A SIMPLE APPROACH TO QUADROCOPTER FORMATION FLYING TEST SETUP FOR EDUCATION AND DEVELOPMENT

Qasim Ali, Sergio Montenegro

Aerospace Information Technology, University of Würzburg (GERMANY)

Abstract

A simple test setup has been developed at Institute of Aerospace Information Technology, University of Würzburg, Germany to realize basic functionalities for formation flight of quadrocopters. The test environment is planned to be utilized for developing and validating the algorithms for formation flying capability in real environment as well as for education purpose. An already existing test bed for single quadrocopter was extended with necessary inter-communication and distributed control mechanism to test the algorithms for formation flights in 2 degrees of freedom (roll / pitch). This study encompasses the domain of communication, control engineering and embedded systems programming. Bluetooth protocol has been used for inter-communication between two quadrocopters. A simple approach of PID control in combination with Kalman filter has been exploited. MATLAB Instrument Control Toolbox has been used for data display, plotting and analysis. Plots can be drawn in real-time and received information can also be stored in the form of files for later use and analysis. The test setup has been developed indigenously and at considerably low cost. Emphasis has been placed on simplicity to facilitate students learning process. Several lessons have been learnt during the course of development of this setup. Proposed setup is quite flexible that can be modified as per changing requirements.

Keywords: Design and development, formation flight, instrument control toolbox, Matlab, quadrocopter, test setup, unmanned aerial vehicle.

1 INTRODUCTION

With the advancement in Micro Electro-Mechanical System (MEMS) technology, Avionics and miniaturization of sensors; Mini Unmanned Aerial Vehicles (MUAVs) have drawn considerable attention, particularly during the last decade. Due to their affordability for common and versatile applications [1], ranging from toys to highly sophisticated applications like offshore wind power station monitoring, their popularity is growing exponentially. In order to increase efficiency and redundancy, researchers all over the world are now concentrating towards multiple MUAVs flying together and performing cooperative tasks. Some of the valuable applications in the domain of cooperative control include cooperative grasping and transport [2], traffic monitoring, search and rescue, mobile communication relays, pesticide spraying and weather monitoring etc. In recent years, Vertical Take-Off & Landing (VTOL) vehicles received more attention due to a number of advantages over fixed wing vehicles which are commensurate with their usage. VTOL vehicles are able to fly inside enclosed spaces and buildings without compromising on safety requirements. Though realization of multi-UAV coupled flight is complex, however obvious advantages justify the laborious work involved.

Cooperative flight is a multi-disciplinary topic involving Aerospace Engineering, Avionics, Control Engineering, Mechanical Engineering, Communication Systems and Information Technology; therefore addressed by researchers from diversified background. In recent years major contribution and innovation came from Information Technology involving embedded systems programming. Institute of Aerospace Information Technology, Wuerzburg University is distinctive in the perspective that it focuses on information technology only in the domain of aerospace and is the only Institute of its kind in Germany. It is building its own quadrocopters frame and programming algorithms. The Institute quadrocopter, shown in Fig. 1, spans 78 cm including rotor blades and weighs about 1.25 kg. It is able to lift approx. 1 kg of payload and has endurance of about 10 -15 minutes (depending on rotors speed) with 3 cell LiPo batteries (3Ah) and hence more flexibility to perform a number of tasks. The Institute had developed a test bench for quadrocopter [3] that is being used not only for education purpose but also for further development. The setup was fascinating for a large number of students who eagerly did their Bachelor and Master theses making use of this test bench. For our present study, same test bench was extended to two platforms (one *leader* and other *follower*) with necessary inter-communication to test the algorithms for formation flights. MathWorks MATLAB® Instrument Control

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Toolbox™ (ICT) was exploited to plot and analyse the data that is being received in real time through Bluetooth.

