IMU and Compass Sensors for Wireless Control of 6 DOF Parallel Manupulator

Wan Rahiman* and Kho Kee Chen

Abstract—Almost six decades ago, the first parallel manipulator designed by Gough V. E. with his team for tire test system, and then Stewart D. designed with different configuration to build a platform with 6 degrees-of-freedom (DOF) as flight simulator. Until today, many researchers are inspired by Gough-Stewart platform with exploit the parallel manipulator potential over serial manipulator. Thus, in this paper, a new model of 6 DOF parallel link manipulator with rotary actuator driven by DC servo motors is fabricate and control using wireless controller integrated with Inertial Measurement Unit (IMU) sensor and campus sensor. The control methods are to orientate the upper platform of parallel manipulator follow the orientation of remote controller. The IMU sensor unit consists of ITG-3200 gyroscope and ADXL345 accelerometer which combine together with HMC5883L magnetometer sensor (compass) to control three axis rotation orientations. In addition, the analog joystick is use to control linear position of the upper platform. These sensors will then embed onto remote controller. The Kalman filter is implemented to predict and estimate the sensor orientation. The control system using simplify inverse kinematics algorithm to compute each trajectory angle of rotary actuator. An Arduino microcontroller boards are use as main processor unit for overall control system and nRF24L01+ transceiver module use to wireless communication between remote controller and parallel manipulator model.

***Keywords*—6 DOF, Kalman Filter, inverse kinematic**

I. Introduction

During the past two decades, parallel manipulator systems have become one of the research attentions in robotics. The first published article by Steward in 1965, proposed a 6 degree-of-freedom (DOF) mechanism control by 6 motors as safety flight training simulator for helicopter pilot. The parallel link manipulator is also known as steward platform manipulator or hexapod [1,2]. The popularity of parallel manipulator has been increased by the fact that parallel manipulators possess some specific advantages over serial manipulators, i.e., higher rigidity and load-carrying capacity and better dynamic performance [3,4]. The closed loop kinematic structure yields a force output to manipulator weight ratio more than on order of magnitude greater than most industrial robots [5]. As an industrial manipulator, the parallel manipulator can be applied into many application fields. The parallel manipulator is mostly use to reduce motion simulation for light simulator and driving simulator. In expanding its potential, the parallel manipulator is applied into automation of many light machining applications such as surface finishing, edge finishing, routing, and profile milling. In astronomical application, the parallel manipulator also used as radio telescope platform as it can rotate in the direction of polarization without employing additional drive motor [6]. However, one of the major problems in robot kinematics is the forward kinematic analysis to determine the upper platform motion [7]. With given each link lengths to determine the upper platform position, 30 nonlinear algebraic equations must be solved simultaneously. For inverse kinematic, there are few steps complex computation requires to compute the actuator output. Thus most of control systems for parallel manipulator require computer aided software to perform the computation. Due to the time-consuming for computation, the response rate of parallel manipulator is slower.

In this paper, we propose a standard procedure to control via 2.4GHz frequency for 6 DOF parallel manipulator. The main objective is to enable the parallel manipulator control using orientation and position sensor and to observe the motion of sensor orientation of the upper platform of the parallel manipulator. This provides an alternative real time motion control of parallel manipulator by the sensors beside simulation software.

The outline of the paper is as follows. In section II, we briefly give a hardware configuration to formulate kinematic calculation of the matching problem and present an alternative real time for motion control. In Section III, review the process for the hardware and software design procedure with an alternative technique applied to the system. A filter based on Kalman prediction is described in Section IV, and in Section V the results of the experiments are reported. We conclude the paper in Section VI.

Wan Rahiman*
Khoo Kee Chen

School of Electrical and Electronic Engineering, Universiti Sains Malaysia
Pulau Pinang, Malaysia

II. Hardware Configuration

A. *IMU and Compass Sensors*

An Inertial Measurement Unit (IMU) is a system made up of an accelerometer and a gyroscope working in tandem to compensate for the pitfalls of each other [3]. The gyroscope sensor is fast response device measure the angular velocity of body rotation motion. But, it suffers from drift due to accumulated errors by integration to obtain angle information from acceleration. Meanwhile, the accelerometer has a good steady state response, but has slower response and suffers from high frequency noise. One of the models, Digital IMU 6 DOF is comprised with tri-axial accelerometer (ADXL345) and tri-axial gyroscope (ITG-3200) as shown in Fig. 1. The model able to measure 6 DOF measurement.

