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Development and Evaluation of System Level Architecture for Autonomous Mini Helicopter

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Abstract**—**Autonomous vehicles have been in development for several years as they can find use in a wide variety of missions such as surveillance, rescue, terrain mapping, etc. Currently, a research on development of an autonomous mini helicopter is under progress at Department of Aerospace Engineering, IIT Kanpur, India. This research project mainly focuses on developing various sensors and communication units, actuators and integrating them onboard a mini helicopter and interfacing them with ground station, having the control logic algorithm to provide autonomous control and navigation capability. The objective of this paper is to describe the complete system architecture comprising of ground station, wireless systems for communication and onboard electronics. This paper also explains the RPM control logic algorithm deployed at the ground station unit. The results of autonomous flight of mini helicopter are also discussed in this paper.

Keywords**—**Ground station, wireless communication, autonomous mini helicopter, onboard system.

I. Introduction

In recent years, the understanding and development of unmanned aerial vehicles has grown exponentially. These vehicles can fly either autonomously by computers or under the remote control of a pilot at the ground station. Although unmanned aerial vehicles have been designed and developed for performing military missions, currently the trend is to extend their applicability to civil missions such as firefighting, critical infrastructure protection or remote surveillance [1]. The main advantage of unmanned aerial vehicle is the absence of the pilot on board the vehicle. This feature allows using them in dangerous and risky missions for the safety and the lives of pilots. Unmanned rotary wing vehicles have attracted a great deal of attention all over the world, due to their unique hovering capability and ability to land and takeoff from confined spaces [2]. There are many types of unmanned rotary wing vehicles like single main rotor- tail rotor combination, tilt rotor, co-axial rotor [3] and multi rotor (quad or more) system. Quadrotor vehicle consists of two pairs of counter-rotating rotors located at the vertices of a square frame. Due to its simple mechanical structure, it has been envisaged for various applications. Ref [4] describes the steps of designing, building and simulating an intelligent flight control module for a quadrotor UAV. Quadrotors have a limited payload capacity because they require four motors for operation, which consumes more power than conventional UAV. This reduces the number of sensors and mission critical equipment they are able to carry. Due to this limitation researchers have turned to vision based techniques for navigation of UAVs. In [5], vision based navigation provides the basic control functions of keeping the quadrotor attitude control, controlling the vehicle trajectories when flying in free spaces, and keeping the altitude at proper height over ground. In [6] and [7], the authors have designed a control mechanism that will maintain the horizontal attitude of quadrotor helicopter under all circumstances. The objective of ref [8] was to broaden the applicability of the quadrotor helicopter through the development of an airframe that enables the aircraft to maintain a horizontal attitude even when moving or being subjected to crosswinds. In [9], a newly developed Ducted Fan Object (DFO) equipped with normal and reverse rotation ducted fan to cancel gyro moment effect was successfully tested for stable take off/landing and hovering. In [10], a path planning method based on linear programming is proposed in the relative coordination to complete an autonomous landing task.

The development of new unmanned platforms capable of performing autonomous operations is nowadays becoming a major research area. Major universities and academic institutions around the world are working on developing autonomous aerial vehicles [11]. Department of Science and Technology, Govt. of India initiated a research activity at IIT Kanpur to set up a laboratory for design and development of autonomous mini helicopter. Autonomous systems represent a promising evolving area in particular with respect to research in embedded systems. These embedded systems have specific requirements such as high reliability and realtime response, security and performance. An architecture model takes all these issues into account, and that provide compliance with standards and enables accurate development [12]. The major focus of this research activity is to develop system level architecture for a mini helicopter such as ground station unit, onboard systems, and communication systems and control logic algorithm to provide the autonomous control. Accordingly, the research activity was grouped into three main categories viz., ground station unit, communication systems, and onboard systems. A ground station is usually a computation unit running a software application which is used for controlling the vehicle by sending signals and receiving onboard sensors data. Its purpose is to provide facilities for human control of the vehicle and display real time data about the condition of the vehicle. Onboard

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electronics includes the sensors IMU, RPM, sonar, gyro which sends the flight data to the ground station for feedback and actuators which are used to control the helicopter. Wireless system enables mini helicopter to transmit data to and receive control commands from ground station unit. During the progress of this research, test setups for sensors and actuators have been designed and developed [13].

II. GROUND STATION

The ground station design is one of the most important factors in the success of an autonomous flying vehicle. For the mini helicopter, all the control logic calculation takes place on the ground station. Ground station of mini helicopter is as shown in **Figure 1**. It consists of a personal computer system, National Instruments PXI 1042-Q Real Time system, RC transmitter and wireless units [14]. This PXI system is a headless embedded system, which means it does not have a monitor, keyboard or mouse that lets the user interact with it directly. It also does not have any hard disk storage. RT PXI has 3 slots with data acquisition and signal generation cards and 8109 embedded controller. This RT PXI communicates with the main computer through an Ethernet cable. The main computer is host computer, and PXI is known as target computer. Control algorithm is developed in the host computer using LabView real time graphical programming language and then deployed into the PXI system. The main control logic runs on the PXI and the user interface runs on the host computer simultaneously so that user inputs are communicated to the target and all the sensor and control inputs and outputs are shared to the host computer. Also to minimize time delays, the communication between the two systems has to be as compact and short as possible. This is done by sharing the least amount of information possible between them. These are known as network shared variables.

