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Research Article

Design and Simulation of 3Degree of Freedom (DOF) Motion Platform

Shailendra Shisode[†*], Ganesh Shrigandhi[†], Rohit Magar, Sandeep Mistari, Renuka Patel, Abhishek Lokhande and Mandar M. Lele[†]

[†]Mechanical Engineering Department, Savitribai Phule Pune University, MIT College of Engineering, Kothrud, Pune, India
[‡]Mechanical Engineering Department, Savitribai Phule Pune University, VIIT,Kondhawa (Bk), Pune, India

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Abstract

The successful development of a three degree of freedom motion simulation platform, capable of simulating a car driving on road, is prepared. The motion simulation platform was developed to practically simulate and test an unmanned road vehicle's capability of driving on a road, before practically being demonstrated on an actual. All aspects of the motion simulation platform's development are considered, from the conceptual design to its practical implementation. The mechanical design and construction of a motion simulation platform, as well as the electronics and software to enable the operation of this motion simulation platform, are presented. Mathematical models of the process and platform orientation are developed. A controller architecture capable of regulating the process, resulted in the successful control of the motion simulation platform. Practical motion simulation results of Intelligent Motion Technology Pvt. Ltd, demonstrate the motion simulation platform's success. The successful development of the motion simulation platform can largely be attributed to extensive research, planning and evaluation of the different development phases.

Keywords: *Three degree of freedom motion, Motion simulator, Motion Platforms, Tilt sensors, Brushless servomotors.*

1. Introduction

It is required that a motion simulation platform is developed which is capable of simulating the motion of a Vehicle. The primary objective of the motion simulation platform is to lift total weight of 300 kg. This has been put into place in order that driver can get training before actually drive any vehicle. The development of such a motion simulation platform reduces costs and risk, creating the ability to test driving skills and ability to handle the conditions, until they have proven to drive successfully and reliably. For such a type of motion various types of motion simulation platforms exist, spanning over a broad spectrum of scale and cost, which are able to simulate different Degrees of Freedom (DOF). The most typical high-end motion simulation platform able to provide six DOF is the Stewart platform, which can simulate three translational DOF and three rotational DOF. Motion simulation platforms in general are very expensive, even for two or three DOF motion simulation platforms. This work, however, will focus on developing a low-cost three DOF motion simulation platform able to simulate heave, pitch and roll motions.

1.1 Problem Description and Objectives

Degrees of freedom (DOF) is the number of parameters that define the configuration of a mechanical system. The degrees of freedom of a body are the number of independent parameters that define the displacement and deformation of the body. This is a fundamental concept relating to systems of moving bodies in mechanical engineering, aeronautical engineering, robotics, and structural engineering. The position of a single car (engine) moving along a track has one degree of freedom, because the position of the car is defined by the distance along the track.

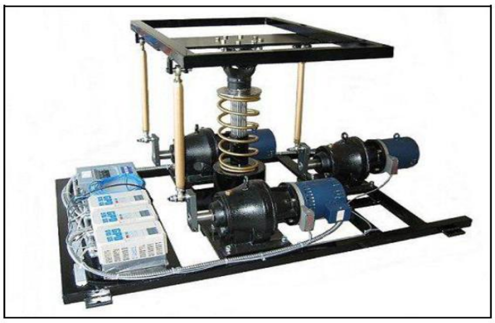

Fig.1 3-DOF and 6-DOF Motion Simulation Platform

A train of rigid cars connected by hinges to an engine still has only one degree of freedom because the positions of the cars behind the engine are constrained by the shape of the track. An automobile can be considered to be a rigid body traveling on a plane (a

*Corresponding author: **Shailendra Shisode**

flat, two-dimensional space). This body has three independent degrees of freedom consisting of two components of translation and one angle of rotation. Skidding or drifting is a good example of an automobile's three independent degrees of freedom.

The position of rigid body in space is defined by three components of translation and three components of rotation, which means that it has six degrees of freedom. The exact constraint mechanical design method manages the degrees of freedom to neither under constrain nor over constrain a device.

