INVITED PAPER

# DEVELOPMENT OF AUTONOMOUS MINI HELICOPTER: CHALLENGES FACED

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**Abstract**

*Design and development of autonomous or unmanned rotary wing vehicles have attracted a great deal of attention all over the world. Due to their unique capability to hover, these vehicles have potential applications in both civil and military sectors. Recently a research activity has been initiated at IIT Kanpur to set up a laboratory for design and development of an autonomous mini-helicopter. The major focus of this research activity is to design and integrate the sensors (Inertial Measurement Unit consisting of accelerometers and gyroscopes, magnetic sensor, SONAR and GPS) and communication systems (W-LAN and on-board computer) in a model helicopter, and provide the autonomous control and navigation capability. During the progress of this research and development effort, several testing systems have been designed and developed while facing several challenges at every stage of development. In addition, this high technology activity has provided an opportunity to the students to get hands on experience in the multidisciplinary aspects involved in the design and development of an autonomous mini-helicopter. The objective of this paper is to provide an over view of the challenges faced (till date) and how these problems have been addressed.*

## Introduction

Unmanned aerial vehicles (UAVs) have played a very important role in the recent years and have transformed the way wars are waged and intelligence is gathered. Given a mission to accomplish, these vehicles would be able to plan a path, avoid obstacles, and reach their destination. The role of human being in the vehicle would be taken over by sensors, control algorithms and computation units to perform desired tasks [1]. This field is drawing more attention from many researchers due to the usage of latest technologies like microelectronics and intelligent systems. Development of autonomous mini-helicopter has been taken up by numerous research groups to harness their abilities. To make students more aware about these technologies in the helicopter field, IIT Kanpur took up this research activity a few years back. It was decided that a mini-helicopter model would be procured and a ground station, on-board electronics, wireless communication and control algorithm for autonomous flight would be developed around it.

Accordingly, the research activity was grouped under three categories viz., mechanical systems, electronics systems and control algorithm and its implementation. The mechanical systems consisted of designing test rigs, gears, transmission couplers, vehicle maintenance, engine maintenance, rotor load measurements, etc. The electronic systems consisted of procurement, customization, mounting and integration of IMU, gyro, SONAR, rpm sensor, wireless sensors and actuators with the vehicle and interface of radio units with the ground station. The control algorithm implementation consisted of development of the logic in the ground station computation systems using LabVIEW software. This paper will explain the efforts put in to overcome the challenges in the mechanical systems, electronic systems and control algorithm design and implementation.

## Mechanical Systems

### 3-Axis Test Rig

A 3-axis test rig was specifically designed to have pitch, roll and yaw motions which can be independently locked or set free in any or all of the axes. Fig.1(a) shows the 3-axis test rig. The helicopter is mounted on this set up for control logic experiments and inertia estimation as shown in Fig.1(b). The test rig comprises of two frames made of wood and a plate made of aluminum. The center plate is mounted on a bearing to assist in the yaw motion.

The vehicle is clamped to this plate firmly. The outer frame aids in the pitching motion while the inner frame assists in the roll motion. This test rig was extensively used to design and test the rpm, pitch, roll and yaw control algorithms with the helicopter firmly clamped to the base plate.

The test rig was heavier compared to the weight of the mini-helicopter affecting the moment of inertia and the location of the center of gravity (c.g.) of the complete system. This also meant that the axis of rotation of the vehicle is about axes different from those passing through the c.g. of the vehicle. Thus the control algorithms designed for stability of the mini-helicopter on the test rig had to be modified in accordance with the above mentioned properties when tests were performed in free flight. Vibration of the mini-helicopter on the test rig had to be overcome by designing a new landing gear with polymer sleeves. The power supply and the control signals to the mini-helicopter were through wires from the ground station. The wires used to frequently get entangled particularly during yaw control experiments. This was overcome in free flight by shifting to wireless supply of control signals and on-board power supply through lithium polymer (LiPo) batteries.

### Engine Maintenance and Overhaul

The power plant used in the mini-helicopter is a 2 cycle piston valve type gasoline air cooled engine. Its displacement is 25.4 cc, maximum output 1.77 kw, max. torque is 0.16 kg-m and weighs 1.77kg. The fuel used is premixed in the ratio 25 (Gasoline):1 (High grade 2 cycle engine oil). The purity of the fuel had to be ensured with multiple rounds of filtering. Different filtering materials were used to remove the impurities present in the fuel. During initial flight tests, frequently the engine would cease to work or be erratic in its functioning due to these particles getting clogged in the carburetor. The usage of a clunk placed in the fuel tank as shown in Fig.2(a), reduced the level of these impurities in the carburetor. This in turn reduced the effort put into the maintenance of the engine as shown in Fig.2(b). The Carburetor has two screws to set the fuel intake and vary the performance of the engine. It was realized that any modification to the original settings was unnecessary and that the best performance of the engine is obtained when the company settings are left untouched.

## Helicopter Maintenance

### Main Rotor Gear

Being the critical component in the transmission of power from the engine to the main rotor and tail rotor, the main rotor gear requires high strength to bear the static and dynamic loads at high rpm. Main Gear has two parts; one is the spur gear for transmission of engine power to main rotor, while the bevel gear transmits power to the tail rotor. The gear ratio from engine to main rotor to tail rotor is 7.5: 1:4.67. As shown in Fig.3(a) and (b), frequent failure of the main gear was experienced due to improper meshing of the teeth, underperformance during dynamic loading and lack of quality control in the manufacturing techniques. A CAD model was prepared and stress estimation was carried out taking into consideration the operating range of the engine torque and rpm. Several materials were tested for the required strength of the gear. Nylon 6/6 with 30% carbon turned out to be the best material that can withstand these loads.

### Tail Transmission Coupler

Similar to the main rotor gear, the tail rotor transmission coupler is a crucial component in the power transmission to tail rotor, which balances the main rotor torque and also controls the heading (yaw) of the helicopter. It is therefore imperative for the tail transmission coupler to have enough strength to bear the maximum loads. Due to increased load the tail transmission coupler failed as shown in Fig.4(a). As shown in Fig.4(b) a model was prepared, and a new coupler using Nylon 6/6 with 30% carbon was manufactured. Fabricated transmission coupler is shown in Fig.4(c).

### Clutch Liner

The centrifugal clutch transmits the engine output to the main gear. The effectiveness of this transmission depends on the amount of contact that takes place between the clutch and the liner. The liner material gets heated up and wears out, as shown in Fig.5. This in turn leads to a very hot clutch bell and fluctuations in rpm after a brief run. These two phenomena are the major indicators of the problem. It is important to check the liner material from time to time for any exhaust deposits. These deposits smooth out the surface and reduce the effectiveness of the gripping of the centrifugal clutch to the bell.