Figure 1: Digital 6 DOF IMU

A compass sensors is built with only magnetometer to measure magnetic fields surrounding the sensors body [8]. With power supply applied, the sensor converts any incident magnetic field in the sensitive axis directions to a differential voltage output. However, the compass sensor also suffers from tilt effect when measuring earth magnetic field. The tilt effect can be compensated through calculation with measurement from accelerometer [9]. One of the models, HMC5883 is built with tri-axial magnetometer or known as compass sensor (as shown in Fig. 2).

Figure 2: Compass Sensor

Both IMU and Compass sensors are combined for orientation measurement. These sensors combine with position sensor user in fastening tool tracking system [10] the sensor reading is filter with different kind of filter to give better orientation angle. The common filter applied is Kalman Filter, Particles Filter and Quaternion representation. The tri-axial accelerometers also used for human motion capture to emulate upper body motion in a virtual 3D environment. The combination of accelerometer and magnetometer is used for 3D orientation tracking is performed [11-13].

B. *Wireless Transceiver*

There are variety model of 2.4 GHz wireless transceiver, one of the common use is nRF24L01+. This unit is an ultra-low power transceiver for the 2.4 GHz frequency band which is very well suited to build simple but efficient. It is interface with Serial Peripheral Interface (SPI) bus. This wireless device is able to support multi-point transmission system. Based on Guangwei Chen and Esther Rodriques-Villegas research [14], the nRF24L01+ is tested for medical application. This test is to find wearable wireless monitoring medical device among different models. The Nordic nRF24L01+ is used as time synchronisation on a wireless sensor network custom designed for traffic monitoring applications. Meanwhile, the RF chip nRF24L01+ used as wireless multi-pint temperature transmission system [15]. The transceiver nRF24L01+ used for wireless data transceiver system for field data acquisition, using modularised designing, to achieve the wireless data transmission in small hydropower stations based on [14]. The test result show the transceiver has high data transfer rate, easy installing and strong anti-interference ability.

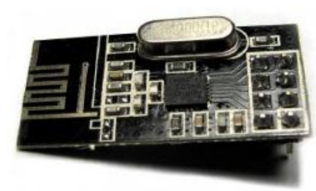

Figure 3: Wireless transmitter

III. Design Procedure

The overall connections of electronic devices use that on parallel manipulator as shown in Figure 4. Each of the devices is labeled as voltage regulator units (A), 11.1V Li-Po battery (B), nRF24L01+ transceiver (C), 8-channel servo controller (E) and six DC servo motors (S1-S6) with Arduino Mega 2560 microcontroller (D) as main processor.

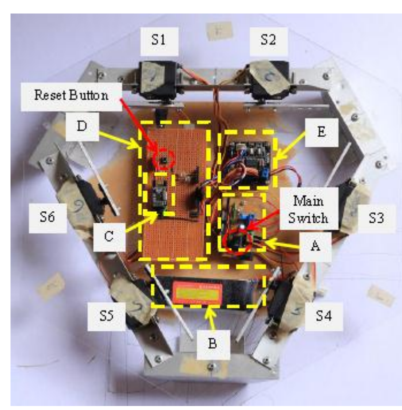

Figure 4: Fixed Base of Parallel Manipulator

An 11.1V rechargeable Li-Po battery voltage supply is use to power up all the electronic devices on the parallel manipulator and control by Main Switch. The voltage regulator unit is use to regulate the input 11.1V to 6V for DC servo motors usage. There are 4 pieces of LM7806 Voltage regulator are use regulate the voltage supply in parallel connection. This to prevent overheating or overloaded to the LM7806 as six units of servo motor require high current to run. The servo controller is connected to Arduino Mega 2560 use serial communication to get the position and speed values for each servo motor. Then, all six units of servo motor are connected to servo controller at specified channel pins. To receive the orientation and position values from remote controller, one unit of nRF24L01+ transceiver is used. The data received are then read by Arduino Mega 2560 using SPI communication and compute each servo motor output angle.

