Low Cost Guidance, Navigation, and Control Solutions for a Miniature Air Vehicle in GPS Denied Environments

Girish Chowdhary, John Ottander, Erwan Salaün, Eric Johnson
UAV Research Facility, Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332.

ABSTRACT

This paper discusses methods, algorithms, and results for control of Miniature Air Vehicles (MAV) operating in cluttered GPS denied environments. Off the shelf range sensors are used to provide local position information. The output of the sensors is processed through a Kalman filter algorithm enabled with outlier detection that reduces the likelihood of allowing bad measurements to corrupt control output. A simple Guidance Navigation and Control algorithm is proposed that ensures that maximum indoor area is explored by exploiting the inherent structure of indoor environments. A key aspect of the proposed approach is that it relies only on information from low cost commercially available range sensors and the proposed UAV along with all sensors and communication devices can cost as little as USD900. Furthermore, the algorithms presented here do not pose a significant computational burden on onboard embedded processors. A method for rapidly developing and testing control algorithms is also presented that uses the user friendly MATLAB environment.

Introduction

The ability to operate indoors and in cluttered environments has great potential benefits. However, significant technological challenges exist in order to ensure reliable operation in such environments. Most current algorithms for Unmanned Aerial Systems (UAS) Guidance Navigation and Control (GNC) rely heavily on Global Positioning Signals (GPS) signals, and hence are not suitable for indoor navigation where GPS signal is normally not available. Furthermore, the UAS must be sufficiently small in order to successfully navigate cluttered indoor environments. This poses a significant constraint on the amount of computational and sensory power that can be carried onboard the UAS. Finally, the UAS should be designed to be expendable due to the dangerous environments it needs to operate in, hence low cost, low weight sensors need to be employed. These restrictions pose significant technological challenges for the design of reliable Miniature Air Vehicle (MAV) platforms capable of navigating cluttered areas in a GPS denied environment.

A reasonable requirement for a MAV operating in indoor environments is that the MAV be able to explore maximum indoor area in reasonable amount of time and transmit the information acquired to a remote ground station. In this paper, we propose a novel approach to GPS denied navigation that leverages the inherent stability properties of certain Miniature Aerial Vehicles (MAV) with low cost, low weight, Commercial Off The Shelf (COTS) Sensors. We propose a guidance system that combines simple low level guidance policy with high level guidance goals in order to complete the mission requirements. We also propose a method for rapid testing and in flight validation of control algorithms for MAV in real time using commercially available tools. Finally we present results that show the effectiveness of our approach in navigating cluttered indoor environments.

Selection of Vehicle

UAVs capable of indoor flight must be able to hover, turn on the spot, vertically take off and land (VTOL), as well as be extremely maneuverable to get out of tight spots. Traditional rotorcraft (those with single rotor and a tail rotor) fit these requirements, however they are dynamically unstable and hence require closed loop feedback for stabilization. This involves developing an elaborate sensor suite that is able to estimate the vehicle angular rates, velocity, position, and attitude. Such a sensor suite may be costly (both in terms of cost of sensors and related computational burden in processing the information) and may not be realistically accurate in a GPS denied environments (for reasons mentioned in the next section). A solution here is to use a dynamically stable VTOL platform that is also highly maneuverable and reliable. A Coaxial rotorcraft is dynamically stable, compact, has low noise, and is sufficiently maneuverable.

The Esky Big Lama (see Figure 1) is a coaxial rotorcraft that was found to be sufficiently reliable and robust for the purpose of this work. The vehicle is a counter-rotating coaxial helicopter

Figure 1 ***The ESky E020 "Big Lama" coaxial helicopter. Note: the tail rotor on this aircraft is neither functional nor required for flight.***

with no tail rotor. The upper rotor is stabilized by a Bell stabilizer and is RPM controlled. The lower rotor is connected to a 2-servo swash plate and also has RPM control. The system is a four channel helicopter with pitch, roll, yaw, and throttle control, with a yaw-damping gyro to improve handling qualities. Some additional technical specifications for the stock aircraft are: main rotor diameter of 460mm, takeoff weight 410g, 800mAh 11.1V LiPo Battery, 75MHz FM radio.