### Nuts and Bolts

Apart from the above mentioned, there are numerous other moving parts, nuts and bolts in the mini-helicopter that have a finite life time. Tail Swash plate is one such moving part which adjusts the tail rotor blade angle to maintain the heading of the mini-helicopter. It requires checking and cleaning every time a run is made as exhaust soot settles on the tail shaft creating friction between the swash plate and the shaft. This can lead to improper heading control of the mini-helicopter. The original tail boom supporting rod connectors are made out of plastic. These help reduce the vibration of the tail boom by connecting the fuselage to the tail boom. But due to the heat of the engine, these connectors melt. They were replaced by aluminum connectors. During one of the flight tests, the tail drive shaft was severed into two pieces because of a protruding rivet inside the tail boom. The vehicle though could be landed safely though the heading control was lost due to the tethers stopping the vehicle from autorotation.

## Electronics and Wireless Communications

The electronics and the wireless communication part of the project comprises of ground station, on-board sensor integration board, rpm sensor, wireless X-Bee units, IMU, SONAR, UBEC and LiPo batteries.

### Ground Station

The ground station consists of a computation unit running a software application that also has communication established with the avionics of the mini-helicopter. Its purpose is to display real time data about the attitude, position and health of the vehicle while generating the vehicle control commands. It serves as a virtual cockpit. Two National Instruments' PXI 1050 systems are used for data acquisition and computation. A control algorithm is designed in the PXI system using LabVIEW (graphical programming language) software which is used to stabilize the mini helicopter in hover [4]. Fig.6 shows the complete ground station with two PXI units interfaced with the communication systems.

The control of the mini helicopter is achieved by controlling the servo actuators on the vehicle using the radio unit. Initially the pwm signals to the servos on board the mini-helicopter were generated by the PXI system and fed to the servos using a wire. The length, thickness and material of the wire determined the fidelity with which the generated pwm signal was transmitted. Having tried a few types of wires, it was identified that a LAN cable of length 20m with copper core would be the best suitable. Also an on board repeater circuit was used to take in the distorted signal and generate the noiseless signal. Later, these became redundant when wireless radio units began to be used to transmit the signals. These radio units are interfaced with the PXI systems such that they 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. In the LabVIEW software, the engineer is provided with an option to transfer the control of individual channels to the RC pilot. This can help fly the mini-helicopter in semi-autonomous mode where some of the channels are controlled by the PXI system while the RC pilot is trying to control the rest of the channels. Any input fed into the radio unit by the RC pilot is saved by the PXI system for analysis as a voltage in the range 0.4v to 4.7v. This technique is shown in a schematic in Fig.7. Another unique capability incorporated into the control software is that, the control software and an RC pilot can send inputs to the on-board servos simultaneously.

A conventional radio unit used for flying a mini-helicopter has two levers connected to four potentiometers letting an RC pilot give inputs to the servo actuators. These inputs are transmitted through separate channels to control the servos on board the vehicle. Channel 1 connects to the longitudinal servo on the mini-helicopter. Forward-aft movement of this lever controls the direction of rotation of the servo head / horn. Left - right movement of Channel 2 activates the lateral servo. Channel 4 lever movements activate the tail servo and is used to control the yaw of the vehicle by changing the tail rotor blade pitch angle. For an RC pilot, the collective and throttle servos are coupled and connected to the Channel 3. If the Channel 3 is on the right side then it is termed mode 2 and if it is on the left side then it is mode 1 radio. Channel 5 is used to supply the auxiliary signal from the radio unit to the AVCS controller. However, in our ground station, the collective and throttle have been decoupled to help us research the collective and throttle controls independently. Thus two radio units are being used, where four channels of one of the radio units are connected to the longitudinal, lateral, collective and tail servos and the signal is transmitted at 72 MHz. Throttle is separately connected to another radio unit and the signal is transmitted at 40 MHz.

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 signals / 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 of these modules are currently wired to the ground station through RS-232 port. The IMU data is received by one X-Bee sensor and sent to one PXI system, while the rpm and SONAR data are sent to both the PXI systems.

**On Board Electronics and Sensors**

On board electronics include the sensors (IMU, gyro, rpm, SONAR) which send the flight data to the ground station for feedback and actuators (servo) which are used to control the mini-helicopter.

**Inertial Measurement Unit (IMU)**

The most important sensor on board the mini helicopter is the IMU. [5]. Microstrain's 3DM-GX1 shown in Fig.8 is the IMU currently strapped to the mini helicopter. This IMU consists of three accelerometers which give X-Y-Z linear instantaneous accelerations, three rate gyros which give angular rates about X-Y-Z axes and three magnetometers providing pitch angle, roll angle and yaw angle of the vehicle on which the IMU is mounted. It has a high data rate and sends signals at the rate of 38,400 bits per second. The performance of the IMU is largely dependent on the extent to which it is isolated from vibration and large magnetic fields. The Euler angle estimation of the IMU is prone to fluctuations after some period of time of usage of the IMU, as the influences of the nearby magnetic fields affect the angle estimation. Periodic calibration of the IMU for hard-iron effects has to be done. It is difficult to say when exactly the IMU starts to behave erratically, but when the heading control starts to go bad it is suggested to have an IMU 3D calibration done. Also, as a result of the vibration on the mini-helicopter the acceleration and angular rate data is noisy. To reduce this noise vibration isolators had to be provided, since the performance of the control algorithm depends on the estimate of the parameters used for feedback.

**Servo Actuators and GY611 Gyro**

Servo actuators are electromechanical components mounted on the mini-helicopter and are attached to the main rotor swash plate, tail rotor swash plate and the throttle knob through linkages. The movement of the servo arms is a result of a pulse width modulated (pwm) signal fed to the servo. Fig.9 shows two different models of servos used on the current mini-helicopter. Four Futaba S3151 servos for throttle, collective, lateral and longitudinal inputs are used along with S9256 servo for tail collective input. Along with the tail servo, MEMS based GY611 gyro with its controller is used for holding the heading of the vehicle during flight. GY611 gyro consists of a controller and a gyro sensor. The sensor is a single axis rate gyro. It can sense the rate of rotation about an axis perpendicular to its base and accordingly generate an analog voltage. The gyro is mounted on the vehicle and the signals generated by it will act as feed back to the controller providing vital information about the yaw rate of the vehicle. The servos need power supply from a battery that has a good power rating. If the battery is not able to supply current in the order of 4A, the servos start 'chattering' when loaded. The servo S3151 has lower resolution and response time when compared to S9256. Attempts to use the S3151 as tail servo for heading control did not yield good heading results as shown in Fig.10

**SONAR (SOund Navigation And Ranging)**

SONAR is a sensor that uses sound propagation to navigate, communicate or detect objects. SONAR transmits a pulse of sound outside the range of human hearing. This pulse travels at the speed of sound away from the ranger in a cone shape. The echo is reflected back to the receiver of the SONAR when any object comes into the path of the transmitted pulse. SONAR detects the echo by listening for the returning wavefronts. Shown in Fig.11 is SRF08 model of SONAR that is currently in use to estimate the height of the vehicle from ground. The SRF08 offers ranging information from 3cm to 6m in steps of 1cm. After transmitting the pulse, ranger waits for the reflected echo for a time interval set by the SRF08 itself. This time can be read from the ranger. The SRF08 is interfaced with a microcontroller using the Inter-Integrated Circuit (I2C) bus. During static calibration it was observed that the SONAR can predict height up to 2m with high level of accuracy. But when it was mounted on the mini-helicopter the data was erratic. The maximum height shown by the sonar was 0.8m and the oscillations in the data were plenty as shown in Fig.12(a). This was due to the acoustic noise of the mini-helicopter engine. Averaging and filtering were used to reduce the noise in the data to make it usable for height control feedback as shown in Fig.12(b).