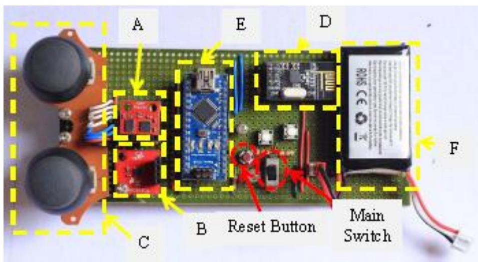

Figure 5: Remote Control

Meanwhile, the remote controller is made up of an IMU sensor (A), Compass sensor (B), analogue joystick (C) and nRF24L01+ (D) with main processor of Arduino Nano microcontroller (E) as shown in Figure 5. The IMU and Compass sensor are used to measure the three axis orientation, while analogue joysticks are used to control three axis linear positions. This allows the upper platform of the parallel manipulator is control by replicate the orientation and position measure by remote controller. As remote controller must transmit the orientation and position readings to parallel manipulator wirelessly, another unit of nRF24L01+ transceiver is used to transmit the data. The remote controller is power up by 7.4V rechargeable Li-Po battery (F) through Main Switch. The overall devices map form combination parallel manipulator and remote controller in this project as shown in Figure 6.

In the other side, the software design for this project is consist of two separate parts. The first part is used to control the parallel manipulator which programmed into Arduino Mega 2560. Another part of the software is design to measure the orientation and position with Kalman filter which programmed into Arduino Nano. In the first part of software design, the program is start with declare all the variable and constant parameters. Then, the serial communication and SPI are initialised. Two channel of serial port are used, one is for serial communication between laptop and another one is to communication between to servo controller. While, SPI communication is use for communicating between nRF24L01+ 2.4GHz wireless transceiver. The initial position values of each servo motor will send follow by 8 second delays. This to ensure all servos is moved and reaches the origin position.

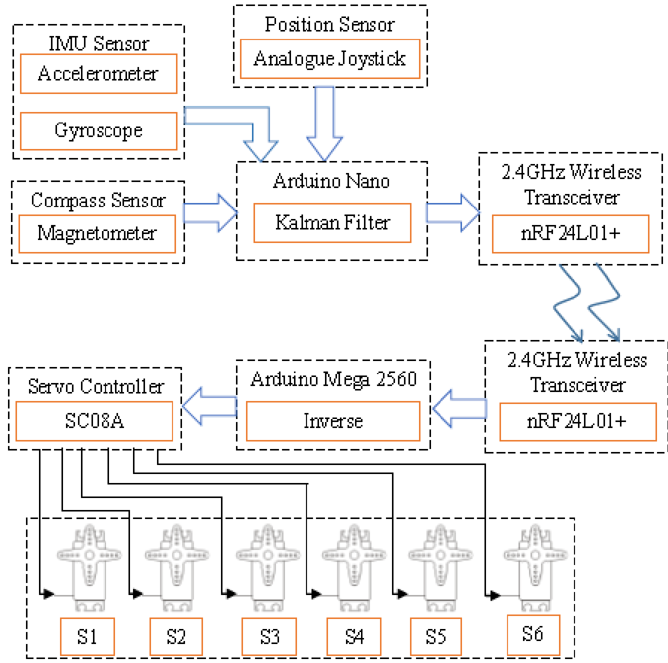

Figure 6: Block Diagram of Complete 6 DOF Parallel Manipulator

Proving mathematical coordination for each end-effector points are solved [16] and all the joints of its base and moving platform are located in respective planes. Initialisation begins with all the setting; the program run into loop cycle start with receives the orientation and position values from wireless transceiver. The values received are in byte format, thus conversion to float format must applied to ensure correct values. Then, the coordinate points of each end-effectors P and centre rotation of actuator O are compute according to each separate equation. Follow by, compute all the unknown values of A, B and C which from the equation. Next, move into smaller loop which to compute two unknown values of x in quadratic equation by given each values of A, B and C. Each of iteration of smaller loop, the two value of x is used to compute the output position angles, θ of servo motors. Both the output position angles, θ is substitute back to equation to choose one correct angle value. The smaller loop is repeated for six times to compute all the six position angles for each servo motors.

Then, the six position angles are converted into position value range from 0 to 8000. These values used by servo controller to control the position of the servo motor. Once complete conversion, the position values are send to servo controller in sequence start from 1st servo to 6th servo. Thus the program will looping again with receive data from wireless transceiver or stop running if reset button is pressed. The overall flow is shown in Figure 7.

