with, and it is complicated to work with because the screen became too crowded and there are several windows covering the screen. For this reason and the fact that Satellites have ground control stations and the operators in the station use simple and organized screens to control the Satellite remotely, these two reasons force us to design an interface for this design.

## IV. RESULTS AND CONCLUSIONS

The results taken by rotating the designed (3-Axis Stabilized Satellite), (5) Degrees each step (this data named discrete data) and the time spent for this (5 Deg.) recorded for each step, after that making the relation between the angle of rotation and time required for rotation, for the results to be taken the position of the Satellite set to the max position in order to determine the full scale of rotation for every axis. The first data taken practically named discrete data the second data is calculated mathematically and named theoretical data, the theoretical data determined by calculating the angular velocity of the rotation from the discrete data in (Deg./sec.) then the time taken for every rotation calculated, the third data that taken practically but this time not discrete but uninterrupted data, the continuous data is the data taken from the minimum Degree to the full scale of rotation without any stop in the measurement, after all data taken, the graphs of theoretical and discrete also continuous data compared to each other.

Figure (10) show the relation between time and angle of rotation around Pitch, the three curves are extremely identical. It mean that in forward and backward rotations the time taken for both rotations are very close to each other and this because the Pitch axis motor only responsible to rotate the body of the Satellite who is made from aluminium.

For the theoretical data, the angular velocity for the forward rotation is (0.30 Deg. /sec.) and for the backward rotation is (0.3241 Deg. /sec.). Clearly the total time taken for the backward rotations from "Zero" to "Max" angle is as follows (107.99, 106.62, and 108) seconds for discrete, continuous, and theoretical results respectively, the difference is very clear, max difference is between the theoretical and continuous total times and it is (1.38 sec.) but actually the theoretical data depending on the rate change of time for the discrete data and the rate of change of the angle in Degree. This will get the angular velocity in (Deg./sec.) this angular velocity can be converted to (rad./sec.) in which it is the standard unit for the angular velocity, the theoretical total time and the discrete total time difference is (0.01 sec.), they are very close to each other, it is important to mention that in the discrete data every time when the data recorded the time of the data include also the starting time of the motors because of this time there is (1.38 sec.) difference between the discrete and the continuous data, moreover there is time difference when the (rod of the jack) jack slides out and when the jack slides in, because when sliding out it is like lifting a mass and the gravity is opposite the force of lifting, but when sliding in the mass the gravity will be in the same direction with the force, this will cause some difference in total time for all graphs taken, for the forward rotation the total times are (114.16, 105.21, 120.14) seconds For the discrete, continuous, and theoretical respectively, the curves again for the discrete, theoretical data are very close to each other but the forward and reverse data has some difference, and this difference is because of the reason of sliding in and out of the jack. In above data the max rotation angle is (36 Deg.). So the Satellite has a capability of rotation up to (36 Deg.) around the Pitch axis, this limitation is because of the length of the jack that slides in and out.

Figures (11) show the relation between time and angle of rotation around the Yaw axis. The three curves are extremely identical. For the theoretical data, the angular velocity for the forward rotation is (1.158 Deg. / sec.) and for the backward is (1.2 Deg. /sec.). The total forward time taken to rotate from zero to (Max.) angle for the three records are (30.2, 49.15, and 30.28) seconds and for the backward are (29.16, 38.53, 29.12) seconds, the rotation around (Yaw) axis shows the comparison between the three records, the total times are so close to each other except the continuous time is somewhat far from the other two values, the motor that responsible to rotate the Satellite around the Yaw axis drives larger load than the motor of Pitch axis. the max capability of rotation around Yaw axis is from (0 Deg. to 35 Deg.), again it is because of the jack length also the Roll axis length limits the capability of the rotation, furthermore the four legs cannot be shorter because the system will be unstable and it will fall down on one of the sides.