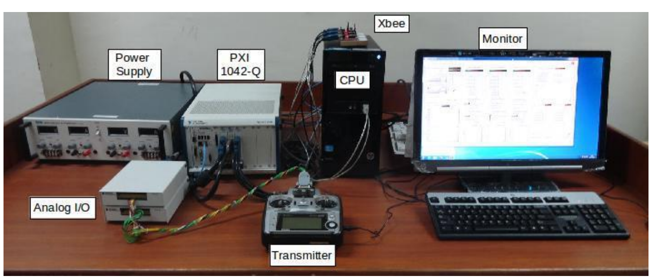

Figure 1 Ground Station Unit

The control of the mini helicopter is achieved by controlling the servo actuators on the vehicle using the radio unit. This radio unit is interfaced with the PXI systems such that it can wirelessly transmit the control signal generated by the PXI system or the signal generated by the radio control (RC) pilot to the servo actuators on the mini-helicopter through the on board receiver units. The Futaba 10CHP 10 channel radio control system along with the R1410DP receiver is used for the wireless control of the helicopter. The system works at a frequency of 35.17 MHz. The transmitter has a total of 2 levers or joysticks. There are 3 knobs and 8 switches available. There are 4 trim buttons present. The programming on the display can be navigated using a dial and a cursor. The transmitter is powered by a rechargeable 9.6V NiCd battery. If need arises, a regulated power supply unit can be used to power the transmitter instead of the battery.

The left joystick is free to move in the fore-aft direction. This is for the collective control. However, the left-right direction is spring loaded so that it always maintains the middle position. This is the tail control. On the other joystick however, both the degrees of freedom are spring loaded. The up-down direction is for the swash-plate pitch or longitudinal motion and the left-right direction is for the swash-plate roll motion. The middle knob is used for throttle control. Each motion of the joystick is connected to the shaft of a potentiometer. Hence there are four potentiometers for the two joysticks. Each knob too is connected to a potentiometer. The potentiometer voltages are fed into the microprocessor of the transmitter, which according to the user settings and programming converts the signals from the joysticks, knobs and switches into appropriate radio signals for each channel and transmits them to the receiver. Normally, the output wire from the potentiometer is connected to the microprocessor in the transmitter. In our case, each potentiometer output wire was split into two parts. The part connected to the potentiometer was sent to the PXI as an input voltage, and the part connected to the transmitter microprocessor was connected with the output voltage from the PXI. **Figure 2** shows the schematic diagram of signal flow at the ground station.

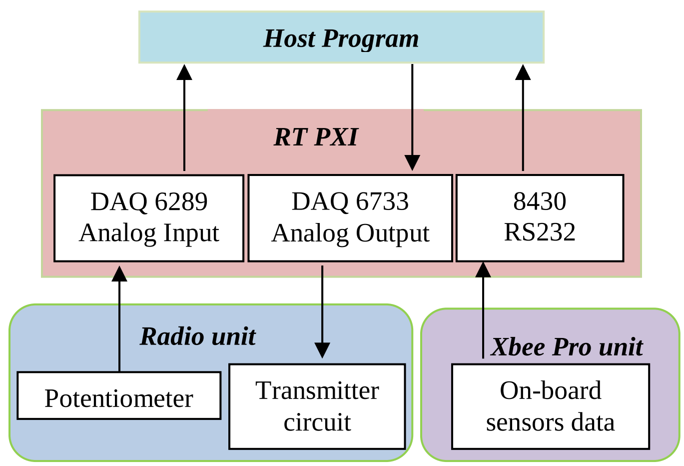

Figure 2 Schematic diagram of signal flow at the ground station

The RT PXI system acquires the on board sensors data from Xbee unit, which is used as feedback for the main control logic. XBee-Pro modules of 60mW power and transmitting at 2.4 GHz are being used for downlink part of the communications. Downlink consists of all the data sent from RPM, sonar and IMU sensors to the ground station at 250 kbps. At the ground station, these X-Bee pro modules receive the data and supply the PXI systems with the data for feedback. Three modules are currently wired to the ground station through RS-232 port.

The front panel of the ground station software for the data visualization and data logging is as shown in the **Figure 3**. The most essential component of the ground station software is the control logic. The main controls involved in helicopter stabilization are RPM, height, pitch roll and yaw control [15]. This was implemented by sending control signals to the servos controlling throttle of the engine, collective, lateral, longitudinal and tail of the mini helicopter.

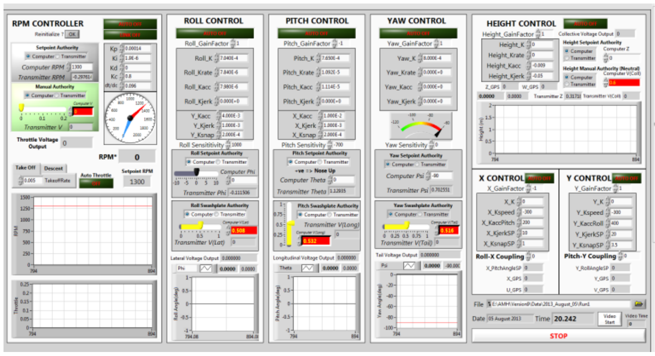

Figure 3 Front panel of the ground station software

The RPM control loop uses the conventional PID closed loop system and a feed forward mechanism to couple the collective pitch angle to the throttle [16]. The closed loop diagram for the RPM control is as shown in the **Figure 4**. In addition to the closed loop control, a feature known as auto throttle is implemented.