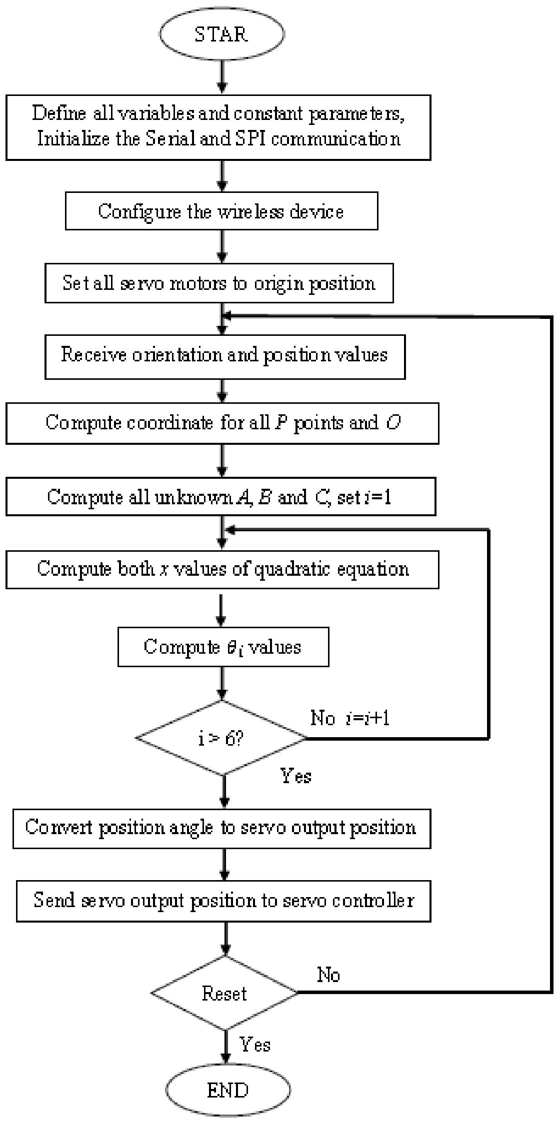

Figure 7: Flow Chart for Parallel Manipulator Software Design

Meanwhile, the overall flow of software designed to operate remote controller unit as shown in Figure 8. The program start with define all the variables and set the constant parameters. Each communication is set also being initialised at the start of program in order to ensure it run smoothly. Then, all the sensors are configured to operate as specified setting and measure the bias values of each sensor. The bias values are measure to reduce drift error of gyroscope and to reset the orientation base on new reference.

After complete the setup process, the program will run into looping cycle start with initialise the timer To to record current time. Then, get the all the sensor reading start from gyroscope to accelerometer to magnetometer. The sensors reading will then minus with previous measured bias values.

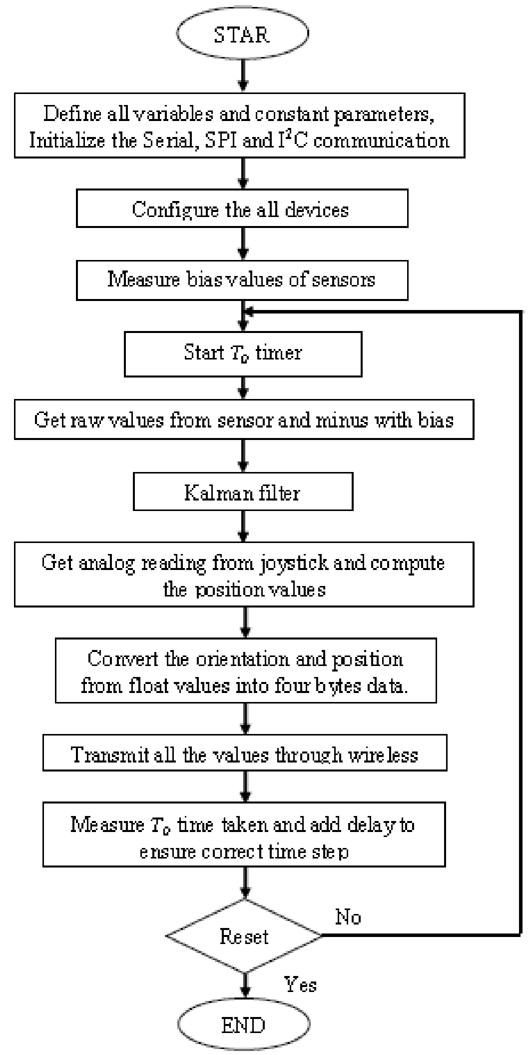

Figure 8: Flow Chart for Remote Controller Software Design

The resulting sensors values are used for Kalman filter to predict or estimate the orientation. The Kalman filter gains are computed too with new prediction values. Next, get the analogue reading from analogue joystick to compute the position reading. As the orientation and position values computed in float values, the float values must converted into four spate bytes data before transmission. This because the length of single data used for each package wireless transmission is in 1 byte or 8 bits.