Fig. 1. Quadrocopter developed by Wuerzburg University

1.1 Related Work

A number of test setups have been developed for testing and validation of formation flight algorithms. Some noteworthy contributions in this domain are listed here. A formation flying test-bed was developed at Deutsches Zentrum für Luft- und Raumfahrt (DLR) Germany to support the design, implementation, testing and validation of real-time embedded Global Positioning System (GPS) based Guidance Navigation and Control (GNC) systems [4]. A testing platform was designed at Aerospace Controls Laboratory, Massachusetts Institute of Technology (MIT) to evaluate and compare different control algorithms for coordinated missions [5]. A micro Unmanned Aerial Vehicle (UAV) test bed at GRASP laboratory of University of Pennsylvania helped to support research on coordinated flight of micro UAVs [6]. A multi-vehicle platform was designed and developed at Stanford University for experimentation and validation of multi-agent control algorithms, using both centralized and decentralized approaches [7]. A UAV test bed was developed jointly by faculty members and the students at Brigham Young University for cooperative control experiments [8]. It provided opportunity for the students to have an exciting multi-discipline experience. A multi-UAV experimental test bed was designed at Utah State University with detailed presentation of algorithms on centralized formation controller [9]. Caltech introduced a platform for testing decentralized control methodologies for multiple vehicle coordination and formation stabilization [10]. This test-bed consisted of eight mobile vehicles, an over-head vision system providing GPS-like position information and wireless Ethernet for communications. These all test beds are quite sophisticated in nature. Our proposed test setup is indigenously developed at the Institute and offers all basic functionalities.

Main contribution of this paper is the realization of quadrocopter formation flight test-bed in 2 Degrees Of Freedom (2DOF) in its simplest form and at considerably low-cost. Our present paper describes in details the communication setup between quadrocopters; and plotting and analysing the results using MATLAB ICT while transmitting attitude information of leader and follower to a desktop PC using serial interface. Total cost for the complete setup is about 800€ (excluding PC). It includes two quadrocopter frames, four controllers / motors on each platform, two Inertial Measurement Units (IMUs), one AVR32 test board, one AVR32 on-board version, two Bluetooth modules, one USART-USB converter board, two rods and ancillary equipment to support quadrocopters. Details of the hardware are provided in further sections of this paper. Main motivation for this work was the development of a basic formation flying test bed with simple control techniques that can later be extended and upgraded for more sophisticated control techniques. Proposed setup is quite flexible and extendable.

Further description of this paper is organized into four sections. Section 2 introduces our test bench system architecture with related hardware components and software. Quadrocopter control and inter-unit communication setup details are described in Section 3. Section 4 narrates the experimental results and effectiveness of proposed approach. Finally conclusions are drawn, and future project directions are envisaged in Section 5.

2 FORMATION FLYING TEST ENVIRONMENT

2.1 Hardware

The quadrocopter on test bench developed at Wuerzburg University [3] is free to move in roll, pitch and yaw, as shown in Fig. 2. With the arranged hardware mechanism, it is possible to gain height up to a certain level; thus it offers four degrees of freedom. Quadrocopter is fixed in x-y plane so it is quite safe to evaluate different algorithms.

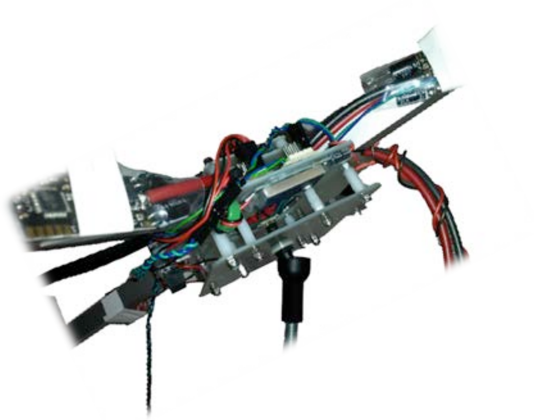

Fig. 2 Quadrocopter test bench mechanism

For our present study, this setup was extended to two stations having mutual communication through Bluetooth protocol that is a wireless version of Universal Synchronous/ Asynchronous Receiver/Transmitter (USART) protocol. Bluetooth BTM-222 modules, shown in Fig. 3, were exploited for this study. It is a class-I device from *Rayson* with a nominal range of 100m and operates in 2.4 GHz frequency range. Leader quadrocopter bluetooth was configured as Slave and follower quadrocopter module as Master, as information flow was from leader to follower. Baud rate was set as 57600 for communication.