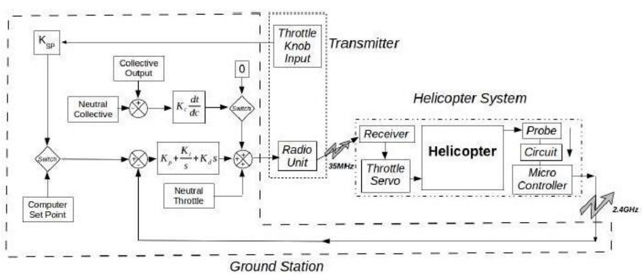

Figure 4 Closed loop RPM control

The auto throttle mechanism is basically a ramp control input to the system. There are two modes for this feature, the take-off mode and the descent mode. In the take-off mode throttle increases linearly with time and in the descent mode throttle decreases linearly with time. In the take-off mode, if the RPM exceeds the set point RPM the feature automatically cuts off and throttle attains a steady value. This feature is very useful for quick increase or decrease in RPM. Once the RPM reaches the set point, auto RPM and collective link should be turned on to hold the RPM at the set point.

The RPM obtained from the sensor is used as a feedback to the throttle. The throttle position when the auto RPM is turned on is stored as the neutral throttle. To this value, the control compensation and feed forward compensation is added. In the control compensation, difference between reference RPM and feedback from the system is multiplied by control gains proportional, integral and derivative values. In the feed forward mechanism, the final output to the collective servo is used to counter the effect of change in aerodynamic drag on the rotor and hence change in RPM. The difference between current collective link and the neutral collective is multiplied by collective link factor and added to the output of the RPM control. The collective link factor is nothing but the slope between the changes in throttle with change in collective. The value of this factor is obtained from open loop experiments.

The pitch control logic is as shown in the **Figure 5**. The closed loop roll control is identical to pitch control loop. It consists of two loops. The inner loop consists of quantities related to angle and its time derivatives. The measured angle is subtracted from the reference angle and multiplied by the angle gain. The rest of the quantities are negated and multiplied by their individual gains which are fed as the control compensation to the servo. This compensation is added to a neutral roll or pitch component. This neutral component can be changed during operation, either from the computer or from the radio transmitter, depending on the authority chosen. The reference angle for the inner loop is a sum of two components. The first component is obtained by multiplying appropriate gains to the error signals. The second component is the value chosen on the computer screen or input by the joystick. This input will be in volts. It is multiplied with a number called sensitivity which converts it into degrees. The sensitivity of the joystick is adjusted by changing the value of Ksp.

Thus roll and pitch of the helicopter are also controlled by the system. However, pilot can give an additional input from the transmitter, to make minor corrections to the helicopter during flight.

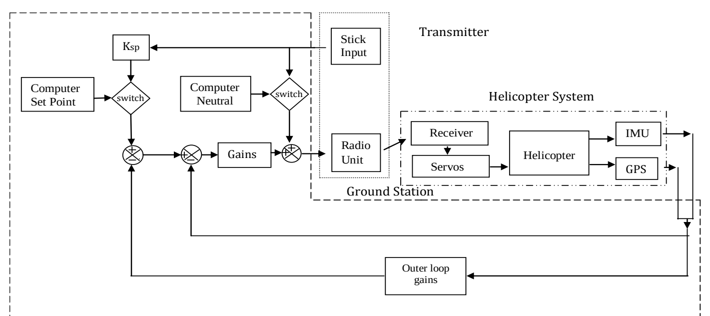

Figure 5 Closed loop pitch control

III. ONBOARD ELECTRONICS

There are several electronic components that have been used on helicopter. Their set up and calibration plays an important role in the conduction of experiments. On board electronics includes the sensors (IMU, RPM, sonar, GPS) which send the flight data to the ground station for feedback and actuators (servo) which are used to control the mini-helicopter.

A. IMU

The inertial measurement unit is at the heart of the control of mini helicopter. The IMU used is the 3DM-GX1 from microstrain [17]. It contains three accelerometers, three rate gyros and three magneto meters. Three magnetometers in the IMU allow better performance for dynamic orientation calculation in attitude and heading [18]. Ref [19], describes the calibration and 6-DOF test of a unique inertial measurement unit (IMU) using a Quadrotor aircraft. The IMU has an embedded microprocessor with which it is able to calculate and output data in the form of Euler angles, accelerations, rotation rates, magnetic field and quaternions. The IMU operates in the polling mode, and uses RS232 serial port communication. In this polling mode, a command is sent to the unit. Based on the required output of the command the instrument replies. The IMU has its own filtering algorithms with which it outputs 'gyro-stabilized' accelerations, rate and angles. There are two types of error that are found in accelerometer and rate gyros. These are bias and drift. A bias is a constant offset component in the sensor output. A drift is an error that keeps on increasing or decreasing linearly with time. The use of gyro stabilized output from the sensor removes these errors to a very large extent. An estimate of the gyro stabilized filtering capability can be seen in **Figure 6**. The black line represents the raw data and the red line represents the gyro stabilized data at the same position.