Once complete the transmission, the timer To will record new current time to determine time taken for the above process by minus previous recorded time. The period of time taken will then added with additional delay to complete the time step period. The time step used to ensure the loop of program running at specified time frame of Kalman filter. After the delay, the program will loop back to getting raw sensors value from the sensors.

IV. Test Procedure

In this project, there are two main tests is perform, performance tests for remote controller and performance tests for parallel manipulator. Both of the testing are carry out to determine the performance and accuracy. This to ensure the control system designed is working accordingly. All the three sensors, accelerometer, gyroscope and magnetometer are used as testing measurement tool. The readings of sensors are collected to examine the performance of Kalman filter to predict the orientation angle and the accuracy of parallel manipulator orientate. All the sensor readings are compute into Euler angle of roll, pitch and yaw angles. The angle data are collected through USB terminal and plot on Matlab Software. The time values for plot graph are bases on Arduino microcontroller internal clock timer.

The remote controller is tested with steady state performance and different speed motion tracking. This to test the performance of Kalman filter implemented into orientation prediction algorithm. As aforementioned, the Kalman filter settings are set within the range which recommended in [17]. The recommended measurement covariance noise is between 0.0001 and 0.001 as these values make the Kalman filter not too sensitive to noise but still able to give optimum orientation tracking. Thus, the measurements covariance noise of Kalman filter is set according to Table 1. The sampling speed for the Kalman filter is set at 50Hz or 20ms for all the testing.

Table 1: Kalman Filter Parameter Values

Parameters	Values
Covariance noise for gyroscopes	0.001
Covariance noise for accelerometers	1
Covariance noise for Magnetometer	0.1
Angle variance	0.001
Angle change rate variance	0.001
Angle and angle change rate variance	0.001

In the steady state test, the remote controller is place on stable platform on top of table. On the same table, there is no vibration or motion happening on top of it. The laptop use to record the data is place as far away from the controller. This to ensure minimal external force or noise introduce to the sensors. Any heavy metal materials and other electronic devices such as smart phone are cleaned from table as this will interfere the magnetometer reading.

Meanwhile, for the slow motion test, the remote controller is placed on observe hand and move slowly at randomly motion with smaller amplitude. This is to test the performance of Kalman filter to predict and estimate the angle of orientation of controller body. The test also is to observe the noise level of accelerometer and magnetometer and drift error for gyroscope.

For fast motion test, the hand movement motion is speed up and randomly with higher motion amplitude. After the movement, the remote controller is place back to origin position. This is to test the accuracy to track back the orientation of controller when it places back to origin position and the performance of motion tracking with high amplitude of motion.

The parallel manipulator model is tested with response speed performance at different servo motor output speed. The observations of motion trajectory of parallel manipulator are also performed to observe the orientation errors. Before performing the test, the parallel manipulator model is undergoes limitation test to determine the motion limitation of the upper platform. Since the forward kinematic analysis use to determine the workspace limitation of parallel manipulator are complex and require plenty of time to written all the equations. Thus, the forward kinematic are not included for this project.

As to determine the workspace limitation or motion range limits, the simple try and error test method is used. The orientation angle of upper platform is programmed to run until it reach the servo motors motion range then transmit the angle value to computer. This is simpler and faster method compares forward kinematic analysis which requires complex matrix calculation.

The servo motors motion range is set to run at -45 degrees to +70 degrees from origin position. The limited range also includes the mechanical limitation from the ball and socket joints and the mechanical structure of the model. This limited range gives optimum motion speed response and prevent any damage or overload to servo motor. The results of the limitation range are recorded in table.

Once completed above test, the parallel manipulator is tested with different servo motor output speed. This to test the time taken for the servo motor to actuate the upper platform to orientate as targeted. The orientation angle is set to step changing as to observe the time taken for the upper platform to orientate. For this testing, only included rotation motions of roll, pitch and yaw as the remote controller is mounted on top of the upper platform as shown as Figure 3.34. The linear motion is unable to test as no suitable linear sensors are available for the testing.