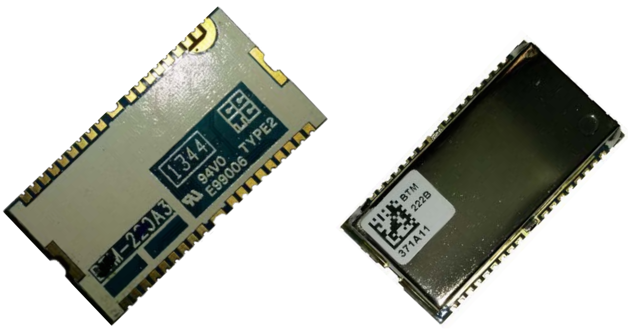

Fig. 3 Bluetooth module BTM-222 (front and back side)

Already existing test bench [3] is utilizing AVR32 micro controllers from Atmel [11] which are available in two versions; one for test purpose and the other for on-board installation shown in Fig. 4 and Fig. 5 respectively. The board has one Two-Wire Interface (TWI) and four USART interfaces. Test-version micro controller also has a small LCD screen for display, several push-buttons and LEDs which can be programmed as required. Further hardware includes an IMU on each station that is being used for determination of quadrocopters orientation. We used IMU3000 Combo from *Sparkfun*, shown in Fig. 6, to measure the attitude information at a rate of 100 Hz. IMU3000 incorporates ADXL345 accelerometer and ITG3200 gyroscope. Four brushless controllers drive the brushless motors.

Fig. 4 AVR32 controller test version

Fig. 5 AVR32 controller on-board version

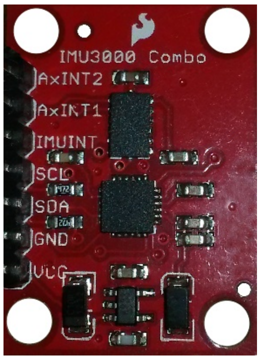

Fig. 6 IMU3000 Combo

2.2 Software

Following three software are used for this study; 1) AVR32 Studio to program the AVR32 micro controllers, 2) Terminal program HTerm for real-time display of attitude information of both quadrocopters, and 3) MATLAB R2014a with Instrument Control Toolbox ver. 3.5 for real-time plotting and storing the attitude information from both quadrocopters received through Bluetooth/ serial interface.

2.2.1 AVR32 Studio

Quadrocopter software was developed in C language by the Institute itself with main contribution by Dipl.-Ing. Nils Gageik. Software is of modular fashion that can easily absorb the modifications and improvements as well as new functions. It makes use of AVR32 Studio that is based on *Eclipse* environment. For this study, AVR32 Studio was used to program the attitude information exchange between the two quadrocopters through Bluetooth, and to send formatted information through Bluetooth/ serial interface to HTerm and MATLAB ICT for display and plotting purpose. Received information was also used at follower quadrocopter as reference value for Proportional-Integral-Derivative (PID) control.

AVR32 Studio is an Integrated Development Environment (IDE) that supports all Atmel 32-bit AVR applications. It is a C/C++ editor with syntax highlighting, navigation and code completion. Main features include project file management, and target configuration and management. The software suite is built on Eclipse for easy integration with third-party plugins for increased functionality. AVR32 Studio also supports development and debugging of standalone (without an operating system) applications [12]. The IDE integrates with the AVR32 GNU toolchain. The GNU C Compiler (GCC) compiles C/C++ programs, while the GNU Debugger (GDB) debugs the target application.

External debugger JTAGICE mkII can also be used that is Atmel's on-chip debugging tool for the AVR® microcontroller family. It supports debugging with AVR's traditional Joint Test Action Group (JTAG) interface [13]. The JTAGICE mkII allows access to all the powerful features of the AVR microcontroller.

2.2.2 Terminal Program HTerm

HTerm is a terminal program running on desktop computer that was used for; 1) configuration of Bluetooth BTM-222 modules, and 2) communication with AVR32 board at a baud rate of 57600 to display the attitude information of both quadrocopters. Communication port can be selected and different parameters like baud rate, data bits, parity bit and stop bit etc can be specified. Information can be exchanged with microcontroller through USART or Bluetooth interface. Output can also be saved in the form of a text file that can be post-processed for analysis purpose.

2.2.3 MATLAB Instrument Control Toolbox

Quadrocopter operation is controlled though embedded programming in C language. However MATLAB ICT was used to display and plot the pitch and roll information of both quadrocopters through USART-USB interface. Plots can be drawn in real-time and received data can also be logged in the form of files for later use and analysis.