Figure (12) show the relation between time and angle of rotation around Roll axis. The three curves are close to each other. For the theoretical records the angular velocity for the forward direction is (4.24 Deg. /sec.) and for the backward is (3.53 Deg. /sec.) it clear that all data are not at the same line but this because of its own reasons; one of the reasons is that all the load of the design is on the motor and on the gears that responsible to rotate the Satellite around the Roll axis, this reason causes problems in starting slowly or some time to fail to start, also this heavy load on this motor causes the rotation be slower in some positions and faster in other positions, but generally the rotation is very fast if it compared with the other rotations around other axes, this fast rotation is because of neglecting the slide in and slide out of the jack, another reason for the above records to be not on the straight line at all points is that weight of the design makes the rotation not to stop at the desired angle of rotation it means that the motor receives the stop signal and it stops at the right time but the weight of the design makes the rotation continues for (1 Deg.) or sometimes (2 Deg.), this will cause some errors in the records and leads to appear like those ones in the sketch shown above, when the rotation is fast it is also be hard to record the data and time taken, so because of this reason for the continuous data to be recorded first the data saved in an ASC file.

The main conclusions of this work can be summarized as follows:

1- The (DASYLab) and the (DAQpersonal3001) used for operating such designed system, so this software and hardware are very powerful tools that provide more flexibility in work.
2- The principles of this automation design can be applied to any other application with or without modification.
3- Any rotation around any axis can be determined using linear type potentiometers. The linear type potentiometer is used to measure the angle of rotation. The equation written in the (DASYLab) to convert the position of the sensor to angle.
4- Several modules are used to limit the rotation of the Satellite and also to rotate up to the required angle, by this way the Satellite can rotate around any of the axes using the controlling interface designed specially to give simplicity to the person who operates the designed Satellite.
5- Several manoeuvres can be performed using three steps in sequence, for every rotation the Satellite moves up to the given value of the angle of rotation that desired then the rotation will stop.
6- There are no reference frames to be compared with the axis frame fixed on the intended Satellite the max angle rotation is zero to (35 Deg.) for the rotation around Pitch and Yaw axes, according to the same axis frame fixed on the designed Satellite.

7- For rotation around "Roll" axis, the max. Angle of rotation is zero to (120 Deg..) as an average, three rotations are also unlike in the angular velocity this because each motor has its distinctive load and applied voltage is also changed during taking the results because if the rated voltage applied for each motor, the rotations will be so fast that it can be impossible to record data.

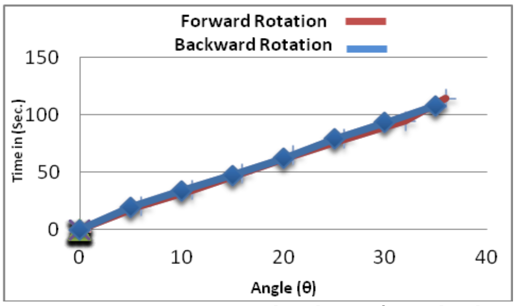

Figure (10): Rotation around pitch axis, forward and backward rotation for discrete case.

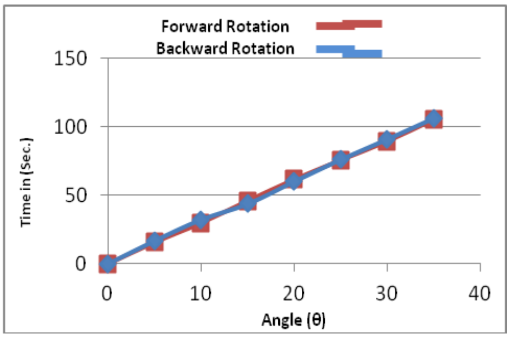

Figure (11): Rotation around pitch axis, forward and backward rotation for Continuous case.

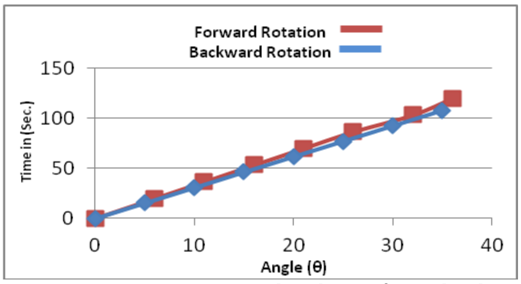

Figure (12): Rotation around pitch axis, forward and backward rotation for Theoretical case.