**RPM Measurement**

It was intended to measure the main rotor rpm and display the reading in real time at a safe distance away from the mini-helicopter in operation. The hardware to be straddled on the vehicle had to be light weight, easy to mount or dismount and resistant to vibration. It was decided to use the principle of magnetic induction to generate electrical pulses from magnets mounted on the main rotor. These magnetic pulses could then be counted using a microcontroller and the rpm measured thereof. After careful inspection of the mini-helicopter, it was realized that the best possible place to measure the rpm would be below the swash plate by mounting a magnetic collar around the shaft and using a probe to collect the pulses as shown in Fig.13. The magnetic collar has 8 magnets embedded in it and for every rotation of the main rotor, 8 pulses are collected by the magnetic probe. These pulses are analog in nature and are transmitted to a sensor integration board where they are counted and transmitted to the ground station. Ideally, more the number of magnets in the magnetic collar, lesser would be the error in estimating the rpm of the main rotor.

The rpm estimation from the pulses in magnetic probe was initially noisy due to vibration. Averaging and filtering techniques had to be used to reduce the effect of these factors. If the distance of the magnetic probe to the magnetic collar is larger than 0.5cm, there is a risk of missing a pulse from a weaker magnet leading to under prediction of rpm. Also, recently one of 8 magnets embedded in the magnetic collar was lost and this led to under prediction of rpm. This creates a difference in performance of the control logic.

**Sensor Integration Board**

A sensor integration board is used for integration of rpm and SONAR data. It consists of a polyester capacitance, a comparator circuit and Basicstamp processor. The capacitance is used to filter out large spikes in the pulses generated by the magnetic probe of the rpm sensor. These filtered out pulses are fed to the comparator circuit. This circuit is used to convert distorted pulses to rectangular pulses. This conversion helps in their easy recognition at the Basicstamp processor for counting.

Basicstamp essentially has all the components of a microcomputer system. It has a microcontroller, a built in ROM which contains a Basic interpreter which enables the Basicstamp to be coded in simple Basic language, an EEPROM, and a clock. The circuitry used for integration of sensor data is as shown in Fig.14. A code is written in this processor which calculates the rpm value by counting number of pulses in a fixed time period of 100ms. SONAR uses I2C communication protocol to communicate with the Basicstamp. The rpm data points come in quick succession but sonar data has some delay as the SONAR takes 65ms to respond to a command requesting the height measurement.

The Basicstamp was coded such that it first sends a command request to the SONAR for output and in the meantime rpm data is sampled. The rpm data is prefixed with the alphabet R and the SONAR data is prefixed with the alphabet S. This aids in easier identification of the data at the ground station. This combined packet of data is sent to an XBee-Pro wireless module on board the helicopter which will transmit this data to the ground station. The composition of the data packet is an important feature as it decides the ratio of the number of rpm data points to that of the sonar data points. Initially, the number of sonar data points was less i.e. one point every 1.5s. This was not enough feedback to control the height of the mini-helicopter. So the number points of the sonar per packet of data were increased.

**Wireless Communication**

Wireless system enables mini helicopter to transmit data to and receive control commands from ground station unit. Wireless communication can be categorized as uplink and downlink [6]. 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. Two Futaba six channel receivers are placed on board the mini-helicopter as shown in Fig.15. One of the receivers operates in the 72 MHz frequency range and the other in 40 MHz frequency range. The former supplies signal to longitudinal, lateral, collective servos along with the tail servo controller while the latter supplies the signal to the throttle servo. The signals to the servos are sent at different frequencies to avoid any interference between the throttle and the other control signals. These receiver units need 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. For this purpose XBee-Pro transceiver modules are used as shown in Fig.16. It has a line of sight range of 1 mile and an urban range of 100 meters. Its frequency of operation is 2.4GHz.

These XBee-Pro modules work in pairs. Each of these modules can transmit and receive data. Two XBee-Pro modules are mounted on the mini helicopter. One of which is used for transmitting IMU data and the other is for transmitting SONAR and rpm combined packet of data. The XBee-Pro configured for receiving data is placed at the ground station as explained earlier. During the run of the mini-helicopter there are losses in the communication between the ground station to the XBee units. This causes the data from the IMU to go to zero from its existing value. This was a dangerous situation as the control inputs become erratic. To eliminate the effect of this, it was decided to use the previous data whenever there is a loss of data due to failure in communication.

**Power Management**

The power to the on board electronics and actuators can be supplied by batteries placed on board. A Lithium Polymer (LiPo) battery of 11.1v (1000mAh) with a Universal Battery Elimination Circuit (UBEC) is used for IMU, XBee-Pro units, Sensor integration board and SONAR. Another LiPo battery of 11.1v (1300mAh) through another UBEC supplies power to the radio receiver units, servos, AVCS controller and gyro.

The UBEC in use is a switching mode dc-dc regulator supplied with a 3 cell 11.1v LiPo battery pack and outputs a consistent safe voltage of 5v or 6v with 8A current. Table-1 shows the power requirements for on board sensors and actuators. Based on these requirements, the UBEC is operated in the 5v or 6v output mode using a switch provided on it. But when the UBEC was operated in 5v output mode, it was observed that the servos were sluggish in their response to inputs. Consequently, the UBEC began to be operated in 6v output mode. When the output of the UBEC is 6v, a 0.7v step down voltage regulator is connected between AVCS controller and rudder servo (S9256) to supply it with 5.3v as it is not capable of handling 6v. In this mode of operation, the servos responded better.

A LiPo battery of 11.1v (1000mAh) and a UBEC are shown in Fig.17. The wires supplying the output of the UBEC are wound over ferrite rings to reduce the electromagnetic interference (EMI) that can disturb the nearby sensors and wireless systems. Care needs to be taken while mounting the UBEC as it can easily interfere with the working of the magnetic sensors in the IMU and the wireless receiver units. In the absence of a UBEC, a voltage regulator was used to supply 5v from the 11.1v battery to the circuits. However, the voltage regulator had the capacity of only 1A max. current. This led to the servos to ‘chatter’ during flight tests. Even after the UBEC began to be used and when the LiPo batteries are fully charged, during the run, there were sudden surges in the inputs to the servos making the helicopter to jump up or nose dive. The exact reason for this could not be ascertained, but when the battery pack was discarded and a new pack was used along with cleaning all connectors, this problem could be eliminated.