This toolbox supports direct communication with serial port interface including Bluetooth protocol to read and write text data (ASCII coded) and binary data [14]. ICT supports Serial Port Profile (SPP) of Bluetooth. SPP Bluetooth devices can be identified and a two-way connection can be established. Remote name or remote ID can be used to communicate with a device. The toolbox can also be used in Simulink environment to fetch the data through serial COM Port. Roll / pitch information of leader is transmitted to follower after every 10ms. However for display and plotting purpose, data rate can also be controlled through embedded programming at follower.

There are three ways to receive data from AVR32 microcontroller to MATLAB ICT through Bluetooth; 1) writing a MATLAB script, 2) Using 'APPS' tab in MATLAB R2014a and then using Bluetooth node under 'Test and Measurement Tool', and 3) through a simple Simulink model using blocks of Instrument Control Toolbox. Method 2 has the limitation that it receives only one chunk of information till a *terminator* is reached, and is therefore not suitable for continuous data collection.

Bluetooth data can be read in two modes; *Continuous* or *Manual*. In *manual* mode, attitude information coming from quadrocopter is not automatically stored in the input buffer. We used *continuous* mode to put the data in input buffer and then reading it and converting ASCII to *double* format before plotting it. Initially only leader attitude information was sent to MATLAB through Bluetooth. Later, we organized that leader sends its roll / pitch information to follower and then we get the attitude information of both quadrocopters to MATLAB though USART-USB converter. MATLAB script is written to establish connection through serial interface between AVR32 micro controller and MATLAB ICT for reading and plotting attitude information. We organized the attitude data in the following order while sending it from micro controller of *follower* to PC;

pitch angle (leader), roll angle (leader), checksum (leader), pitch angle (follower), roll angle (follower)\n

The MATLAB code has been tailored keeping in view the received information order.

3 COMMUNICATION AND CONTROL

3.1 Information to be Shared between MUAVs

A flying vehicle has 12 states in general, namely the position coordinates (x,y,z); velocity components (u,v,w) along the three-axes; roll, pitch and yaw angles (Φ,θ,Ψ); and the angular rates (p,q,r) measured along the three-axes [15]. Relative position, velocity and attitude are considered as the minimum variables to be determined for cooperative control. As quadrocopter position is fixed on a mounting rod, so we transmit leader attitude information (as reference values) to follower using BTM-222 module. Roll / pitch information sent from one AVR board to the other is ASCII coded.

3.2 Communication Media

Communication media including Bluetooth, WiFi and XBee were explored for this study keeping in view bandwidth, cost and power consumption. Bluetooth was selected due to its ease of use, low-cost and low power consumption. Though bandwidth is low, but for our present study this is sufficient to meet the purpose.

3.2.1 Bluetooth Communication

Bluetooth protocol has been used in two scenarios; 1) inter-communication between quadrocopters and 2) communication between quadrocopter and desktop PC. For inter-quadrocopter communication, BTM-222 modules have been used (introduced in sub-section 2.1) and for second scenario, Logilink USB Bluetooth V4.0 Dongle has been used that is also a class 1 device. Logilink dongle is automatically configured, while BTM-222 module is to be configured by the operator before using it.

A USB Bluetooth adaptor is plugged into the computer to establish communication between micro controller and MATLAB ICT, while laptop computers already have a built-in adaptor. When a Bluetooth adaptor is plugged in a PC, two virtual serial ports are generated, that can be seen in the port field, one for incoming data and the other for outgoing data. In case of *incoming* COM port, device initiates the connection and in case of *outgoing* COM port, computer initiates the connection. ICT can identify Bluetooth devices within range when queried. Logilink Bluetooth dongle was used to communicate with Bluetooth of *leader* quadrocopter to acquire the attitude information. Communication architecture among different elements is shown in Fig. 7.