Major system features

a) 3 DOF motion simulation; Electro servo driven;
b) Wave form replication: sine, triangle, rectangular, etc;
c) Replicating motion spectrum;
d) All digital control;
e) Integrated customized design for turn-key project;
f) Local control or remote control;
g) Designed to last for 20 years in harsh application condition;
h) Execution subsystem: low friction, high response valve, built-in displacement sensor;

Major parameters to be consider

a) Roll : ± 5º
b) Pitch : ± 5º
c) Heave : ± 75mm
d) Load : 300kg
e) Motions

Translation

a) Moving up and down (heaving);
b) Moving left and right (swaying);
c) Moving forward and backward (surging);

Rotation

a) Tilting forward and backward (pitching);
b) Turning left and right (yawing);
c) Tilting side to side (rolling);

1.2 Motion Simulator

Motion simulator or motion platform is a mechanism that encapsulates occupants and creates the effect/feelings of being in a moving vehicle. Motion simulators fall into two categories (described below) based on whether the occupant is controlling the vehicle, the more common case for a system described as a simulator; or if the occupant is a passive rider, also referred to as a simulator ride or motion theater.

Examples of a typical (occupant controlled) motion simulator are flight simulators and car/truck vehicle simulators. However, motion applications have moved beyond auto racing and flight sim to include boats, motorcycles, rollercoaster's, tanks, ATVs, and spaceships among many other craft types. Examples of passive ride simulators are theme park rides where an entire theater system; with a projection screen in front of the seats, is in motion on giant actuators. An Enhanced motion vehicle moves the motion base along a track in a show building. See simulator ride and the Ride Simulator section of this article for more details of passive motion simulators. A motion simulator can also be called a motion base, motion chassis or a motion seat. The movement is synchronous with visual display and is designed to add a tactile, or sense of touch, element to video gaming, simulation, and virtual reality. When motion is applied and synchronized to audio and video signals, the result is a combination of sight, sound, and touch. All full motion simulators move the entire occupant compartment and convey not only a change in orientation but also produces the effect of false gravitational forces. These motion cues trick the mind into thinking it is immersed in the simulated environment and experiencing kinematic changes in position, velocity, and acceleration. Failure of the mind to accept the experience can result in motion sickness. Motion platforms can provide movement on up to six degrees of freedom: three rotational degrees of freedom; roll; pitch; yaw; and three translational or linear degrees of freedom; surge; heave; sway. Motion is being applied to an increasing variety of video gaming applications; a visit to a modern video game arcade reveals that gaming in motion is everywhere.

1.3 Systems of Bodies

A system with several bodies would have a combined DOF that is the sum of the DOFs of the bodies, less the internal constraints they may have on relative motion. A mechanism or linkage containing a number of connected rigid bodies may have more than the degrees of freedom for a single rigid body. Here the term degree of freedom is used to describe the number of parameters needed to specify the spatial pose of a linkage. A specific type of linkage is the open kinematic chain, where a set of rigid links are connected at joints; a joint may provide one DOF (hinge/sliding), or two (cylindrical). Such chains occur commonly in robotics, biomechanics, and for satellites and other space structures. A human arm is considered to have seven DOFs. A shoulder gives pitch, yaw, and roll, an elbow allows for pitch and roll, and a wrist allows for pitch and yaw. Only 3 of those movements would be necessary to move the hand to any point in space, but people would lack the ability to grasp things from different angles or directions. A robot (or object) that has mechanisms to control all 6 physical DOF is said to be holonomic. An object with fewer controllable DOFs than total DOFs is said to be non-holonomic, and an object with more controllable DOFs than total DOFs (such as the human arm) is said to be redundant. In mobile robotics, a car-like robot can reach any position and orientation in 2-D space, so it needs 3 DOFs to describe its pose, but at any point, you can move it only by a forward motion and a steering angle. So it has two control DOFs and three representational DOFs; i.e. it is non-holonomic. A fixed-wing aircraft, with 3–4 control DOFs (forward motion, roll, pitch, and to a limited extent, yaw) in a 3-D space, is also non-holonomic, as it cannot move directly up/down or left/right. A summary of formulas and methods for computing the degrees-of-freedom in mechanical systems has been given by Pennestri, Cavacece, and Vita.