**Table-1 : Power Requirements of On-board Sensors and Actuators**

| Component | Requirement | |
|---|---|---|
| | Voltage (v) | Current (mA) |
| Sensor integration board | 5-8 | 50 |
| IMU | 5.2-12 | 65 |
| XBee-Pro+Explorer | 5-15 | 215 (Transmit)<br>55 (Receive) |
| SONAR | 5-6 | 275 |
| Radio receiver unit | 5-6 | 6<br>(at no signal) |
| AVCS Controller + GY611 gyro | 5-6 | 70 |
| S3151 servo | 5-6 | 1000 |
| S9256 servo | 5 | 1000 |

**Mounting**

The accuracy with which the sensors estimate the attitude, tri-axial linear accelerations, tri-axial angular rates, position and height of the vehicle is critical to the stabilization of the vehicle. Thus, the estimation of the vehicle center of gravity and mounting of the IMU are high priority tasks necessary for autonomous hover of the mini-helicopter. The right place to mount these sensors is not easily determinable as there are numerous factors that affect their performance such as: Proximity to c.g., Electromagnetic interference, Vibration, Acoustic noise, etc.

The IMU consists of magnetometers which aid in the determination of the heading of the vehicle by measuring the strength of earth’s magnetic field. Thus, the sensitivity of the magnetometers determines the accuracy with which the attitude is estimated by the IMU [7]. Too sensitive magnetometers result in measurements getting easily affected by nearby electromagnetic disturbances. The engine mounted on the vehicle is a major source of electromagnetic disturbances. If the IMU is mounted close to the engine, the readings tend to be too noisy. Also, any attempts to isolate the IMU from strong magnetic fields would be counterproductive as the earths magnetic field is weaker than the noise from the engine. Thus it is necessary to mount the IMU as far away from the engine as possible.

Effect of vibration has to be considered while mounting the IMU or the other sensors on the mini-helicopter. The biggest challenge is to develop avionics that can reliably function in this vibrating environment. It is thus necessary to isolate the sensors from vibrations. Major sources of vibration on the mini-helicopter are its engine, the main rotor and the tail boom. Vibration isolators are used in mounting the avionics tray to the helicopter landing gear support structure.

Taking into consideration all these factors, it was decided to mount the IMU farthest from the engine on an avionics plate made of balsa stiffened by aluminum channels mounted on carbon fiber made L channels. The LiPo batteries were placed at the other extreme of the IMU to balance the center of gravity. The wireless sensors and the sensor integration board are in between with the SONAR and the UBECs placed below this avionics plate. Shown in Fig.18 is the mini-helicopter with all the sensors on the avionics plate mounted below the landing skid of the mini-helicopter. Fig.19 shows the actual positioning of the sensors and the batteries on the avionics plate beneath the mini-helicopter. The location of the IMU away from the engine and the magnetic collar had to be decided after a series of trials. The battery packs had to be strategically placed to maintain the c.g. of the mini-helicopter.

## Load Measurements

The flying characteristics of a helicopter are influenced by the performance characteristics of the rotor system. For performing free flight of the mini helicopter, it is necessary to know the combination of rpm and blade pitch angle that can lift the helicopter with payload. Therefore, an experiment was conducted to determine the load carrying capability of the mini helicopter rotor system.

Figure 20 shows a two bladed mini helicopter mounted on a load cell, fixed to a tower at a height of 1.87m. For different values of rotor operating rpm, the rotor loads are measured for various collective pitch angle of the main rotor. Kistler six component load cell was used for measuring the loads. When the collective pitch angle is varied, the cyclic blade pitch angles are set at zero values. A cable is used to supply the input signals to the servos and collect the rpm data. The fuel tank of the vehicle is kept outside the load cell to avoid shift in center of gravity of the vehicle during run time. A shift in the center of gravity of the vehicle results in variation of loads measured for the same inputs. The tail rotor is disconnected from the main rotor gear to eliminate loads from the tail rotor [12].

Shown in Fig.21 is the variation of Fx with main rotor blade cyclic pitch angle. From Fig.22, is can be seen that for a collective blade pitch angle of 7.6 deg., the rotor is able to generate a lift (thrust) of 78 N. The torque produced in this operating condition is 3.7 Nm, as shown in Fig.23. Performing load test experiments on testing tower proved to be a difficult task, as it was observed that under certain conditions the vehicle went into ground resonance. Sufficient damping and clamping were provided to avoid the ground resonance during experimental range of operation.

## Control of Mini-Helicopter

### RPM Control

It was intended to model the behavior of the mini-helicopter main rotor for a change in throttle input. The RPM of the main rotor is varied by moving the throttle opening position of the engine. This is achieved by using the throttle servo arm lever. An experiment was carried out on a mini helicopter mounted on a platform. Prior to the conduct of the experiment, the main rotor blade pitch angle was measured in correspondence with collective input. The throttle servo is controlled by a pwm signal with 20ms pulse width and on-time ranging from 0.86 ms to 2.24 ms, i.e. duty cycle ranging from 4.3% to 11% [8].

An open loop experiment was performed in the range of 1000 to 1500 RPM for an increase of 0.2% duty cycle (20ms pulse) input to the throttle servo at 7 deg blade pitch angle [9]. Here, we observe that for 0.2% increase in throttle servo input, the RPM increases by 390. The system response is observed to be slow at higher RPM. Fig.24 shows a curve fit of this data in MATLAB software that resulted in a higher degree transfer function. It is interesting to note that the rise time (time required to reach 70% of final value) is 5 sec, whereas the settling time is about 30 sec. With the identification of the open loop transfer function we proceed to implement suitable closed loop control logic. For closed loop rpm control, there are many types of feedback controllers that are in existence. But the simplest and the most used is the Proportional-Integral-Derivative (PID) controller [10]. Fig.25 shows the implementation of the closed loop logic using a PI controller. Here, the system includes servo, engine, main rotor and RPM sensor. $K_p$ and $K_i$ are the proportional and integral gains whose values are obtained by using MATLAB software [11].

Figure 26 shows a user interface developed in LabVIEW 8.0 is used to implement the closed loop RPM control. In open loop RPM control, the interface allows the user to vary the input to the throttle servo using the keyboard or using the radio transmitter lever. The amount of input fed to the servo is displayed in duty cycle and in volts. The user has the option of saving the data to different files by changing the run number during the execution of the program. Option to move from open loop to closed loop is provided. The instant this option is exercised, the controller will try to stabilize the RPM of the mini-helicopter at the set point specified in the console. During the execution of the program the set point and the $K_p$, $K_i$ gains can be modified from the keyboard. There is a dial and a graph that show the comparison between the anticipated RPM and the actual RPM. Furthermore, there is another option to vary the set point RPM using the radio transmitter throttle lever. This option is generally exercised while trying to make the mini-helicopter safely descend from its hovering position.