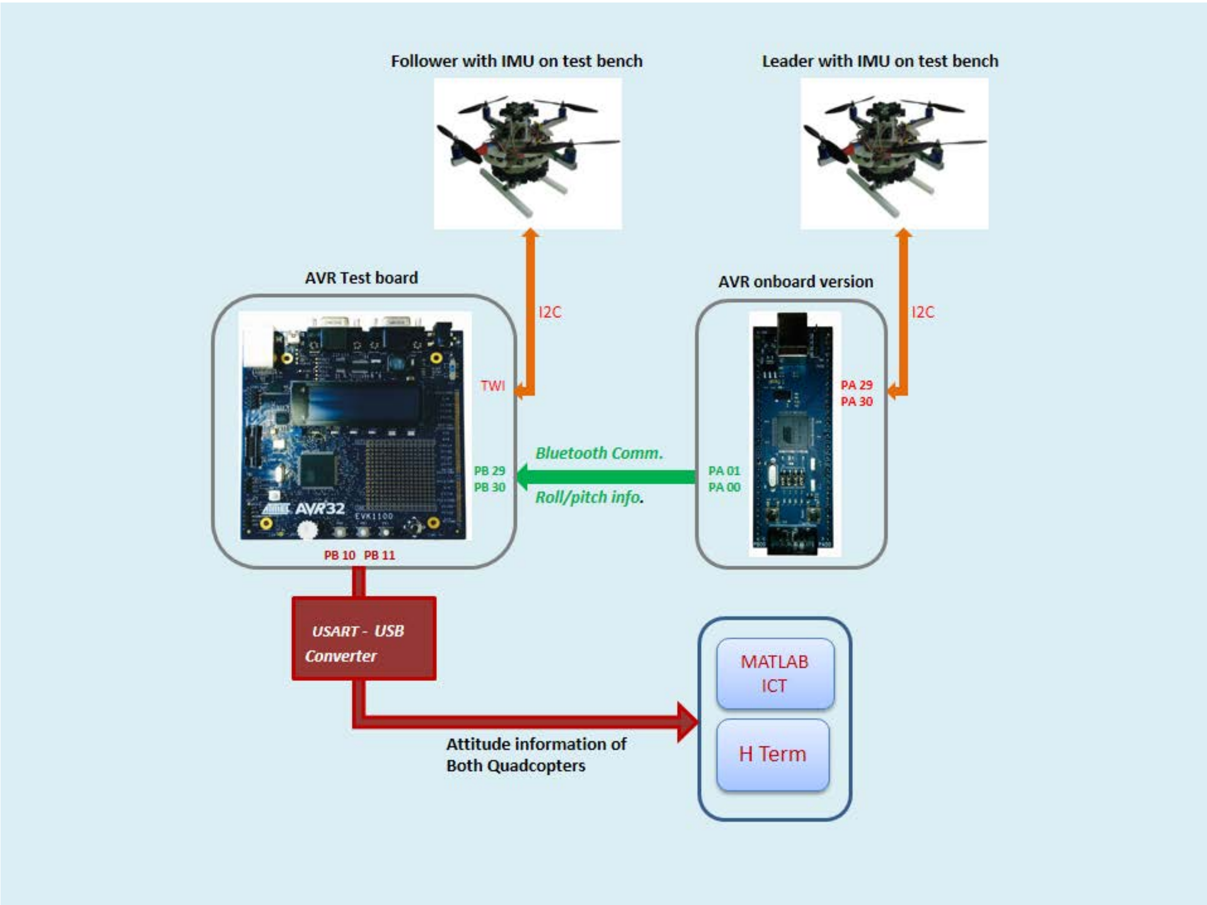

Fig. 7 Layout for complete test setup

3.3 PID Control and Kalman Filter

Before applying sophisticated control techniques, it was planned to employ a comparatively simple approach of PID controller. It is the most widely used controller due to its ease of application. Performance may be improved while using it in combination with Kalman filter. Here Kalman filter reduces the measurement noise to extract the 'true' signal to be used for feedback purpose.

PID controller is principally a linear combination of Proportional, Integral and Differential of error to generate the control signal for the system under consideration. Here error is the difference between reference value and filtered output of the system. PID controller application necessitates to adjust in an iterative manner the three parameters K_P, K_I and K_D, referred to as tuning parameters. K_P is the proportional gain, K_I is the integral gain and K_D is the derivative gain. System performance depends on these three parameters. Mathematically PID control law can be expressed as follows [16]:

$$u(t) = K_p\, e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de(t)}{dt}$$

or alternatively [17];

$$u(t) = K_p\, [e(t) + \frac{1}{T_I} \int_0^t e(\tau)d\tau + T_D \frac{de(t)}{dt}]$$

Here $e(t) = r(t) - y(t)$ is the error signal, K_p is scaling factor, T_I is integral time constant and T_D is derivative time constant. PID control can usually perform in a variety of settings without the need for a precise model of the underlying plant that is a big advantage when system identification is either difficult or imprecise [18]. However this control technique is not suitable for sophisticated applications where high accuracy is required; as PID controller suffers from limitation in optimality and robustness. Also it is demanding to tune the parameters under some conditions.