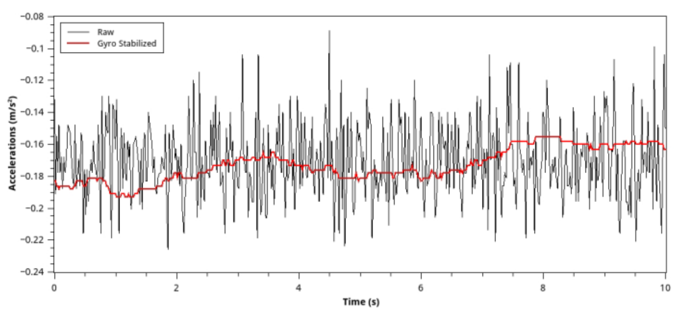

Figure 6 Raw and Gyro Stabilized X acceleration data

B. RPM

The measurement of RPM is performed using a magnetic probe and collar. The collar is attached to the rotor shaft. On the collar eight magnets are fixed such that their north pole point outwards from the collar. The magnetic probe is mounted on the helicopter such that it faces magnets of the collar. The magnetic probe is a self-excited and non-contact based device, which gives a voltage output proportional to the speed of passing magnetic field. The voltage output of the probe for the given magnets and the range of RPM is in between ±0.4v.

Figure 7 RPM SONAR board

This voltage signal is very noisy. This signal will be sent to the RPM SONAR board which eliminates the noise in the circuit and amplifies the signal. **Figure 7** shows the RPM SONAR board. To eliminate the noise in the circuit and amplify the signal, a dual operational amplifier LM358 was implemented as a low pass amplifier circuit and inverting comparator. The output of the comparator portion of the circuit is shown in the **Figure 8**. The Basic Atom Pro microcontroller has been used for the RPM and sonar measurements. The microcontroller has its own language and development environment. Its purpose is to act as an interface between the ground station and the two sensors. It communicates with ground station using serial port interface on the XBee units.

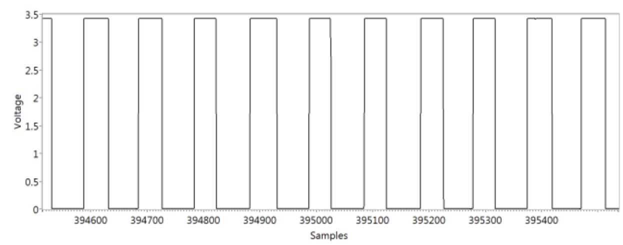

Figure 8 Comparator output

C. SONAR

Sonar is used to determine the height of the vehicle above the ground. The sonar sends out a pulse, and measures the time taken for the pulse to reflect back. It uses the speed of sound in air and the time of flight to determine the distance from the object. One of the critical specifications of the sonar is the frequency of sound used. The frequency of sound determines the cone angle of the sound pulse. As the sound leaves the sonar, it tends to expand to form of a conical lobe. The closest object inside lobe reflects the sound. High frequency sounds form a sharper or small half angle cones. The reflected sound also travels back in the form of a cone. The sonar must lie within this cone to receive this echo. It offers precise ranging information from 3cm to 6m in steps of 1cm. The sonar module communicates using the inter integrated circuit bus. The sonar requires four connections the ground, 5v, SDA and SCL pins. These are communicating with Basic Atom Pro module

D. GPS

The global positioning system is a network of satellites that orbit the earth. These satellites transmit signals that can be received by a GPS antenna. We use a NavStik microcontroller unit connected with a UBlox 6 GPS module, GPS antenna and an lvyXB module for wireless transmission. The expansion board being used with NavStik is the lvyEZ. We are using this expansion board since it allows a telemetry connection and regulates power supply from an input of 5v, which is available from UBEC.

E. Actuators

Servo actuators are the electromechanical components of the mini helicopter. They use error sensing negative feedback to correct the performance of a mechanism. The movement of the servo arms is a result of a pulse width modulated signal fed to the servo. There are two types of servos being used on the helicopter [20]. For the throttle, collective, lateral, longitudinal motions Futaba S3151 servos are used. For the tail rotor S9256 is used. The GY611 gyro is a commercial yaw controller which has been used on the mini helicopter along with the S9256 servo. The S9256 servo operates at a 760µs pulse width corresponds to nearly 1316 Hz. The GY611 gyro gives a more accurate and fast angular rate response to the controller. The controller generates PWM signal for the servo. It obtains feedback as the yaw rate from the gyro, and also the yaw input from the pilot. Based on these it gives a control command to the tail servo. There are two modes available, the normal mode and the AVCS mode. The controller can also switch its control mode from the switch input from channel 5 from ground station radio unit.