Figure 27 shows the performance of the closed loop control logic implemented in the actual system with the same gains as in the simulation. The set point was changed from 1200 to 1400 RPM. The settling time was observed to be 245 sec. This is far greater than the prediction of the simulated model. However, this performance was considered satisfactory as the response was robust even when the system was subjected to disturbances in the form of main rotor blade angle changes. Getting the best curve fit to estimate the transfer function was a challenge as the open loop response was not in any standard form. The values of the gains vary for different operating conditions i.e. for different combinations of rpm and collective. The best set of gain values that would be used for the most likely operating condition had to be obtained by performing experiments on the load cell.

### Yaw Control

Figure 28 shows the two modes of rotation of the vehicle due to the change in the direction of the tail rotor thrust. The tail is said to be in *climb mode* if its motion is along the direction of rotation of the main rotor. It is achieved by giving a positive duty cycle input to the tail rotor servo. The tail is in *descent mode* if the motion of the vehicle is opposite to the direction of rotation of the main rotor. For negative duty cycle input to the tail rotor servo the *d*escent mode is attained. Fig.29 shows the open loop yaw rate characteristics of the mini-helicopter on the test rig, for different inputs to the tail servo. It is noted that the behavior of the vehicle in yaw is different for the climb mode and the descent mode. GY611 gyro was used to stabilize the yaw motion of the mini helicopter. Fig.30 shows the closed loop control logic used for the heading control of the mini-helicopter. Fig.31 shows the yaw angle response of the mini-helicopter on the test rig for set points of +30 deg. and -30 deg. Yaw control is found to be quite satisfactory.

Achieving heading control of the mini-helicopter was difficult without the aid of GY611 gyro or S9256 servo or the AVCS controller. Initially on the 3-axis test rig, it was attempted to control heading of the mini-helicopter using S3151 servo. But the results were not satisfactory as mentioned in the earlier sections. It was also realized that the yaw angle values from 3DM-GX1 IMU cannot provide the feedback fast enough for controlling the heading of the mini-helicopter as the response of the IMU is sluggish because of the various algorithms being used internally to accurately predict the heading of the vehicle.

### Blade Tracking

Before trying to design and implement the pitch and roll control of the mini-helicopter it is necessary to check if the main rotor blades are tracked properly. Early tracking techniques involved the mounting of an IMU on the rotor blades to measure their angle for different collective and cylic inputs and adjust the other blade according to these readings. These were then mapped on to the other blade for symmetry. However, later when a new helicopter was assembled, it was realized that it is difficult to map the settings of the previous helicopter for identical performance. Hence the technique of using chalk and cloth was used as shown in Fig.32.

### Independent Closed Loop Control in Pitch and Roll

Initially, independent control in pitch and roll motions were attempted on the 3-axis test rig. It may be noted that the helicopter is highly unstable when mounted on the test rig, because the c.g of the helicopter is above the hinge axes in pitch and roll motions. The gains used in the independent modes were not able to stabilize the vehicle in coupled mode. Another experiment was performed to test the roll control for an excitation in the pitch motion. Initially, the roll of the vehicle was independently controlled, while the pitching motion was locked. Then, a pitch excitation of 1.22 Hz was manually fed to the system and gains in roll were adjusted to stabilize roll motion.

**Tethered Hover Test**

After achieving independent control in pitch, roll and yaw motions in a test rig and coupled control of pitch and roll in the test rig, tethered hover tests of the mini-helicopter were conducted [14]. During this test, rotor rpm and pitch-roll-yaw control algorithms were integrated and x-y-z acceleration control was also implemented. The gains for attitude control were suitably adjusted to take into account the reduction in the inertia properties of the free helicopter in comparison to helicopter + test rig. In order to have a comparison of the performance of the flight between a human piloted and an auto piloted hover, an experienced radio control pilot was given the task of flying the mini-helicopter with only some channels under his command. This is termed semi-autonomous flight. Tests were performed within the lab and outside the lab as shown in Fig. 33.

As already explained in Fig.7, the user interface developed using LabVIEW in the PXI systems had an option of shifting from computer command to manual command, i.e. the inputs to the servos on board through the radio unit can be generated by the PXI system or by the pilot using the levers of the radio unit. The option of shifting from radio control to computer control is exercised by the engineer handling the PXI systems. The engineer had the option of handing over control of one or some or all channels to the pilot. In semi-autonomous mode, the rpm was controlled by the PXI system. The yaw, pitch, roll and collective were controlled by the pilot. It has to be noted that the collective and rpm were decoupled to conduct independent studies on them [13].

During the experiment of semi-autonomous hover with the aid of a pilot, his radio transmitter lever inputs were tapped and captured as voltages by the PXI system along with the data of the sensors on board the mini-helicopter. This helps understand the correlation between the orientation of the vehicle and the inputs generated by the pilot. The data obtained from the experiment was tabulated as shown in Table-2. The control logic implemented in attitude and x-y position for fully autonomous hover of the mini-helicopter is shown in Fig.34. For height control of the mini-helicopter the control logic is shown in Fig.35. When trying to hover the mini-helicopter in semi-autono-

**Table-2 : Comparison of Flight Data : RC Pilot vs Autonomous Hover**

| | RC Pilot (Apr 07, 2012) 550s - 650s | | | Autonomous (Oct 12, 2012) 935s - 985s | | |
|---|---|---|---|---|---|---|
| | Max | Min | Mean | Max | Min | Mean |
| Pitch Angle (deg) | 12 | -12 | -2.1 | -2.015 | -7.548 | -4.152 |
| Pitch Rate (deg/s) | 15 | -14 | 0 | 7.678 | -7.051 | 0.160 |
| Pitch Acc (deg/s/s) | 54.593 | -58.593 | 0.0582 | 42.138 | -39.919 | -0.143 |
| Longitudinal Input (volts) | 2.78 | 2.16 | 2.479 | 2.505 | 2.479 | 2.488 |
| Roll Angle (deg) | 25 | -7.5 | 4 | 7.142 | -1.716 | 3.451 |
| Roll Rate (deg/s) | 20 | -27 | -0.5 | 21.477 | -21.580 | -0.228 |
| Roll Acc (deg/s/s) | 72.84 | -56.84 | 0.095 | 121.739 | -139.289 | 0.391 |
| Lateral Input (volts) | 3.01 | 2.16 | 2.495 | 2.380 | 2.341 | 2.365 |
| Yaw Angle (deg) | 37.081 | -20.525 | -0.344 | -89.076 | -101.227 | -96.641 |
| Yaw Input (volts) | 2.521 | 2.480 | 2.513 | 2.545 | 2.496 | 2.526 |
| X Acc (m/s/s) | 0.838 | -0.907 | 0.0127 | 0.240 | -0.128 | 0.007 |
| Y Acc (m/s/s) | 1.05 | -1.0899 | -0.0637 | 0.260 | -0.436 | -0.007 |
| Z Acc (m/s/s) | 1.71 | -1.397 | 0.2916 | 0.086 | -0.115 | -0.039 |

mous mode, the pilot, having been used to coupled collective and throttle, found it difficult to land the vehicle. This was because a reduction in collective immediately increased the rpm. Though the rpm was controlled by the pxi system, it takes a long time for the rpm to come back to its reference value. This problem was overcome by coupling the collective input to the throttle input as shown in Fig.36. This allowed for larger fluctuations in collective during hover without disturbing the rpm.