The counter rotating blades of this vehicle ensure that the net torque on the airframe is nearly eliminated. The vehicle was augmented with off the shelf Heading Hold Gyro which ensures that the vehicle maintains its yaw attitude. The Bell stabilizer bar provides this vehicle with a remarkable passive stabilization system. Without going into details of helicopter stability, the Bell stabilizer essentially consists of a decoupled gyroscopic element that holds its attitude in space. If the vehicle encounters a disturbance that changes the attitude of the airframe, the Bell stabilizer remains fixed in space and the resulting attitude difference between the main part of the airframe and the Bell stabilizer causes a restoring effect on the airframe.

The rotorcraft is augmented with closed loop position control based on range sensor measurements. We use information from multiple range sensors positioned along the lateral, longitudinal, and vertical axis of the rotorcraft. The filtered range information is used for close loop position control; furthermore, by processing the range information using a Kalman Filter, estimates of the relative vehicle velocity are formed. The velocity information is also used to aid the closed loop position control.

Navigation Algorithm

UAVs capable of indoor flight must be able to hover, turn on the spot, vertically take off and land (VTOL), as well as be extremely maneuverable to get out of tight spots. This requires precise control and hence precise knowledge of the UAV's state information, which includes precise knowledge of the UAV's relative 3-dimensional position, 3-dimensional velocity, roll, pitch, and yaw angular rates, and angular attitude.

Traditionally, these measurements are formed based on an Inertial Navigation System (INS) which consists of three accelerometers for measuring body frame accelerations and 3 gyroscopes for measuring the angular velocities. Since UAVs capable of operating in indoor environments must be sufficiently small, they must carry electronic COTS accelerometers and gyroscopes. Current state of the art COTS gyros and accelerometers are *strapdown*, that is they are rigidly attached to the UAV frame and are hence subject to rotation with the UAV. This creates a major technological challenge as the INS measurements are now in the body frame and must be transformed to inertial frame if they are to be integrated to estimate the vehicle position and velocity. For this transformation, the body attitudes must be known, however, body attitudes are measured by integrating the angular rate measurements from the gyroscopes. This integration is highly susceptible to biases, noise, and initial misalignment error. The latter occurs due to the fact that exact alignment of the sensor cannot be known prior to sensor initialization. Hence the INS measurements are subject to drift and grow unbounded in a short period of time without correction. This results in instability of the UAV. Modern commercial UAVs use GPS signals as a way to correct for the INS biases and initial misalignment error. This is achieved by comparing the position and velocity obtained by integrating the accelerometer output converted to the inertial frame with those measured from GPS. Using this error an Extended Kalman Filter setup is implemented to simultaneously estimate INS biases, and correct for initial misalignment error. Therefore the role of GPS signals in modern UAVs is not simply to provide a position estimate, but it is also the enabling factor in attitude estimation and velocity control. Hence availability of GPS becomes an integral part of modern navigation system's operation [3], without which current UAVs would not be able to function.

In this paper, we propose an approach that leverages the inherent stability properties of the VTOL coaxial rotorcraft platform. Since the flight platform we use posses desirable stick free attitude stability, the task of the control algorithm is reduced to controlling the position.

We propose the use of low cost active sensors such as Sonar Range Sensors and Infra Red Range Sensors. Modern Sonar based range sensors are small, reliable, and low cost. They can provide range information of up to 20 ft. This range information can be used to enforce obstacle avoidance. Furthermore, using this range information, simple guidance policies such as wall follow, corridor follow, aperture search etc. can be used to ensure that maximum indoor area is explored. However, information from these sensors is often subject to noise and interference from companion sensors and must be further processed before using in the control algorithm.