F. Power Units

The universal battery elimination circuit is connected to the battery at 11.1v. It has two regulated outputs, which can be at 5v or 6v depending on the requirement. There are two UBECs being used on the mini helicopter. One UBEC labeled sensor UBEC, which powers RPM-Sonar circuit and the IMU. The other UBEC is labeled as the servo UBEC, which powers the receiver circuit and sensor unit.

IV. COMMUNICATION SYSTEM

There are two types of communication units being used for the experiments. For sending commands to the actuators on the system a modified RC transmitter is used. The data from the on board sensors is sent to the ground station by the XBee wireless module. Wireless communication can be categorized as uplink and downlink.

Uplink constitutes all the signals which are being sent from the ground station to the helicopter using radio transmitter and receiver units. The working of the transmitter units has already been explained in the earlier sections. Wireless radio receiver units complement the radio transmitter units. Futaba 10 channel receiver is placed on board the mini-helicopter. This receiver unit needs to be placed away from electromagnetic noise sources like the IC engine so as to eliminate any interference and malfunction of the servos.

Downlink consists of transmitting on board sensor data from helicopter to the ground station. There are a total of six XBee Pro modules being used. Three of them are the transmitting onboard sensors data which are installed on the helicopter, while the corresponding receiving units are connected to the ground station. These XBee Pro units are configured such that they should not interfere with each other. The configuration of these XBee Pro will be done by using XCTU software. The three pairs are used for IMU, RPM-Sonar, and GPS data respectively. IMU is the important sensor among all, which gives vehicle attitude, rates, and translational accelerations. The data from IMU plays a vital role in stabilizing the vehicle. So it has a higher data rate compared to other two sensors. Thus we are using separate XBee Pro for IMU. Another XBee Pro is used for transmitting combined data of RPM and Sonar. Third XBee Pro unit is used to transmit GPS data. This XBee transmitting data at 9600 baud rate whereas the other two XBee are transmitting data at 38400 baud rate.

The XBee Pro units communicate using the serial port interface. The three XBee Pro receiver units are mounted on the RS232 explorer boards at the ground station. The board is powered by using USB cables and RS232 ports from the PXI are connected to the XBee Pro to obtain the data. The operating frequency of these XBee Pro modules is 2.4GHz. It has an Indoor range of 90m and line of sight range of 1600m.

V. SEMI-AUTONOMOUS FLIGHT TEST

After the integration of on-board sensors and implementation of ground station, the mini helicopter was flown with tethers inside the laboratory [21] as shown in **Figure 9**. All the data such as throttle, collective inputs and vehicle state from the onboard sensors during hovering of the helicopter was acquired by the Real Time PXI system and was stored in host computer. The graphs related to this flight are plotted in **Figure 10-26**.

Figure 9 Indoor semi-autonomous flight

The RPM of the main rotor is varied by moving the throttle opening position of the engine. This is done by using the throttle servo arm lever. The throttle servo is controlled by a pwm signal which is transmitted by radio unit. **Figure 10** shows the main rotor RPM of the mini helicopter and the corresponding throttle value is shown in **Figure 11**.

Initially RPM starts increasing linearly with throttle and it holds at 1300 as the closed loop RPM control was turned on and set point was given 1300. Approximately it took 100sec to reach RPM set point value. It can reach at faster rate if we increase auto throttle take off rate.

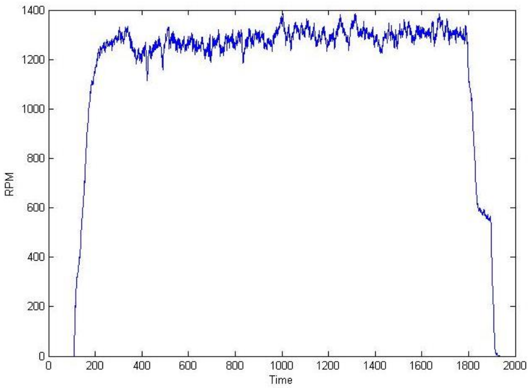

Figure 10 RPM input

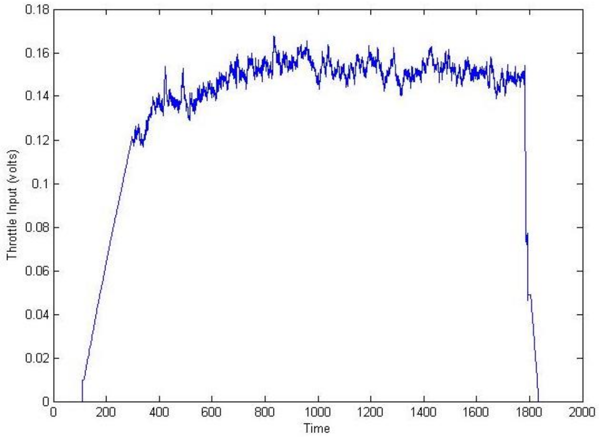

Figure 11 Throttle input

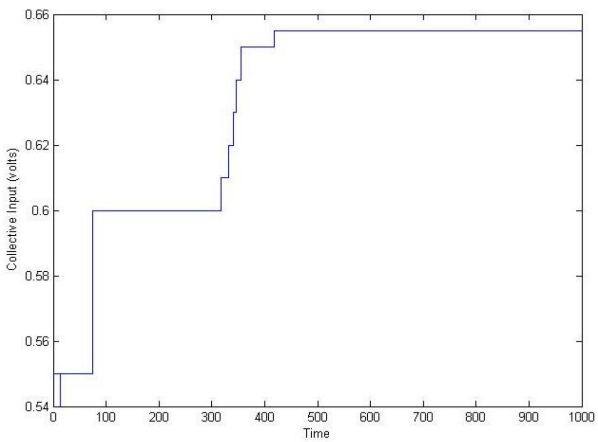

Figure 12 Collective input

The collective input to the helicopter is shown in **Figure 12**. Initially it was at 0.6volts. We increased this value by 0.01 steps and helicopter was hovering at 0.655 volts of collective.