The control logic developed has the option of shifting from autonomous control to pilot control midflight. In pilot aided autonomous flight, the pilot can be given the control of a few parameters so as to achieve pilot+computer controlled mixed flight mode [3]. But the software implementation of this had become complicated with a lot of panels visible to the engineer operating the system leading to confusion during the run. It required the engineer to trim some parameters such that there was seamless transfer of control of mini-helicopter from PXI system to pilot. If these parameters were not properly trimmed, there was a risk of the values 'jumping' from their current value to the values obtained from the radio unit. This 'jumping' was later avoided by capturing the current status of the radio and matching it with the current status of the parameter. It is termed as 'stick centering'. This greatly reduced the effort of the engineer during run time allowing him to concentrate on more critical tasks.

With the progress of the work, the control algorithms became more intense leading to over load of the system resources. This problem has been overcome by the development of state of the art real time systems that can take more computation load. After every experiment large files of data is collected along with a video. Analysis of the data used to take up considerable amount of time due to the vast number of parameters involved. A data and video library have been made that store the information in folders organized according to date and the run number. A simpler plotting programme has been developed that can plot the data with just a few clicks.

## Conclusions

The challenges faced so far in trying to attain autonomous hover have taught valuable lessons which help in further improvement of control algorithm for untethered hover, auto take-off / landing and forward flight tests. Fully autonomous hover of mini-helicopter is achievable with the right combination of sensors, computation units and wireless systems. Comparing the hover flight by pilot and autonomous hover flight, it is noted that that the autonomous hover of mini-helicopter is very stable. However, many more challenges lie ahead and need to be overcome for attaining the lofty goal of fully autonomous flight under various conditions.

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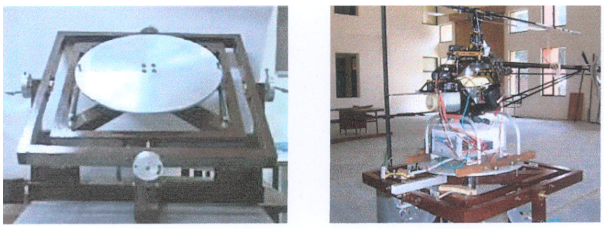
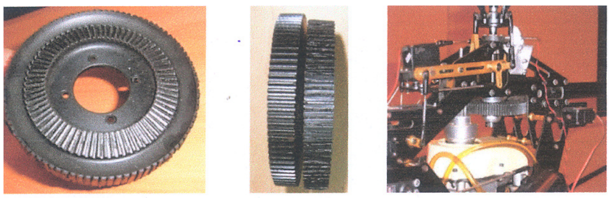


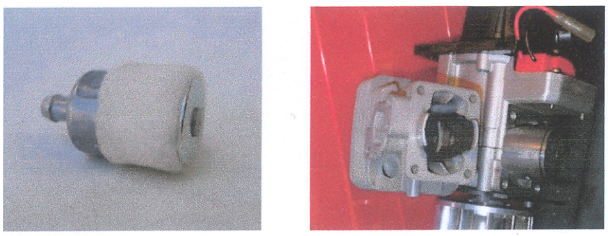
(a) (b)

*Fig.1 (a) 3-Axis Test Rig (b) Mini-helicopter Mounted on 3-Axis Test Rig*



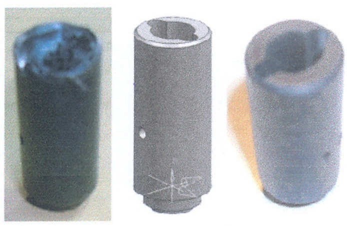
(a) (b) (c)

*Fig.3 (a) Damaged Bevel Gear (b) Damaged Spur Gear (c) Manufactured Main Gear Mounted on the Mini-helicopter*



(a) (b)

*Fig.2 (a) Fuel Clunk (b) Engine Piston Opened for Maintenance*



(a) (b) (c)

*Fig.4 Tail Shaft Coupler (a) Damaged (b) CAD Model (c) Manufactured*

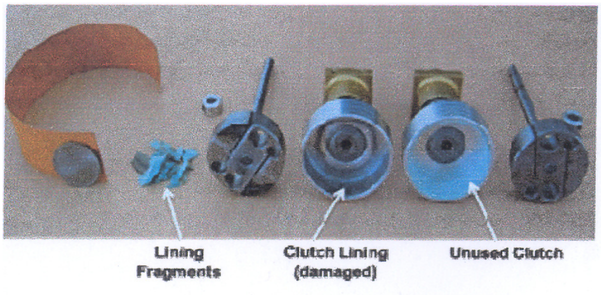



*Fig.5 Clutch Liner Damaged vs Undamaged*

*Fig.9 Futaba S3151 Servo (Left) and S9256 Servo with GY611 Gyro and Controller (Right)*

*Fig.6 Ground Station Control Unit*

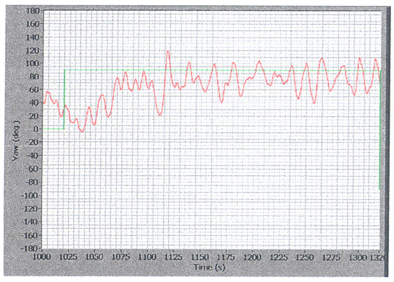


*Fig.10 Yaw Angle Control Using S3151 without the Aid of GY611 Gyro*

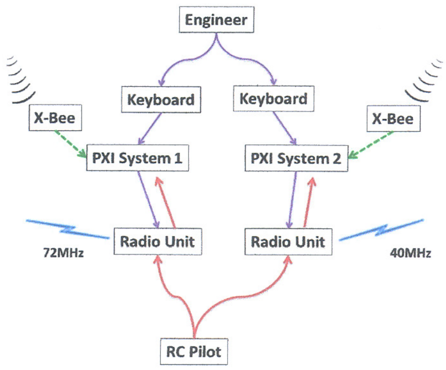



*Fig.7 Schematic of Signal and Data Flow on the Ground Station*

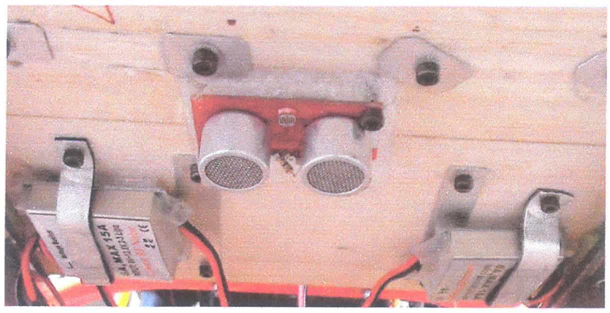


*Fig.11 SRF08 SONAR Mounted Underneath the Avionics Plate on the Mini-helicopter*