Particularly, sonar range sensors are often subject to erroneous output due to interference from other sonar sensors, multi-path effects, and material absorbing the sound waves. We handle this problem by employing a smart filtering algorithm that uses computed information about the filtered data in the Kalman filter covariance matrix to ignore measurements with statistically improbable residuals. However, the information about these outliers are stored and utilized if a true discontinuity has occurred in which the case the estimate is adjusted. This way, reliable relative position and velocity information can be estimated using low cost sensors.

To demonstrate the performance of the filter a manually controlled flight test was performed. The result is shown in figure 2. The measurements are not reliable at larger ranges but the filter is able to successfully ignore the outliers and still track the correct range using the good data points. In addition, note that the range rate was successfully estimated and is not affected by the outliers.

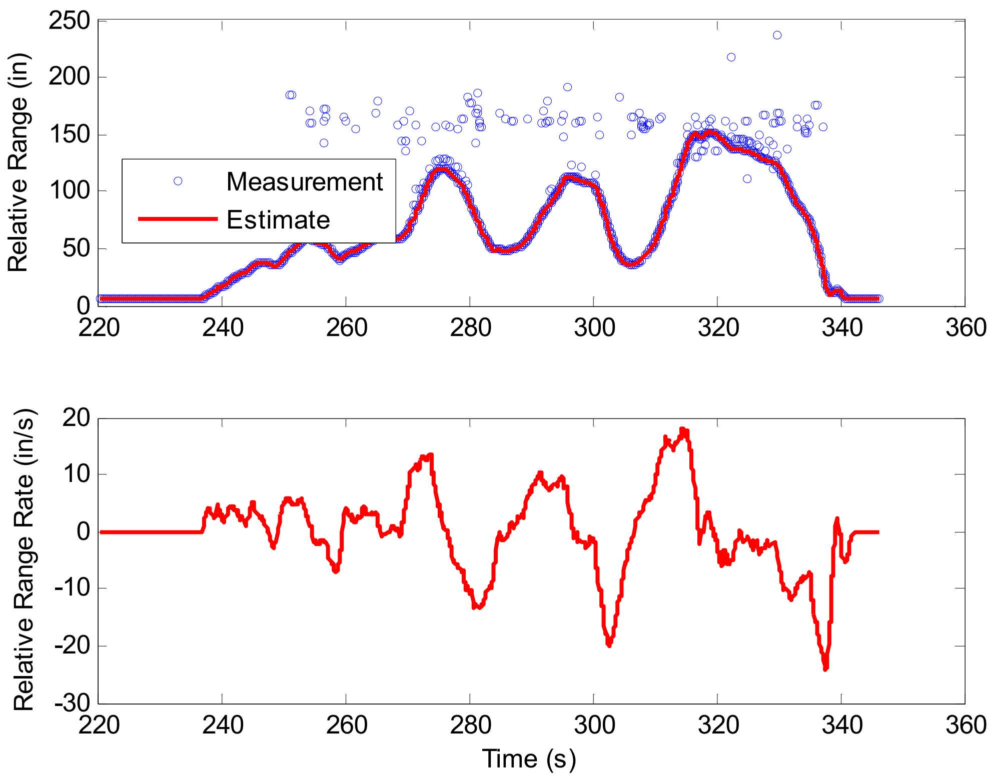

Figure 2: Downward looking sonar data during demonstration flight.

Guidance Algorithm

The task of the Guidance algorithm is to plan a path such that the mission objectives are met. We assume that the mission goal is to relay live video information from the area of interest to a remote observer. Traditionally, the path of planning an optimum path such that efficient reconnaissance information can be gathered is solved by using predefined global maps and the knowledge of the absolute information of the vehicle with respect to the map [1]. However, guidance in GPS denied environment remains a significant technological challenge due to the lack of absolute position information. MAVs operating in indoor environments need to simultaneously gather information about the immediate surrounding (also known as mapping) and find its position within this surrounding (also known as localization).