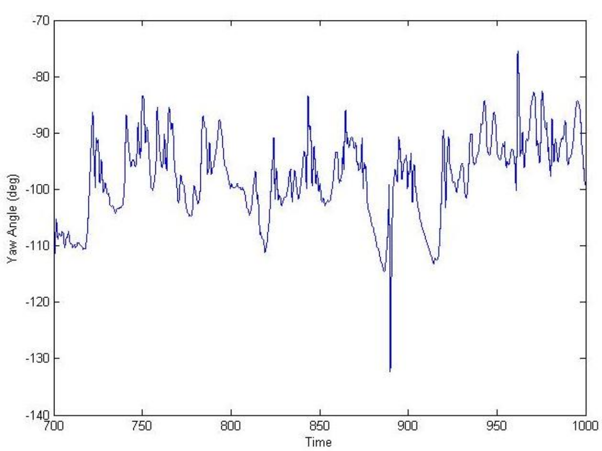

Figure 13 Yaw angle

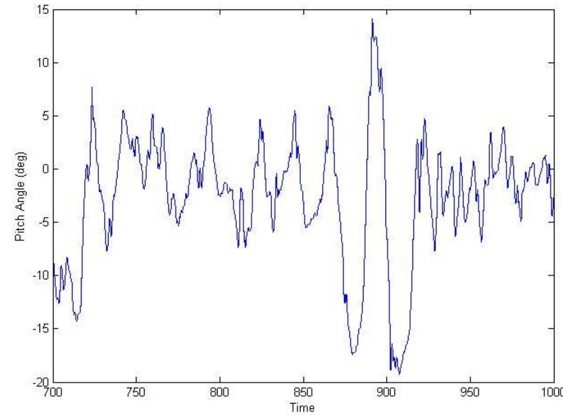

Figure 14 Pitch angle

Yaw angle of mini helicopter is as shown in **Figure 13**.The pitch angle and pitch rate of the mini helicopter are shown in **Figure 14** and **Figure 15**. The pilot could hold the vehicle mostly between +6deg to -6deg except during a short period when the angle changes between +15deg to -20deg. During this time the pitch rate observed is in between +10deg/s to -10deg/s.

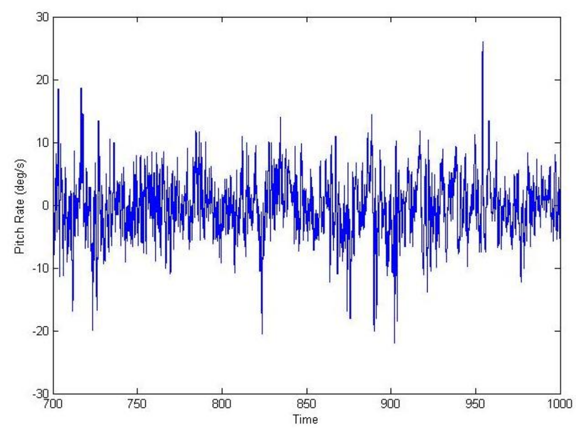

Figure 15 Pitch rate

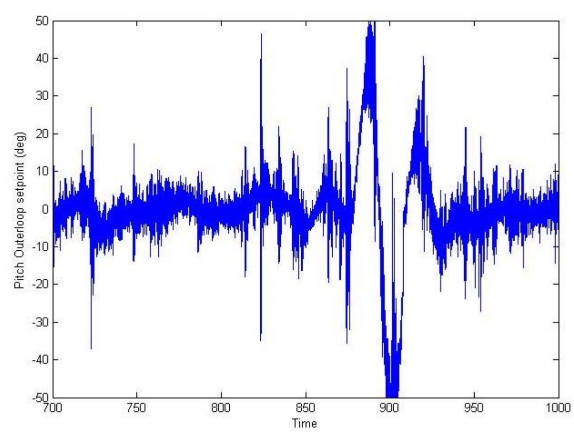

Figure 16 Pitch outer loop set point

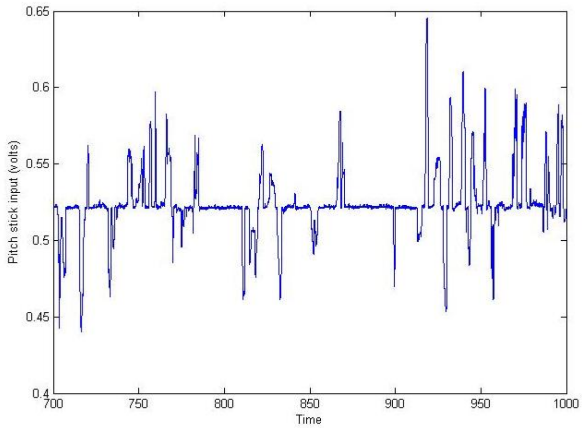

Figure 17 Pitch input by the pilot

The pitch feedback input given by the system is shown in **Figure 16**. The longitudinal input given by the pilot to maneuver the vehicle in this attitude band is in between 0.45 to 0.6 with a mean of 0.522 as shown in **Figure 17**.