V. Experimental Results

In this section, the performance test of both parallel manipulator and remote controller is performed. The remote controller is tested with steady state performance and different speed motion tracking. This to test the performance of Kalman filter implemented into orientation prediction algorithm. These test result are shown at respective subsection.

Meanwhile, the parallel manipulator model is undergoes response speed performance test with different servo motor output speed. The observation of motion trajectory of parallel manipulator is also performed to observe the orientation errors. The orientation motion of upper platform is measure by remote controller which fastened on top. This to ensure the control system of the parallel manipulator is orientated the upper platform according to measurement of remote controller. All the testing results are shown in each subsection include discussion.

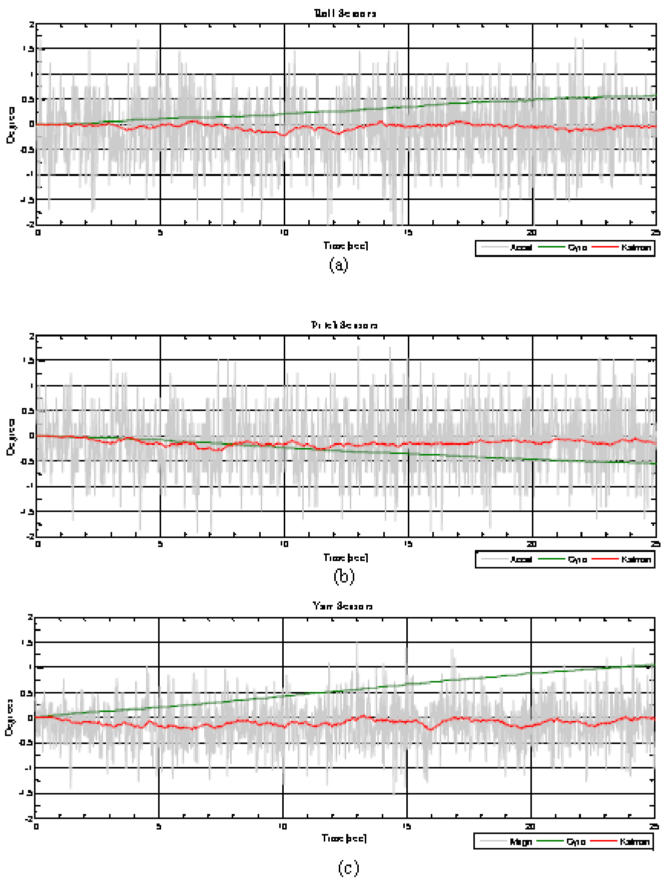

Figure 9: Steady State Test Result: (a) Roll sensors, (b) Pitch sensors, and (c) Yaw sensors

The first testing for Kalman filter performance is stead state testing. The sensor results are plotted base on three rotation angles which are roll, pitch and yaw. The orientation values are computed and plotted as illustrated in Figure 9. The raw readings from the accelerometer are plotted with grey colour for graphs on Figure 9(a) and Figure 9(b), while the raw readings from the magnetometer are plotted with grey colour only for graph of Figure 9(c). The gyroscope readings and Kalman prediction are plotted with green and red colour respectively for all the above three figures. The sensor readings from accelerometer and gyroscope have significant noise level. The computed angle values for accelerometer and gyroscope is fluctuating at ±1.5 degrees and ±1.0 degree respectively. For the gyroscope readings, the calculate angles are drifting along the time. There is +1 degree drifting for yaw angle while for roll angles and pitch angles are +0.5 degrees and -0.5 degrees respectively. This shown the gyroscope sensors are having drift error alone period of time.

Thus, implement the Kalman filter to handle to noise signal and drifting. From above observation, the Kalman filter is performing well and able to reduces the noise and overcome drift. The predicted angles are within the range of ±0.3 degrees for all three axis. The average angle values for each direction are -0.05987, -0.14977 and -0.10964 degrees for roll, pitch and yaw respectively. Hence, the setting for the Kalman filter is acceptable for steady state test.