Various approaches have been used towards solving the Simultaneous Localization and Mapping (SLAM) problem [e.g. 2, 4]. However, these approaches require significant computational power and access to sophisticated sensors. In this paper, we propose an alternate approach that allows us to successfully navigate maximum indoor area without having to explicitly solve the SLAM problem. Our approach is based on the simple fact that all indoor environments have walls. Walls are easy to identify, and have a smooth structure. Furthermore, it is possible to traverse the complete perimeter of an indoor environment by simply following the walls. In the proposed approach, we use walls in an indoor environment for reference. The proposed controller is designed to find a wall, it then maintains a predefined distance from the wall using forward looking range sensor. Measurements from two forward looking range sensors are combined to obtain a relative heading with respect to the wall. This information is then used in the heading controller that ensures that the rotorcraft maintains a constant heading with respect to the wall. In this manner, by simply tracking the walls and moving sideward it is possible to traverse significant indoor areas in reasonable amount of time.

Clearly, this approach has several limitations; firstly, it is possible that the MAV will exit the indoor environments by flying straight out of a window while following a wall. Secondly, walls in indoor environments almost always have furniture stacked alongside of them, this can pose significant obstacles that need to be detected and avoided. The latter problem can be easily solved by mounting a sideward looking range sensor that detects obstacles. The first problem can be addressed by detecting bright sunlight and avoiding going towards the light. We note that this approach allows maximum information gathering with minimum computational cost.

Control Algorithm

Leveraging the inherent attitude stabilization afforded by the coaxial rotorcraft platform used, the task of the controller is reduced to providing stick deflections such that the vehicle is able to track a commanded position. The controller has access only to the local range information, however, by exploiting the fact that indoor structures have walls, the controller can be designed to follow the walls. This circumvents the requirement of requiring a global position fix and increases the reliability of the local range measurements.

The control architecture used here is the PID. The rotorcraft dynamics around a valid trim value can be approximated by a linear model of the form:

$$\dot{x} = Ax + B(u + u_{trim}) \qquad \text{Equation 1}$$

Where, x is the state of the system which includes the position, velocity, and the angular rates. The control input is given by u, note that this control input is intended to provide a correction around the trim of the rotorcraft, given by u_{trim}. Let the commanded position be given by x_c which can be a constant command or the output of a reference model:

$$\dot{x}_c = A_{rm}x_c + B_{rm}r \qquad \text{Equation 2}$$

Where $r(t)$ is a reference input to the reference model. The error between the state and the command is:

$$e = x - x_c \qquad \text{Equation 3}$$

This results in the error system:

$$\dot{e} = Ae + (A - A_{rm})x_c + Bu - B_{rm}r \qquad \text{Equation 4}$$

The PID control action can be summarized by the following equation:

$$u = K_p e + K_d \dot{e} + K_i \int_{t_0}^{t} e(t)dt \qquad \text{Equation 5}$$

Closed loop stability can now be ensured by choosing the PID gains K_p, K_d, K_i such that the error system (Equation 4) is rendered stable.

The key to successful and reliable implementation of PID control lies in the estimation of the derivative and the integral term. It is preferable to use direct measurements to form the derivative of the error $\dot{e}$, and the integral term $\int_{t_0}^{t} e(t)dt$. This architecture requires measurements of the state derivative. In the case presented in this paper, position is to be controlled, hence the measurement of the system velocity and integral of position will be required. However, these measurements are not always available, and hence an approximation must be used. Traditionally, the error is directly differentiated to obtain $\dot{e}$, however this method is highly susceptible to measurement error and noise. We propose the use of Kalman filter based local velocity estimator as described in the previous section on Navigation.

Due to the lack of accurate angular rate information, the traditional method of nested control loops cannot be utilized for control of MAVs without rate feedback operating in GPS denied environments. We circumvent the rate feedback by selecting a inherently stable platform, please refer to the section on Selection of Vehicle for further information. The control action can now be achieved by using four independent control loops:

1. Altitude Hold: The function of this control loop is to use the filtered measurements from the downward pointed sonar for altitude control. A PID architecture is used, where the derivative of the position is calculated using a Kalman filter architecture as mentioned in the section on Navigation Algorithm. During vehicle operation, varying battery voltage level affects the throttle trim value. To counter this effect, an integral part is required in the controller. Instead of integrating the position as is traditionally done, the servo commands output by the controller can also be integrated. In this way the system can inherently handle actuator saturation and integration windup. Furthermore, servo commands are easier to measure since they are assigned by the controller. Figure 3 shows the schematic of the altitude control loop. The lateral and the longitudinal loop have similar architecture.