PID controller and Kalman filter were used in [19] to design UAV formation flight control system for speed and pitch angle, and *simulation results* demonstrated feasibility of the method. The study concluded in [19] demonstrated that Kalman and PID control performs adequately for short transition, and anti-disturbance. Results showed good stability, precision and control. For our present study, we have employed the technique on *real hardware* for roll and pitch angle only. It fulfils the requirement of real-time and accurate control.

Filtered attitude information of Leader quadrocopter was communicated to follower quadrocopter with an interval of 10ms where it was treated as reference values to generate the error signal for implementation of PID control. PID control comes into action for each received information. Follower reacted to the received information to exhibit the same attitude. Proposed approach is shown in Fig. 8.

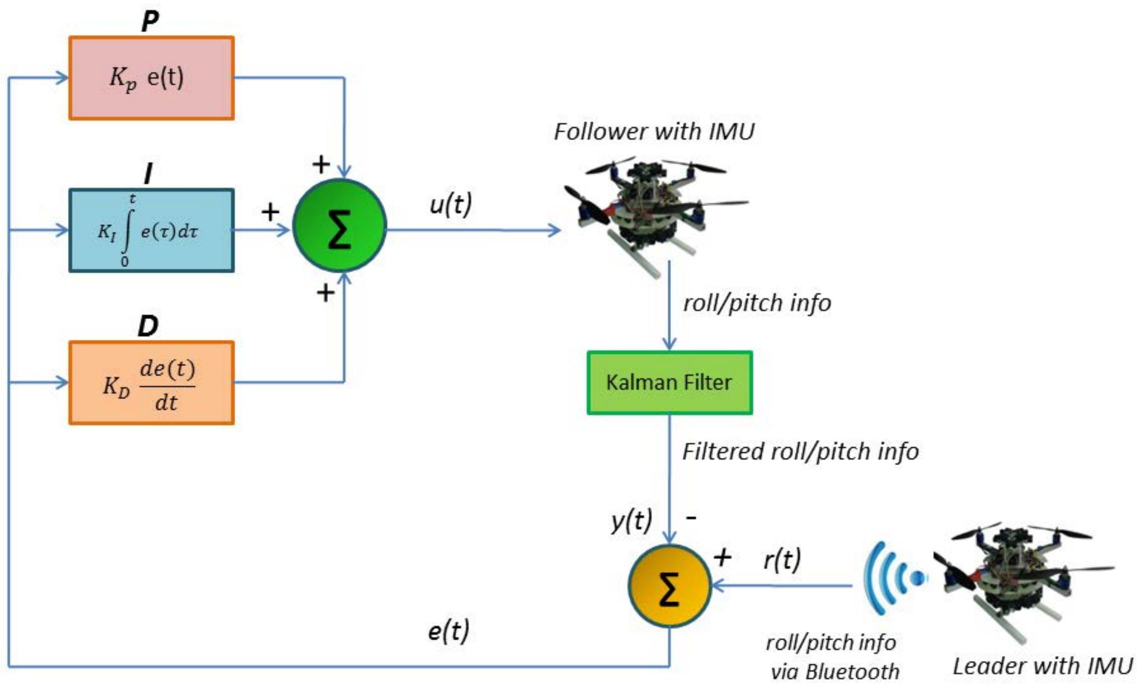

Fig. 8 Block diagram for implementation of PID control in leader-follower architecture

This scheme can later be extended with inclusion of yaw and 3D position for formation flying in real time while incorporating suitable sensors. This is the simplest approach that can be used for formation flight of multiple quadrocopters. Students can implement other control algorithms as well that can be tested and subsequently employed for formation flying in real-time.