VI. Conclusion

Hence, from the data observation the Kalman filter able to predict or estimate the orientation of controller body with slightly errors. There are prediction errors due to setting value of the measurement covariance noise. The setting set for Kalman filter in this project is for small range of motion as the orientation range for parallel manipulator is limited. The setting also set to ensure no violently motion to control the parallel manipulator as this may overload the DC servo motors and the power regulator circuit.

Acknowledgment

We would like to thank our staffs and Universiti Sains Malaysia for providing funding under the RUI grant (1001/PELECT/814170) in order to pursue our research in data link systems.

References

[1] D. Stewart, “A platform with six degrees of freedom”, Proceedings of the Institution of Mechanical Engineers 1965-1966, 1965, pp. 371-386.

[2] H.Jiang, M. Kesteven, W. Wilson, L. Chao-Te, N. Hiroaki, C. Ming-Tan, T. Huang, P. Koch, J. Chang, and D. Kubo, “A distributed control system for a radio telescope with six-meter hexapod mount,” in Control and Automation, IEEE International Conference on, Christchurch, Dec 2009, pp.2003-2010.

[3] J.P. Merlet, “Parallel manipulators: state of the art and perspectives” in Advanced Robotics. Vol.8 No.6, 1994, pp. 589-596.

[4] E. F. Fichter, “A Stewart Platform Based Manipulator: General Theory and Practical Construction”, in The International Journal of Robotics Research, pp. 157-182, June 1986,

[5] M. Maza, S. Val, and S. Baselga, “Control architecture of parallel and spherical driving simulators and related human factors,” in Robot and Human Interactive Communication, 10th IEEE International Workshop on, Bordeaux, Paris, pp.541-545, 2001

[6] N. Mimura, Y. Funahashi, "A new analytical system applying 6 DOF parallel link manipulator for evaluating motion sensation," in Robotics and Automation, IEEE International Conference on, vol.1, pp.227-233, May 1995,

[7] X. Huang, Q. Liao, S. Wei, and X. Qiang, “Forward Kinematics of the 6-6 Steward Platform with Planar Base and Platform Using Algebraic Elimination,” Proc. of the IEEE Int. Conf. On Automation and Logistics, pp. 2655-2659, Aug 2007

[8] C.A. Herda, "Implementation of a quadrotor unmanned aerial vehicle." California State University, 2012.

[9] S. Nasiri, L. Shang-Hung, D. Sachs, and J. Jiang, "Motion processing: the next breakthrough function in handsets." in InvenSense Inc., July 2009, 2010.

[10] S.H.Won, F. Golnaraghi, and W.W. Melek, "A fastening tool tracking system using an IMU and a position sensor with Kalman filters and a fuzzy expert system." in Industrial Electronics, IEEE Transactions on, 2009. 56(5): p. 1782-1792.

[11] E. Bachmann, I. Deman, U.Y. Usta, R.B. McGhee, X.P. Yun and M.J. Zyda, "Orientation tracking for humans and robots using inertial sensors." in Computational Intelligence." in Robotics and Automation, 1999. CIRA'99. Proceedings. 1999 IEEE International Symposium on. 1999.

[12] S. Naghshineh, G. Ameri, and M. Zereshki, "Human Motion Capture using Tri-Axial accelerometers". 2009.

[13] B. Huyghe, J. Doutreloigne, and J. Vanfleteren, "3D orientation tracking based on unscented Kalman filtering of accelerometer and magnetometer data." in Sensors Applications Symposium, 2009. SAS 2009. IEEE. 2009. IEEE.

[14] G. Chen, and E. Rodriguez-Villegas, "System-level design trade-offs for truly wearable wireless medical devices." in Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE. 2010. IEEE.

[15] N. Tackett, E. Jovanov, and A. Milenkovic, "An implementation of time synchronization in low-power wireless sensor networks." in System Theory (SSST), 2011 IEEE 43rd Southeastern Symposium on. 2011. IEEE.

[16] K. Kee Chen, "Wireless control of 6 DOF Parallel Manipulator with IMU Sensor (Accelerometer and Gyroscope) and Compass Sensor (Magnetometer)," in The Dissertation for Bachelor of Engineering, Universiti Sains Malaysia, 2013

[17] H. Ferdinando, H. Khoswanto, and D. Purwanto, "Embedded Kalman Filter for Inertial Measurement Unit (IMU) on the ATMega8535," Innovations in Intelligent Systems and Applications (INISTA), 2012 International Symposium on, Trabzon, July 2012, pp.1-5.