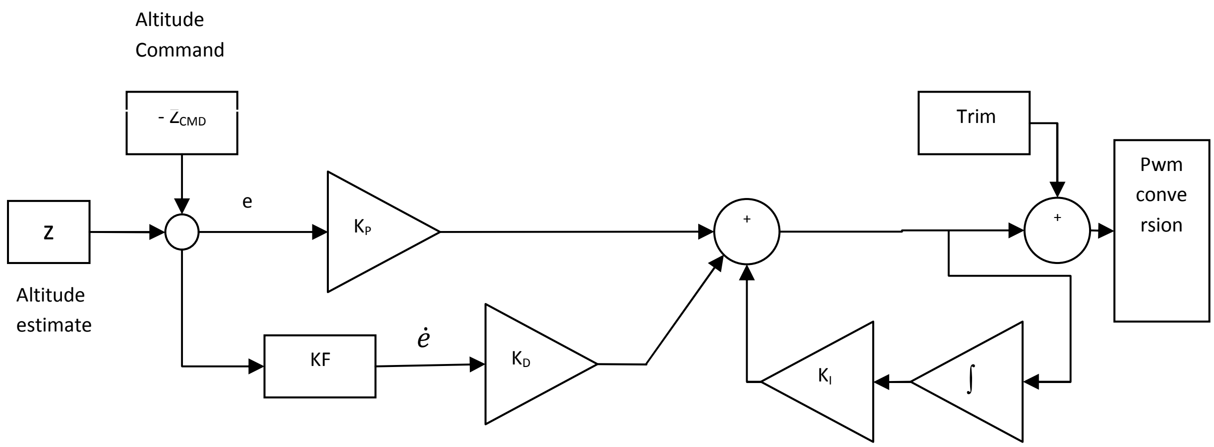

Figure 3: ***Architecture of the altitude hold controller***

2. Heading Hold: The function of this control loop is to control the heading of the rotorcraft. The heading information is formulated by using dual Infra Red (IR) range sensors mounted with a mutual offset. The purpose of the heading hold is to maintain a relative heading with respect to a local reference, such as a wall. Let x_L denote the range estimate from the left IR sensor, x_R denote the range estimate from the right IR sensor, Ψ denote the relative heading of the rotorcraft, and let L denote the mutual horizontal offset between the two sensors, then the heading estimate can be formulated as in Equation 6.IR sensors are accurate only within a limited range of an obstacle, hence this heading estimate is highly susceptible to noise. A computationally efficient way of handling this issue is to filter the IR range measurements instead using an Extended Kalman Filter to filter the heading measurements.

$$\Psi = \text{atan}\,(\frac{x_R - x_L}{L}) \qquad \text{Equation 6}$$

3. Longitudinal Position Control: The function of the longitudinal control loop is to ensure that the MAV maintains a fixed relative distance from an obstacle. The main purpose is to ensure that the MAV maintains a fixed relative distance with respect to a wall. Longitudinal control is achieved by using forward mounted sonar measurements and forward mounted IR measurements. IR measurements should only be used while in close range of the obstacle. The architecture of the longitudinal position control is similar to that of the altitude hold.
4. Lateral Position Control: The function of lateral position control is to detect and avoid obstacles lying in the lateral path of the UAV. The control loop architecture is similar to the altitude hold controller.