2. Concept Generation and Investigation

With the engineering specifications and types of linear actuators now defined, concepts can be generated to try developing a possible mechanical solution for the design of such a motion simulation platform. Throughout the generation process many different concepts were investigated and reviewed, although only four of the main functional concepts are considered. The fourth concept that was considered is shown in Figure 2. This concept can be considered to be relatively simpler in design as compared to previous concepts. This design consists of three pneumatic cylinders each connected to the base unit by means of a single degree of freedom lower joint. The top platform is connected to each pneumatic cylinder by means of a two degree of freedom upper joint. Similarly to that of concept 2, this design has a small amount of coupling into undesired degrees of freedom due to the fact that no horizontally constrained centre point exists about which the top platform can simultaneously roll and pitch. This is due to the constraints created by using single degree of freedom lower joints. The main advantages and disadvantages of concept 4 are outlined below:

Advantages:

a) Relatively simple design as compared to previous concepts
b) Low to moderate design costs involved
c) Less joints, as compared to previous concepts, result in a lower possibility for
'play' on the top platform
d)Light weight and relatively easily to disassemble into mobile parts

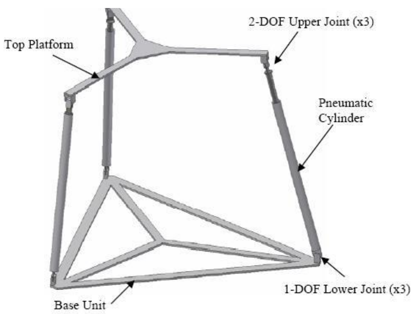

Fig.2 Concept

Disadvantages

a) Small amount of coupling into undesired degrees of freedom, due to system design
b) Lower joints need to be well designed to withstand high forces
c) All three pneumatic actuators need to have stroke lengths of more than a meter

After the concept was carefully evaluated, it was decided to accept it for the final detailed mechanical design, primarily due to its relatively simple design and lower design costs as compared to previous concepts. It was concluded that this design would be the best option with the available funding. The advantages of the design are considered to outweigh the disadvantages, including the small amount of coupling into undesired degrees of freedom. It is considered that the amount of coupling will be very small and will minimally affect the design goal of the system.

3. Mechanical Design

The main mechanical system is comprised primarily of three assemblies, namely, servo motor, servo controlled planetary gear box, simulation platform and base structure. The various sub-assemblies and components required in completing these three primary assemblies like base frame ,simulation platform, universal joint, crank and lever, spring, spring support are designed. Some standard components like brushless servomotor, Linear bearings, Gear box are selected according to design requirement. The motor selected is Baldor BSM 80N 350 and its features.

- Extra high insulated stator design for protection - Baldor's commitment to provide you with a quality product;
- Superior bearings with improved Exxon Polyrex® EMpolyrex grease to provide 4 times greater life - Baldor's commitment to you to provide a reliable product;
- Premium high temperature 200°C moisture resistance, multi-coated copper wire for ability to cope with large current spikes - Baldor's commitment to provide you with a superior product.

3.1 High Accuracy Digital Tilt Sensor

ARN-TS2D gives precise tilt information about roll and pitch axis in digital serial RS232 format in static or non accelerated environment. Output is available at continuous user selectable rate. The device uses new-age sensors employing MEMS accelerometers and embedded processing to give accurate information where applications demand so. The device is factory calibrated and tested with no general need for onsite calibration. ARN-TS2D tilt sensor is small in size and low cost making them ideal for OEM applications. These sensors can tolerate harsh environments such as factories, plants and construction and render outstanding performance over wide temperature conditions. This sensor comes with industrial type circular connector, therefore it is very suitable for automotive, marine, building, robotic and automation applications

AE Series 2-Stage Planetary Gearbox -- AE155 - 100 Special design for continuous (S1) or cyclic (S5) duty operation

a) Output torque T2N : 14 Nm - 2000 Nm
b) Ratios 1-stage : 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10 2-stage : 15/20/25/30/35/40/45/50/60/70/80/90/100
c) Low backlash 1-stage : ≤8 arc/min 2-stage : ≤12 arc/min
d) high efficiency 1-stage : 97% 2-stage : 94%
e) Easy mount
f) Low Noise
g) Compact structure