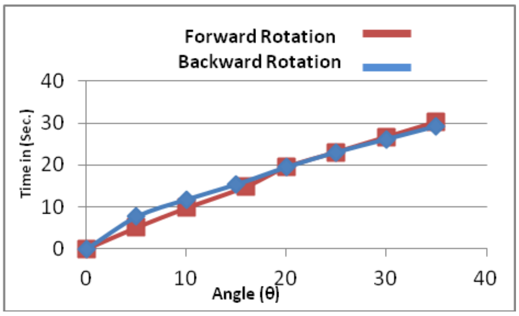

Figure (13): Rotation around Yaw axis, forward and backward rotation for the discrete case.

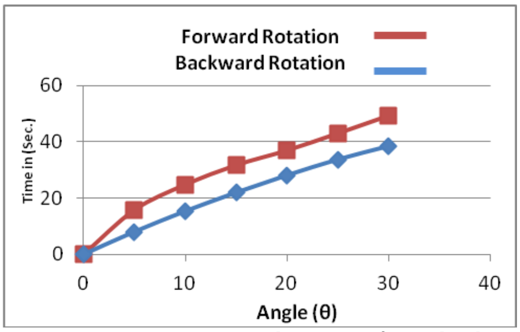

Figure (14): Rotation around Yaw axis, forward and backward rotation for the continuous case.

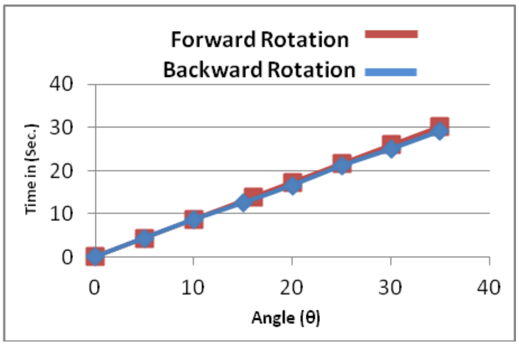

Figure (15): Rotation around Yaw axis, forward and backward rotation for the theoretical case.

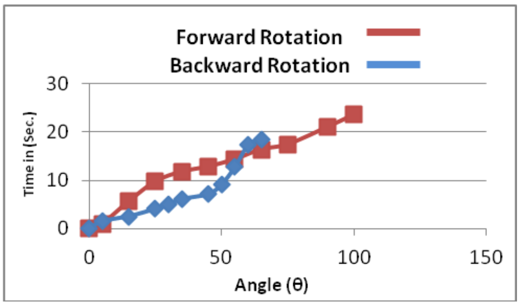

Figure (16): Rotation around Roll axis, forward and backward rotation for the discrete case.

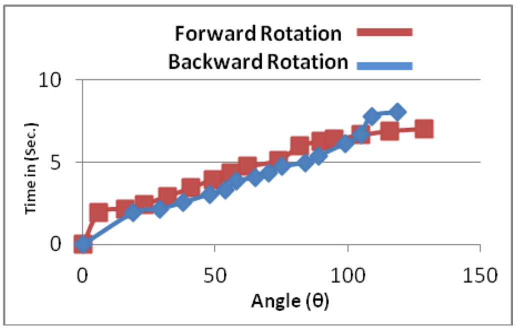

Figure (17): Rotation around Roll axis, forward and backward rotation for the continuous case.

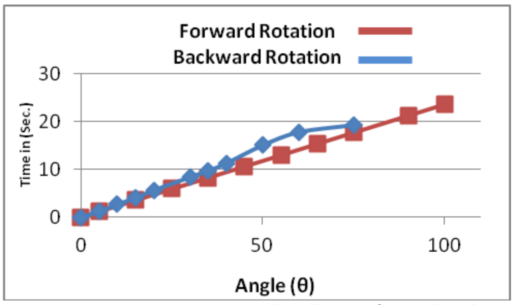


Figure (18): Rotation around Roll axis, forward and backward rotation for the theoretical case.


## ACKNOWLEDGMENT (HEADING 5)

The preferred spelling of the word "acknowledgment" in America is without an "e" after the "g". Avoid the stilted expression, "One of us (R. B. G.) thanks . . ." Instead, try "R. B. G. thanks". Put sponsor acknowledgments in the unnumbered footnote on the first page.


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