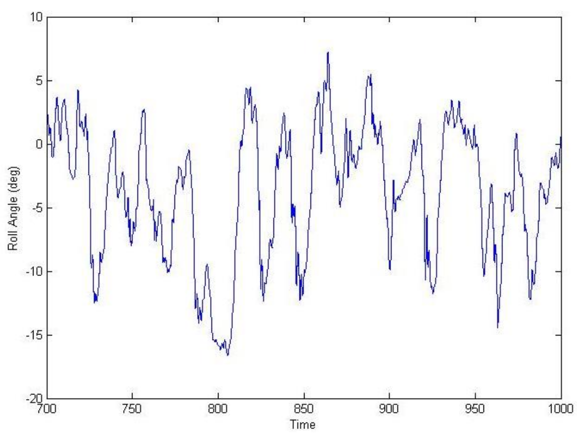

Figure 18 Roll angle

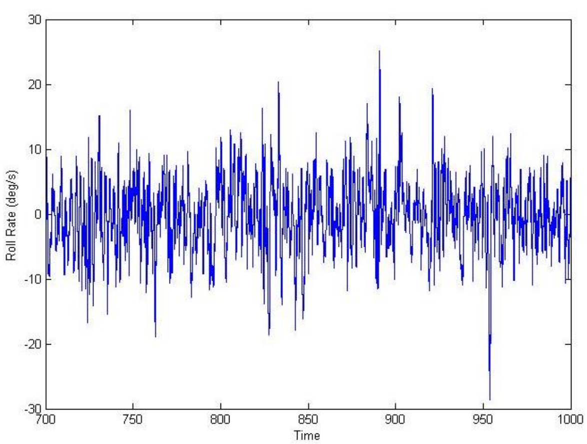

Figure 19 Roll rate

The roll angle and roll rate of the mini helicopter are shown in the **Figure 18** and **Figure 19**. The pilot could hold the vehicle between +5deg to -10deg, except during certain time instants. During this time the roll rate observed is in between +15deg/s to -15deg/s. The roll feedback input given by the system is shown in **Figure 20**.

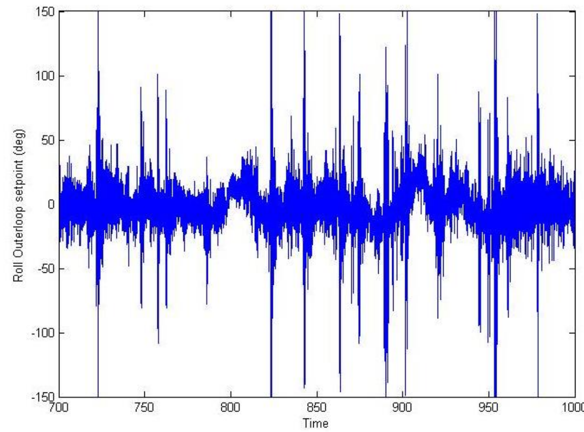

Figure 20 Roll outer loop set point

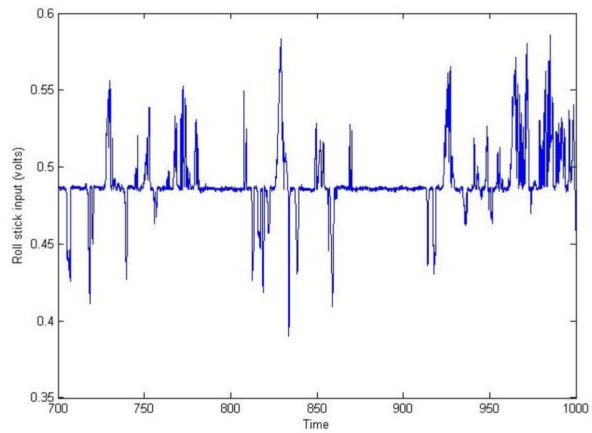

Figure 21 Roll input by the pilot

The lateral input given by the pilot to maneuver the vehicle in this attitude band is in between 0.42 to 0.58 with a mean of 0.486 as shown in **Figure 21**.

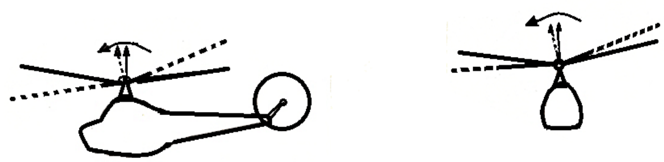

Figure 22 Longitudinal control and lateral control

When pilot applies longitudinal control, a pitching moment is produced about the center of gravity of the helicopter due to a tilt of the main rotor thrust vector shown in **Figure 22**. As a consequences of the tilt, a component of the rotor thrust acts in the direction of tilt. Hence an application of longitudinal control results in a rotation in pitch and a forward/backward motion (X translational) of the helicopter. Similarly an application of lateral control results in rolling moment and sideward motion (Y translational) of the helicopter.