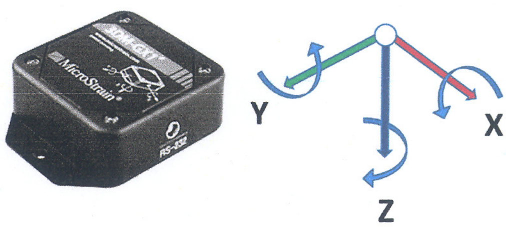
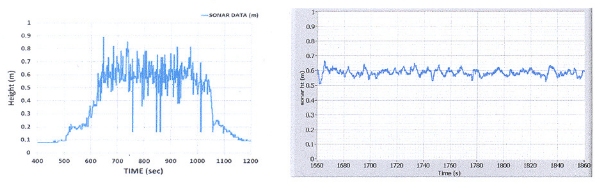



*Fig.8 Microstrain 3DM-GX1 IMU*



(a) (b)

*Fig.12 (a) Noisy Sonar Data (b) Processed Noise Free Sonar Data*

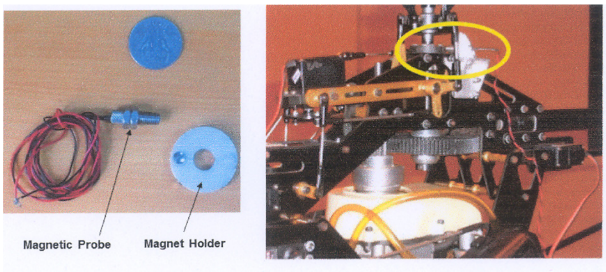



*Fig.13 Measurement of RPM - Hardware and Mounting*

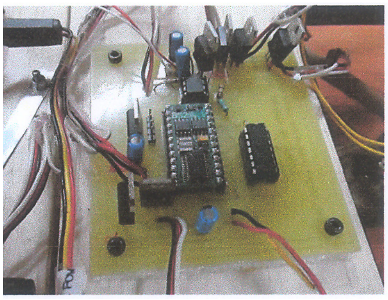


*Fig.14 On-board Sensor Integration Circuit*

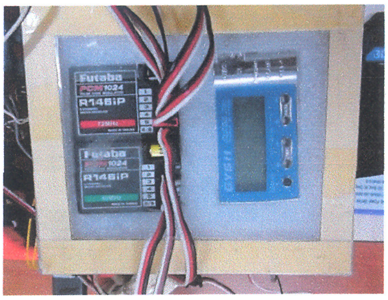



*Fig.15 Radio Receiver Units*

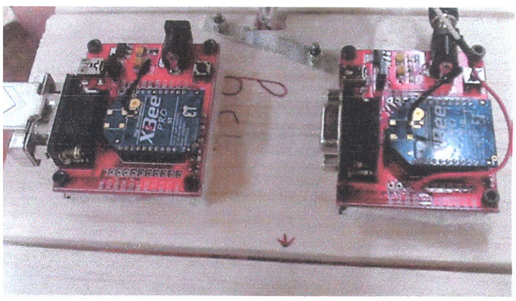



*Fig.16 Wireless XBee-Pro Units*


*Fig.17 LiPo Battery - 11.1 v at 1000mAh Capacity and an 8A UBEC*

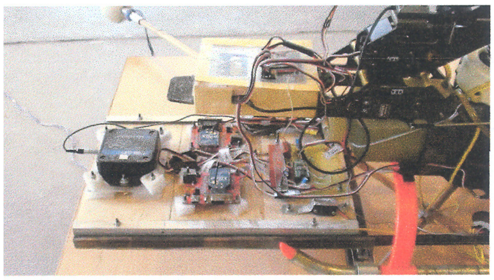


*Fig.18 Mini-helicopter with On-board Electronics*

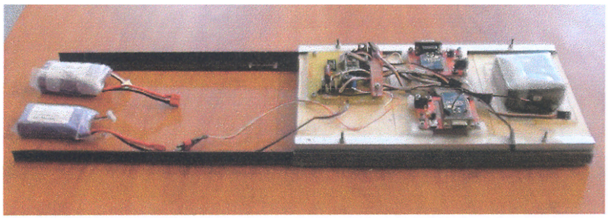


*Fig.19 Placement of Various Sensors and Batteries on the Avionics Plate Beneath the Mini-helicopter*

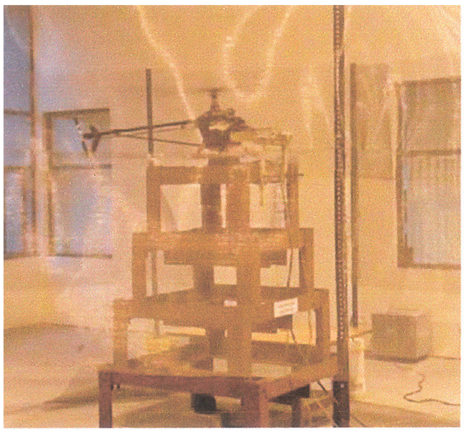


*Fig.20 A Mini-helicopter with Load Cell Mounted on a Tower to Measure Rotor Blades*