Performance Specifications

Gear Ratio	100 : 1
Rated Output Torque	3982 In-lbs
Maximum Input Speed	6000 rpm
Backlash	12.00 arc/min
Efficiency	94.00 %
Gearing	Helical; Planetary

Standard Gear head

AE Series 2-Stage Planetary Gearbox -- AE155 - 100 Features

a) Standard backlash is 15 to 10 arc-min max
b) Round face with tapped holes
c) Integrated, self-locking input pinion clamps onto motor shaft
d) Lubrication - grease - 15 K hours
e) Satellite gear shaft is cantilever supported in carrier (needle bearings)
f) Satellite gear teeth - deep case hardened and finish ground
g) Medium to high torque/size & torsional stiffness

Gear head housing - aluminum input module, steel output module

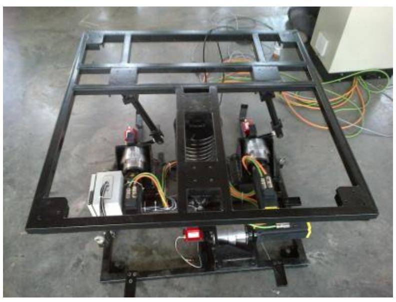

Fig.3 Setup of 3DOF Motion Platform

4. Motion Simulation

The motion platform can be exited in three possible modes:

a) Forward kinematics mode: In this mode the independent motors positions are driven by the input signals. Forward kinematics algorithms are employed to calculate the top platform position and rotation (speed and acceleration) and motors speed, acceleration, torque and power.
b) Inverse kinematics mode: In this mode the independent degrees of freedom are driven by the input signals. An inverse kinematics algorithm is employed to calculate the required motors positions, speeds, acceleration, torque and power. The speed an acceleration of the top motion platform is calculated as well.
c) Specific forces mode: In this mode the independent specific forces and angular velocities are processed by a classical washout filter to produce the required platform position and rotation. The output of the washout filters are used as an input to the inverse kinematics mode. The position, speed and acceleration of the top motion platform and the position, speed, acceleration, torque and power of the motors is calculated. Motion Platform Designer provides the following ways to input the data signals in one of the three possible modes:

a) Signal generators (configurable sin, square, triangle, ramp and constant)
b) File (text line-oriented file)

Motion Platform Designer can output the motors positions, top platform position/rotation and the platform specific forces and angular velocities. Data can be outputted to a:

- File (text line-oriented file)

The build-in classical washout filter can be configured independently per motion axis (surge, sway, heave, roll, pitch, yaw). For every axis, the input signal can be shaped by configurable gain and limiters. The cut-off frequencies of the independent filters can be configured to achieve the best washout effects considering the limited motion platform volume.

The motors are positioned in a symmetrical fashion: M1 and M2 forward and M3 backward. The position of the motors can be changed by changing the corresponding dimensions setting values (a, b and c). The motors are equipped with motor arms. The length of the motor arm can be adjusted by changing the motor arm length setting value (d). The initial height of the motion platform can be adjusted by changing the value e. The rod length value (from join to join) is automatically calculated every time the platform dimensions are changed. The center column is equipped with a spring to compensate for the weight in the neutral position. It is a so called press spring. When pressed, the spring will produce the force to the opposite direction. Every spring has a normal (unpressed) length, and a spring constant. The spring constant represents the force which is produced when the spring is pressed. Ex: It the spring is 0.6 m in a normal state, when a spring with spring constant of 1000 N/m will produce 200 N opposite force when pressed to the length of 0.4 m. 200 N force can compensate 20 kg of weight. The spring normal length and the spring constant can be adjusted by changing the x0 and k values. For the calculation of the motor torques and power a payload mass can be positioned of the top of the platform.