4 RESULTS

Attitude information of leader quadrocopter was sent to follower that followed the same attitude values making use of PID control combined with Kalman filter. Attitude information of both quadrocopters was directed to MATLAB ICT for data plotting and analysis purpose. Main concern was communication data packet loss and communication / computation latency. Data integrity was addressed with the introduction of checksum function. Results to this effect are shown in Fig. 9 for 1 minute that indicates that the follower followed to leader attitude in real-time without causing much time delay. It also shows the effectiveness of PID control (in combination with Kalman filter) that is considered to be a simple control technique, though it served the purpose. The scheme has been extensively tested and refined during the course of development. As a simple checksum function has been implemented, so we can see a jump phenomenon (for two readings out of six thousand readings) in sensor measurements for the leader. It suggests that data integrity mechanism may be further improved. The test setup is basically a foundation for implementation of sophisticated techniques in the domain of distributed control. It is planned to be used as an educational tool and for testing and validating the algorithms for cooperative control in real-environment.

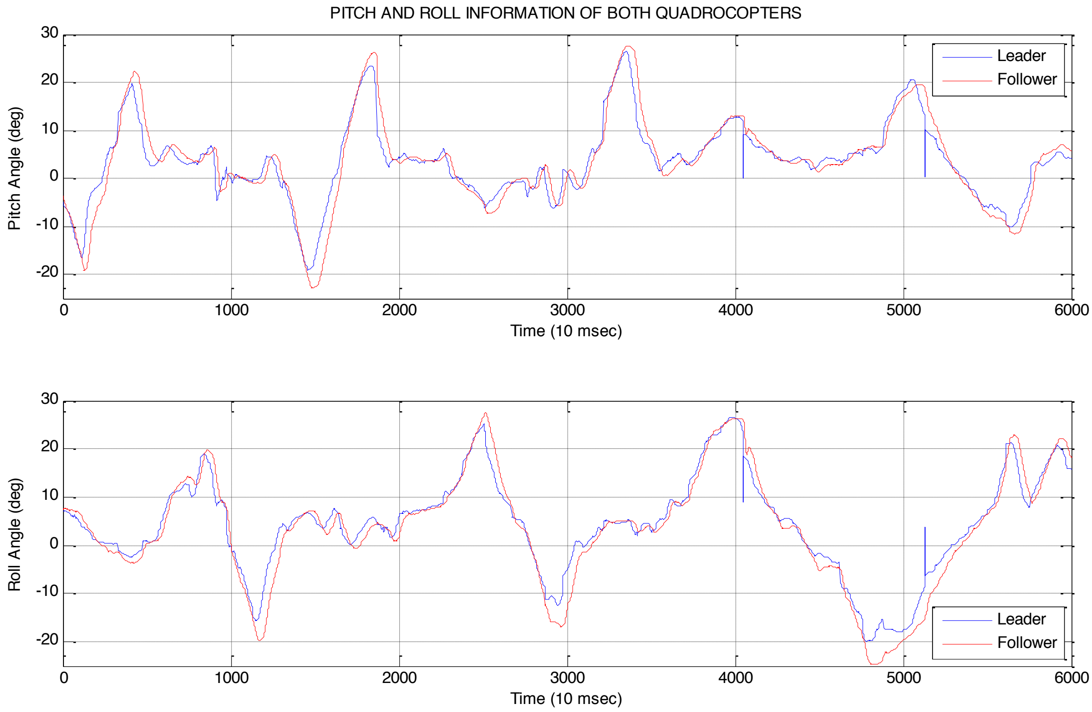

Fig. 9 Attitude information of both quadrocopters

5 CONCLUSION AND FUTURE WORK

An elementary real-time formation flying test set-up in 2DOF has been conceived at Institute of Aerospace Information Technology, Wuerzburg University. Proposed approach appears to be useful for further research projects as well as for education purpose. It served as a basis for realization of synchronized attitude of two quadrocopters in real-time. Same setup can be extended to multiple quadrocopters making synchronized motions. A magnetometer can be added to extend the setup to 3DOF (roll / pitch / yaw). As it is possible for quadrocopter on rod to gain height up to a certain level, so with the addition of a height sensor the setup may even be extended for forth degree of freedom. Existing ground station for controlling one quadrocopter is also planned to be extended for two quadrocopters. Transmitted data integrity algorithm may also be improved.

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