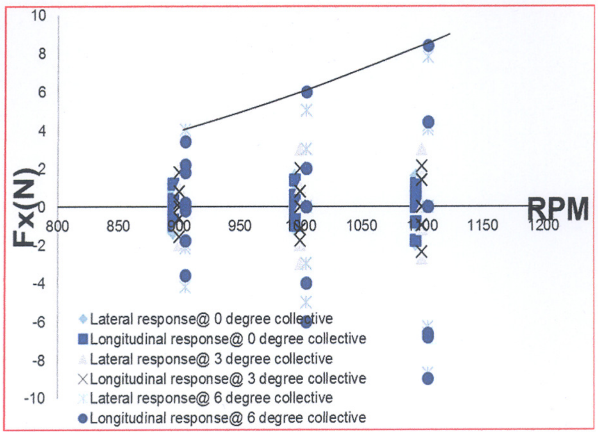



*Fig.21 Variation of Fx with Main Rotor Blade Cyclic Pitch Angle*

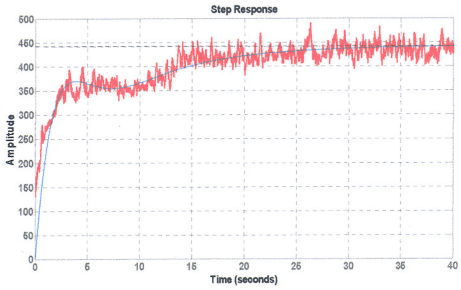



*Fig.24 Open Loop Response of RPM and Its Curve Fit*

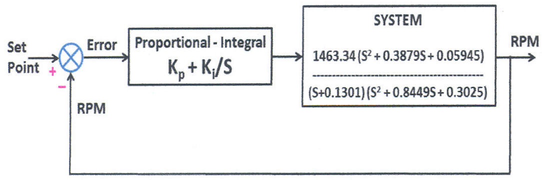



*Fig.25 Closed Loop Control of Main Rotor RPM*

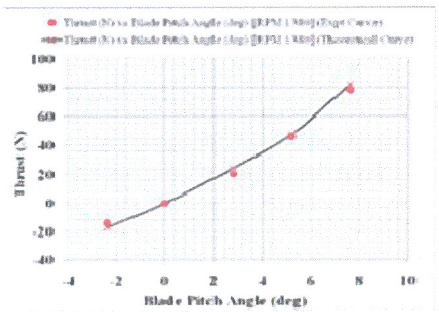



*Fig.22 Variation of Rotor Thrust with Blade Pitch Angle*

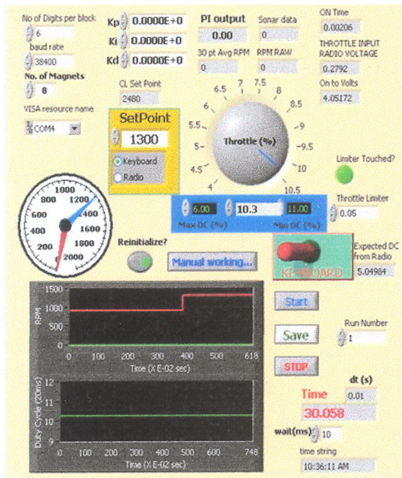



*Fig.26 User Interface for Implementation of RPM Control*

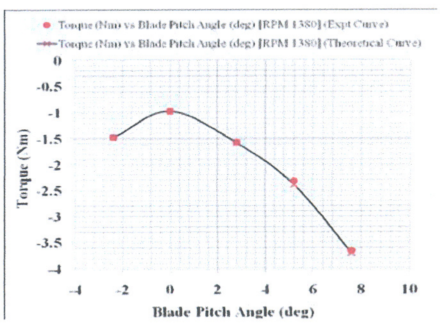



*Fig.23 Variation of Rotor Torque with Blade Pitch Angle*

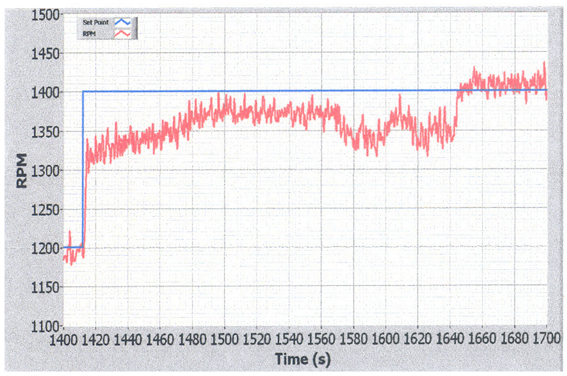



*Fig.27 Closed Loop RPM Response of the Actual System for 1400 RPM as Set Point*

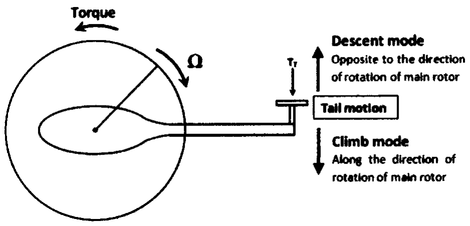



*Fig.28 Tail Motion with Respect to Mini-Helicopter Main Rotor Rotation (View from Top)*

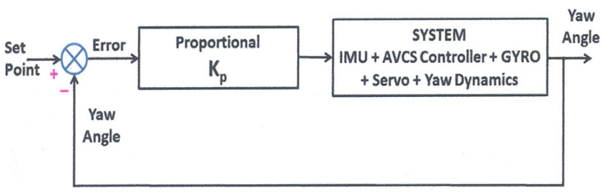



*Fig.30 Closed Loop Yaw Control Logic*

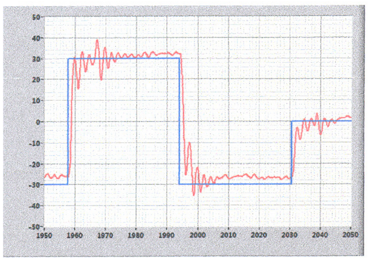


*Fig.31 Closed Loop Yaw Angle Control for Set Points +30 deg and -30 deg*

*Fig.33 Flight Test of the Mini-helicopter Outisde the Lab*

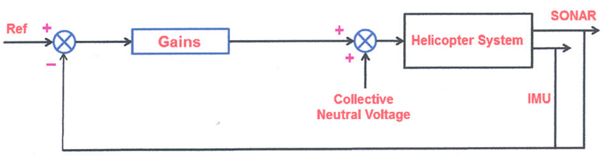



*Fig.35 Closed Loop Control Logic for Height Control*

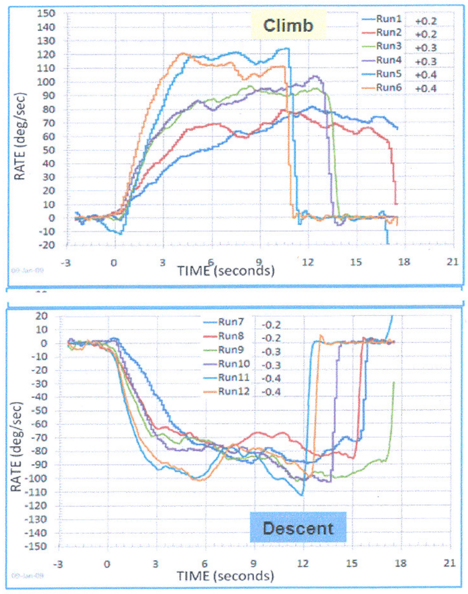



*Fig.29 Open Loop Yaw Rate Response in Climb Mode and Descent Mode for Various Tail Servo Inputs*


*Fig.32 Blade Tracking of the Mini-helicopter Using a Transverse and Cloth*

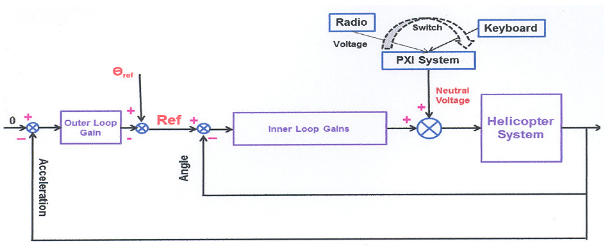



*Fig.34 Closed Loop Control Logic for Attitude and x-y Position Hold*

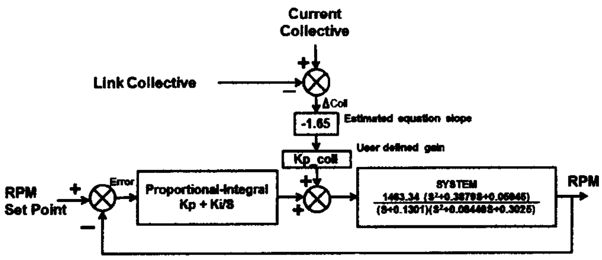



*Fig.36 Collective to Throttle Input Coupling for Stable RPM*