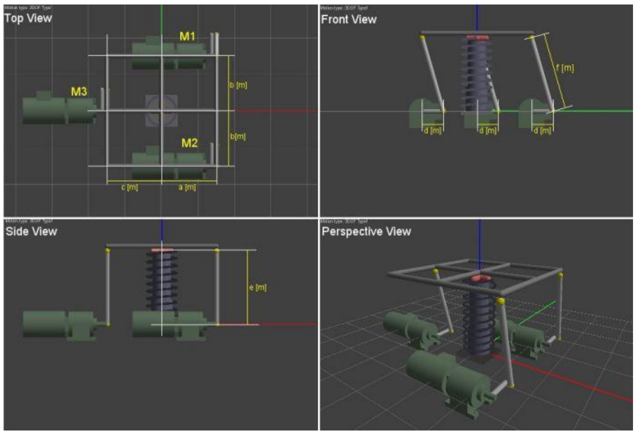

Fig.4 Views of Setup

4.1 Input: Signal Generator

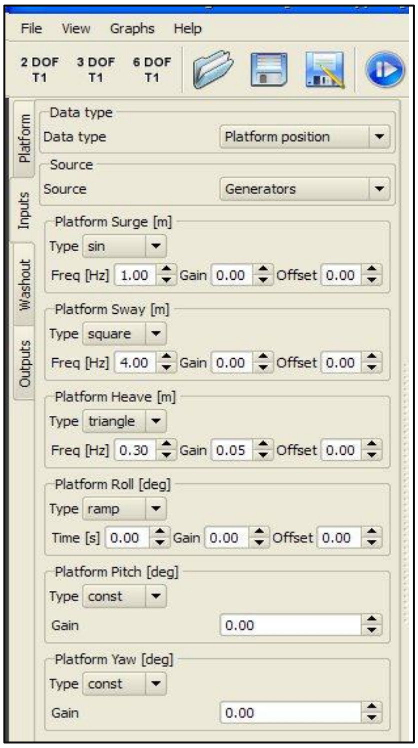

Fig.5 Input-Signal Generator

Different signals can be generated and used as an input for driving the motors and platform. Current version supports the following types of signals like Sin, Square, triangle, Ramp, Const etc.

4.2 File

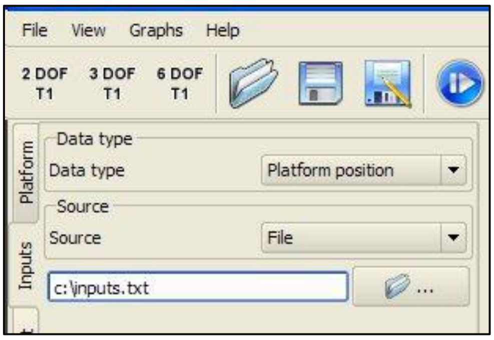

Fig. 6 File

A simple comma separated line based text file can be used as a data source. The text file consists of one or more lines of values. A line consists of exactly 6 float values separated by a comma. Depending of the mode of operation, the values are interpreted differently. For Forward kinematics mode, the values represent the desired motors positions. For motion systems with less than 6 motors, the corresponding values are ignored. For Inverse kinematics mode, the values represent Surge, Sway, Heave, Roll, Pitch and Yaw. For motion systems with less than 6 DOF, the corresponding motion position and rotation are ignored. For specific forces mode, the first 3 values represent the specific forces along the x, y and z axis and the last three values represent the angular velocities along the x, y and z axis. To put it into the time perspective, the lines of the values in the text file should represent values with a time difference of 20 ms. this means, for a test file of 1 second, a text file should contain 50 lines.