Thus the linear acceleration of the mini helicopter in X and Y directions are as shown in **Figure 23** and **Figure 24**. The band, in which the pilot is able to control the vehicle, is about 2.5 m/s^2 to -3 m/s^2. The corresponding Y direction acceleration is about 2.5m/s^2 to -1.5m/s^2. The estimated X and Y velocities of the mini helicopter are as shown in **Figure 25** and **Figure 26**.

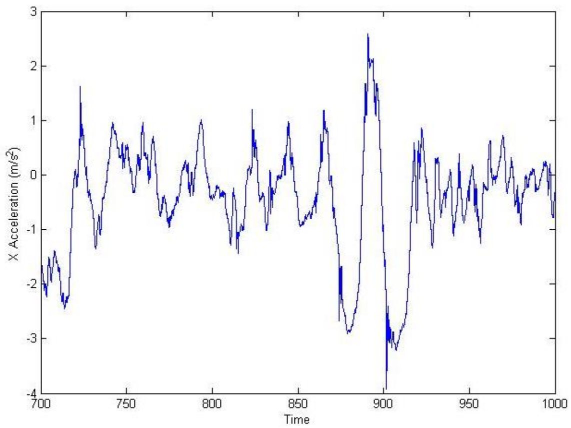

Figure 23 X acceleration

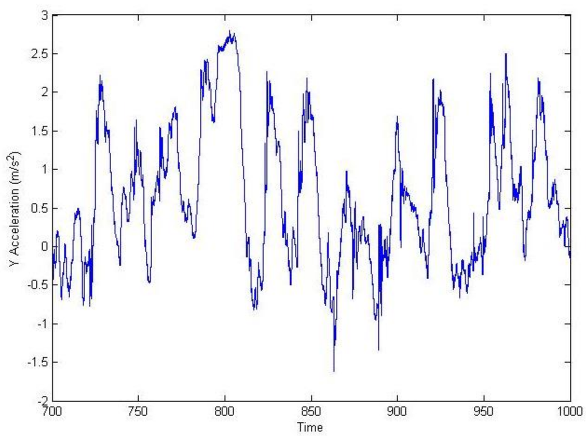

Figure 24 Y acceleration

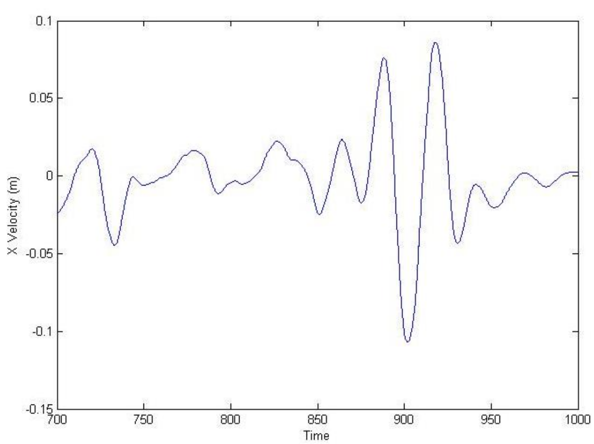

Figure 25 X velocity

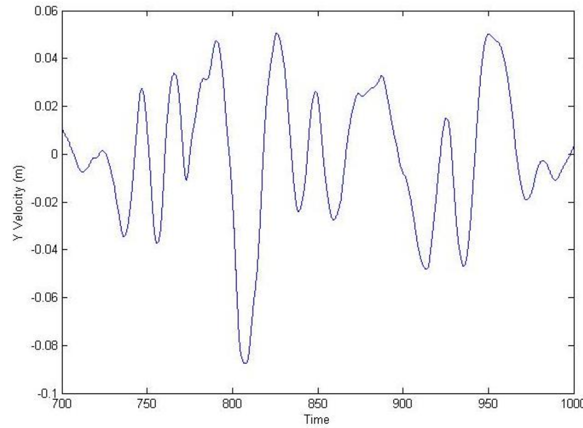

Figure 26 Y velocity

VI. CONCLUSIONS

This paper described the architecture of various systems which are being used to achieve autonomous control for mini helicopter. Ground station unit consist of Realtime PXI which computes control logic and transmits control signals to helicopter and personal computer for data logging and saving were built. On board electronics consists of sensors, power supply were developed and tested. The on board sensors data was acquired by ground station control unit as feedback. The ground station control was built to allow manual, autonomous and mixed input to the vehicle. The planned flight experiments conducted for stable hover of the mini helicopter were successful. From these experiments we have observed that the neutral point of helicopter was changing as the fuel of vehicle goes down. A proper algorithm should be incorporated to get the exact neutral position according to the fuel change. Cross coupling of the pilot input to the lateral and longitudinal servos has been incorporated and tests are in progress to fine tune the magnitude of these coupling factors. Further research can be done to develop onboard computer system which improves the control response of the vehicle as the sensors data will be updated at much faster rate.

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