A Rapid Method of Validating Algorithms in Flight

In order to ease the process of validation of GNC algorithms in flight, we propose a method of rapidly testing proposed algorithms using commercially available MATLAB software and COTS datalinks. In this architecture, the task of the onboard computer is to simply process the sensor information and transmit the information to a remote ground station using a standard serial datalink using the commercially available 2.4GHz Xbee employing the IEEE 802.15.4 standard. The information is then processed in MATLAB using MATLAB's inherent serial port communication tools. We then use MATLAB scripts to perform the required Control, Guidance, and Navigation calculations and generate the servo pwm signals. These signals are then transmitted to the rotorcraft using a trainer port on a RC transmitter. In this way, the bulk of the computation is moved offboard to the user friendly MATLAB operating environment. This allows the control designer to leverage a host of inbuilt MATLAB functions as well as allow real time plotting, expediting greatly the process of validating GNC concepts in real time on flight hardware. Furthermore, this method renders the architecture highly flexible, since all servo manipulations are done through RC transmitters exploiting the inbuilt RC receiver of the airframe.

It should be noted that offboard processing using the proposed MATAB based validation method introduces significant time delays in the data. This results in conservative controller gains.

Flight Test Results

Once the control structure is validated in MATLAB, it can be ported over to an off the shelf embedded processor onboard the vehicle. Onboard processing allows for high bandwidth control as time delays introduced by the datalink required in offboard processing can now be eliminated. The proposed algorithms have been tested in flight, we present some exemplary results for the purpose of this paper. The results presented here were recorded on a heavily modified Esky LAMA coaxial counter rotating helicopter as discussed in the section on vehicle selection. The ATMEL ATMEGA 128 onboard embedded processor was used for performing all onboard computations. The ATMEGA costs only about US$38. The only custom fitted sensors used were two sonar based range sensors and two Infra Red range sensors. Further details on the vehicle architecture can be found in the Georgia Institute of Technology IARC 5th mission 2009 team paper.

These results were recorded as the rotorcraft autonomously held altitude at 6 feet while drifting in an indoor environment. The rotorcraft has been enabled with a forward looking Sonar range sensor that activates an obstacle avoidance algorithm which drives the rotorcraft backward whenever an object is within 7 feet of the senor. Figure 4 shows the performance of the altitude hold controller, it is seen that the rotorcraft is able to track the altitude command in spite of corrupt sonar data with various outliers. The first plot in the array of plots shows the performance of the Kalman filter enabled with smart outlier detection with blue lines indicating the measurement from the sonar range sensors, while green line indicating the output of the Kalman Filter. It is seen that the Kalman filter is able to reject many of the outliers resulting in a fairly accurate estimation of the vehicle position and vertical velocity. This accurate state estimation allows the use of simple PID laws that result in successful altitude hold using only a single downward mounted Sonar range sensor. Figure 5 shows the performance of the longitudinal obstacle avoidance controller that attempts to keep a distance of about 7 feet from an obstacle. It is seen that the system is successful in ensuring that the vehicle does not come too close to the obstacle in spite of the corrupt Sonar data.

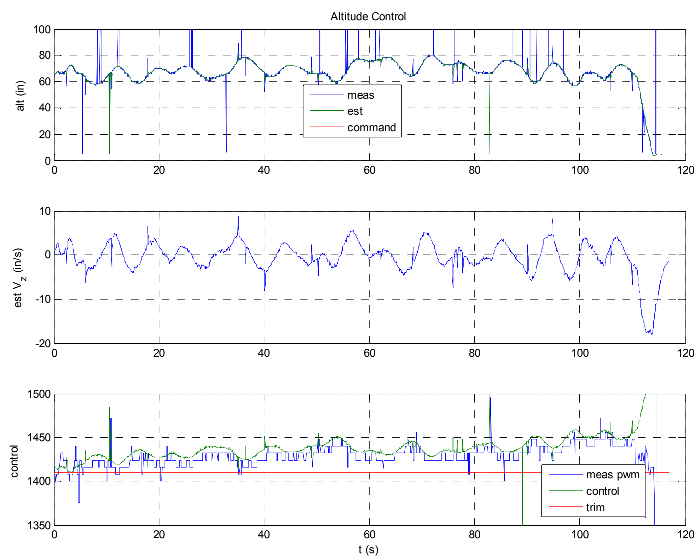

Figure 4 Altitude control using downward mounted sonar.