4.3 Network

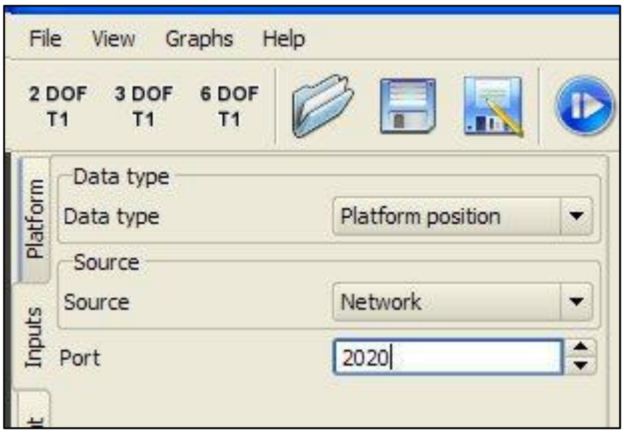

Fig.7 Network

A separate configuration page is available for every signal. For the High Pass channels (Surge (X Axis) , Sway (Y Axis) , Heave (Z Axis), Roll (X Axis), Pitch (Y Axis) and Yaw (Z Axis) the gain, the limit and the cut-off frequency can be independently adjusted. The input signal will be multiplied by the gain before limiting the to desired limit value. After that, the signal will be filtered and only the signal frequencies above the cut-off frequency will be passed for further processing to produce the motion platform position and rotation

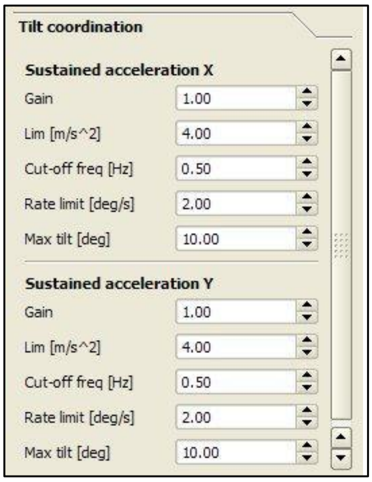

Fig.8 Tilt Conditions

4.4 Outputs

Motion Platform Designer can output the motors positions, top platform position/rotation and the platform specific forces and angular velocities. Data can be outputted to a:

File (text line-oriented file)

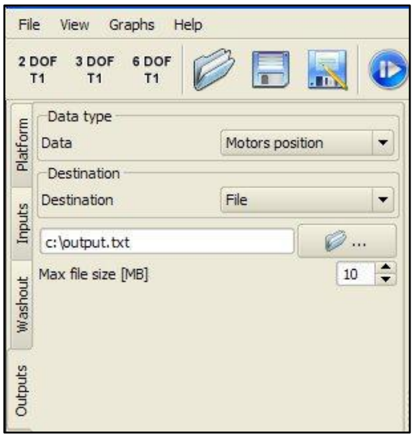

Fig.9 Text line-oriented file

The output can be saved to a file on the disk. It is a comma separated line based text file. Every 20 ms a new line is written to a file. The size of the file can be limited. Depending of the type of the output, the non applicable values are written as zero.

4.5 Graphical representation under various conditions

The graphs windows present a visual representation of the calculated motion platform data. The data is collected continuously during the running of the motion platform. Graphs windows show the last 60 seconds of the recorded data. Using the mouse buttons a region of the graphs can be zoomed-in zoomed-out, scrolled and panned.

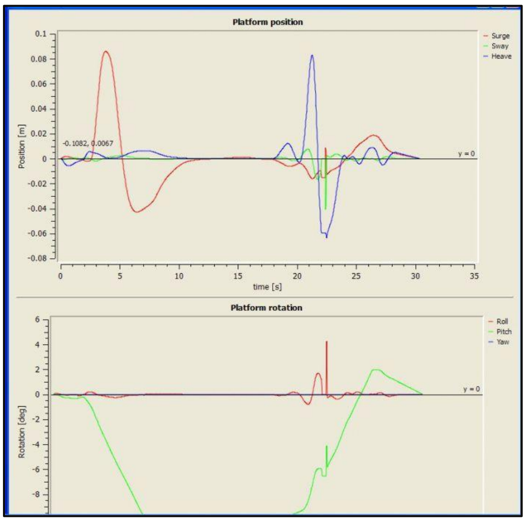

Fig.10 Platform Rotation vs Platform Position

The following graphs are available

a) Commanded platform forces
b) Commanded platform position and rotation
c) Actual platform position and rotation
d) Actual platform position and rotation speeds
e) Actual platform position and rotation acceleration
f) Actual motors position
g) Actual motors velocity
h) Actual motors acceleration
i) Actual motors torques
j) Actual motors power

4.6 Motion Simulation Platform GUI

The GUI was developed using Borland C++ builder to provide a user-friendly interface to the motion simulation platform. This interface can be used to simulate roll, pitch and heave motions. The reference motions are stored in a supporting platform data file, prior to simulation. Measured roll, heave and pitch motions are saved to a platform log file. The GUI also provides a means of updating control variables of any node, without the need to reprogram the microprocessor. The GUI consists of two main pages, the control page and the platform monitor page. The control page lists all major platform control options, shown in Figure 11. Here the controller can be disarmed or armed. When armed, the actuators will extend to an initial specified reference condition. The desired reference to be tracked can be selected from two options. The first option is of that of the roll, pitch and heave motions located in the platform data file. The second option is a self-generated sinusoidal heave reference, where roll and pitch angles are kept at zero. The second option can be used for initial platform testing to ensure that all the actuators are working correctly.

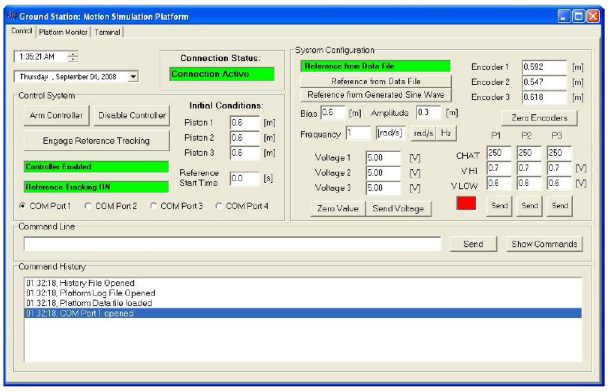

Fig.11 Control Page

The platform monitor page provides an overview of all motion simulation platform operations, shown in Figure 12. This page displays reference and measured platform orientation, as well as reference and measured actuator displacements, which can be viewed graphically. An accumulative Root Mean Square (RMS) error calculator can also be activated to identify the reference displacement tracking ability of each actuator. For safety reasons, an emergency stop button is located on this page to immediately end platform operations, should any problem be identified.

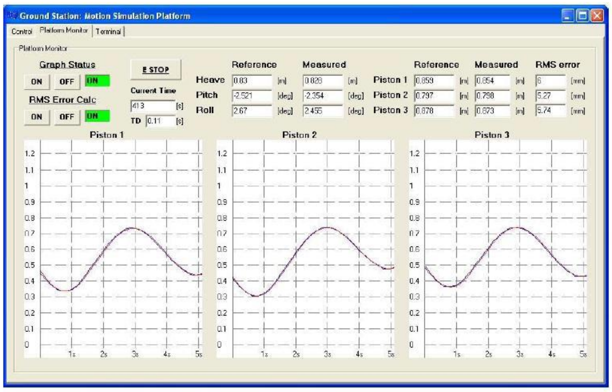

Fig.12 Platform Monitor Page

4.7 Simulation Summary

The electronics and software developed to actuate and control the motion simulation platform were presented. Complete details on the electronics developed, which enables an interface to a single or multiple actuators, were discussed. The computer software, which includes a Simulink interface as well as a motion simulation platform GUI, was presented. The developed electronics and software were found to work well, providing a versatile and user-friendly means to interface from a PC to the mechanical motion simulation platform.

Conclusions

The present investigation indicates that the capability of simulating 3 DOF motion platform under actual conditions. The motion simulation platform was developed to practically simulate and test an unmanned aerial vehicles capability. The conceptual design of a motion simulation platform was carefully investigated, which led to the development of a detailed CAD model of the system. The CAD model was carefully evaluated and potential problems were identified and corrected or redesigned. The final completed CAD model then led to the extremely successful construction of the physical motion simulation platform. The versatile electronics and software developed, required to control and actuate the motion simulation platform, were found to work well and provide a user-friendly means to interface a PC with the mechanical system. The necessary mathematical models of the platform's orientation were developed. All models were extensively tested and evaluated to ensure that a high level of accuracy was obtained. The positioning control of the actuator was then accomplished, which resulted in the implementation of the full control of the motion simulation platform. Finally, all aspects relating to the practical motion simulation of a vehicle were considered and the motion simulation platform's ability to simulate the motion was successfully demonstrated.

Acknowledgment

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