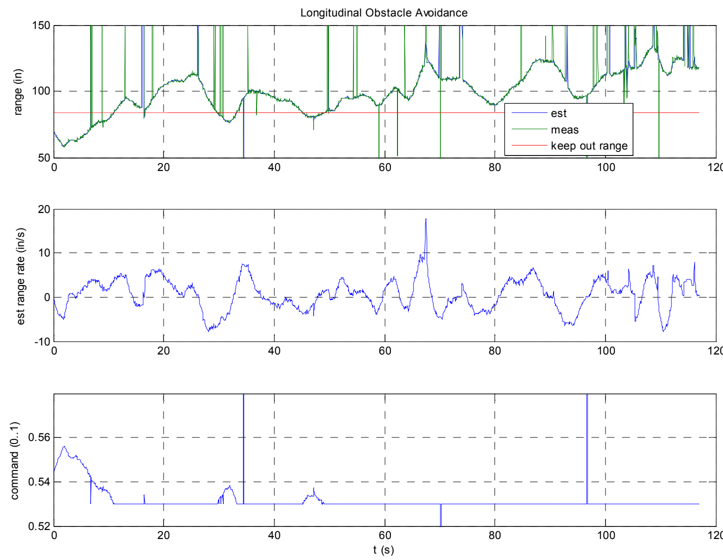

Figure 5 Longitudinal obstacle avoidance using forward mounted Sonar.

Conclusion

We have proposed a method for developing extremely low cost Guidance Navigation and Control solutions for a MAV operating in GPS denied cluttered environments based entirely on range sensors. We assume that a reasonable objective is that the MAV be able to traverse maximum area of the indoor environment in reasonable amount of time. The proposed approach in this paper is based entirely on commercially available low cost range sensors, and no elaborate sensor fusion of multiple sensors is required to achieve the stated objective. We have shown that leveraging the inherent structure of indoor environment (walls in this case), it is possible to develop simple guidance logic that ensures that maximum area of the indoor environment is traversed in a reasonable amount of time. We have noted the significant of choosing the right MAV platform early in the design stage to simplify the GNC problem. Particularly, choosing an inherently stable flight platform with sufficient maneuverability, such as a Coaxial Rotorcraft, allows for the rate estimation and damping and attitude control problem to be circumvented. We have also noted the importance of using smart filtering logic that ensures maximum amount of information is extracted from low cost sensors mounted on heavily vibrating structures.

The aim of this paper was to demonstrate that simple GNC laws can be used to solve the complex problem of indoor navigation in a robust and efficient manner. The proposed approach is well suited for implementation of low cost embedded processors which can be installed on commercially available low cost counter rotating coaxial rotorcrafts. In our experience, it is possible to assemble a complete system for as little as USD 900. Clearly, the proposed approach has several limitations, particualry, simple PID controllers designed based only on range measurements are not as good as human pilots, however, we note that the significant cost benefits and increased reliability due to reliance on simple algorithms far offset the limitations.

In the future, we intend to improve the capabilities of the proposed system by including adaptive trim estimation, smart SLAM logic, and vision enabled GNC.

References:

1. Johnson Eric N., Kannan Suresh, *Adaptive Trajectory Control of Autonomous Helicopters,* AIAA Journal of Guidance Navigation and Control, 2005, Vol 28.
2. Kim Jonghyuk, Sukkarieh Salah, *Autonomous Airborne Navigation in Unknown Terrain Environments*, IEEE transactions on aerospace and electronic systems, vol:40 iss:3 pg:1031, 2004, USA.
3. Wendel,J., Maier, A., Metzger, J., and Trommer G. F., "Comparison of Extended and Sigma-Point Kalman Filters for Tightly Coupled GPS/INS Integration", AIAA paper 2005-6055, August 2005.
4. Van Dyk Parunak Altarum, Michel Purcell, Robert O'Connel, *Digital Phermones for Autonomous Coordination of Swarming UAVs*, Proc. Of 1st AIAA Unmanned Vehicles, Systems, Technologies, and Operation conference, 2002, USA.