

Development of Multi-Nozzle Mobile Platform

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Abstract—The airborne vehicles with integrated VTOL (Vertical Takeoff & Landing) and hovering strategies is one of the remarkable topic that has been extensively investigated and reviewed by the researchers. Controlling such systems is quite a challenging task requiring expertise to handle complex nonlinear maneuvering response. This paper presents the design and development of mobile platform with Adaptive Neuro Fuzzy Inference System (ANFIS) based operational control and stability approach. The experiments have been carried out on the setup utilizing the blocks of multiple nozzles (BMN) generating sufficient thrust to lift the mobile platform that hovers in the air within a certain height. The input to each BMN is in the form of compressed air delivered from compressor. The air mass flow rate is adjusted through electro-mechanical actuators to achieve desired altitude and for handling the balancing issues. The system requires the synchronized regulation of air distribution that evolves by the changes occurring in physical parameters. The real time monitoring and control methodology has been implemented in LABVIEW software. The intelligent strategy employing combination of multiple height sensors and IMU's along with the multiple actuators showed enhanced capability to stabilize the output response with impressive control performance.

Index Terms—T-S ANFIS, Multi Nozzle Block, Thrust Response, Hovering Platform, Synchronization and Stability Control.

I. INTRODUCTION

THE technological advancement in the field of mechatronics has gained significant importance in aerodynamic research. Recent trends in the development of airborne vehicles include stabilized reconfigurable control of dynamic framework with hovering and VTOL capability. These applications are typically employed in multi-copters, helicopters, hover bikes, jet propulsion systems etc. for carrying out surveillance, monitoring, rescue and combat operations [3], [7], [13], [14], [20], [24]. The advantage of adopting such strategies include the maneuvering of platform at a certain height range with high endurance load carrying capability, requiring limited area for launching and docking. The most advanced configuration of these systems are observed in multi rotor drones or jets aircrafts [2], [5], [8], [25], [33]. The aerodynamic processes are highly prone to disturbances induced by external forces and nonlinear dynamic behavior. To cater the associated problems different methodologies are adopted to develop the efficient, reconfigurable and fail safe application. The design of VTOL based air drifting aerial structure requires sophisticated control providing high stability, robustness and resilience towards harsh environmental conditions [3], [9], [15], [18]. Apart from that to improve the overall performance several considerations

are to be made for the selection of appropriate sensors, attenuation of vibrational effects, drag reduction, choice of Data Acquisition and Control (DAC) Unit, mode of communication etc. In this paper novel model comprising of multi-nozzle mobile platform with ANFIS based operational control and stability approaches are analyzed.

Extensive research has been carried out to explore the modes of achieving the VTOL and steady drift by the aerial vehicles. The most popular studies are related to the development of rotor based multi-copters and jet engines. The single rotor helicopters have highly complex mechanisms owing to high maintenance cost and are difficult to control [53]. For these reasons the focus of the research has been shifted towards the multi-rotor systems. The main advantage of using multi-copters include simple construction, small scale, steady hover under payload's and low maintenance cost [16], [17], [23], [25]. The most popular configuration amongst them is the quad-copter UAV that have strong low cost structures with better stability and navigation characteristics [6], [10], [14], [22]. VTOL relying on the modern jet propulsion systems is state of the art technology that has revolutionized the research prospects of aircraft manufacturing. The attitude and the height of drifting platforms are determined by the sensors including Gyros, LIDAR, Infrared, Ultrasonic, GPS etc [2], [3], [25], [26], [33]

The maneuvering of the airborne vehicles is prone to high disturbance with highly uncertain nonlinear behavior. To achieve the stable drift different control strategies have been proposed. Most of the research studies are established on conventional PID technique due to its simple structure and ease of implementation [2], [9], [12], [13], [20], [24]. PID control is generally adopted for the linear systems but it lacks ability to precisely handle the uncertain nonlinear behavior. Other nonlinear approaches including backstepping, kalman filtering, nonlinear hinf, LQR, sliding mode, linearized feedback mechanism have been successfully implemented in [1], [2], [19], [21], [24], [27–30] showing good controllability characteristics but are too complicated and computationally more expensive. The intelligent modes like Neural Network, fuzzy logic, adaptive neuro fuzzy approaches as introduced in [11], [16–18], [22], [52] revealed impressive performance in providing stable flight control providing resilience towards induced disturbances.

To improve the performance of the maneuvering air lifted mobile platforms, several factors are to be reviewed including the structure, utilization of suitable sensors and the controller design. The framework is to be developed in such a way to reduce the air drag and vibrational effects. This can be achieved by utilizing the quad configuration for better steering and variable load carrying capability. The orientation and the height parameters of hovering platform can be measured by

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the combination of array of sensors with utilization of sensor fusion techniques to get accurate results, imparting redundant solution to the system. Finally the intelligent control strategy should be adopted to acquire stable and reconfigurable control even in the harsh conditions.

In this paper the mechatronics approach for the design and development of multi nozzle block based mobile platform has been presented. Small scale apparatus has been setup consisting of cross shape structure with embedded four BMNs at the corners. BMN generates the thrust by converting the air pressure from the compressor into kinetic energy to lift the aerodynamic structure. The platform is allowed to have only vertical and translational movement. IR sensors and IMU (MPU 6050) are used to measure the height and orientation of the platform through data acquisition process. The control and stability is achieved by ANFIS based control architecture whose parameters are tuned by the Genetic Algorithm (GA). Labview software is used to implement the monitoring and operational control process. The current research would demonstrate a novel perspective in the evolution of UAVs.

II. DESIGN CONSIDERATIONS FOR MOBILE PLATFORMS

A. Structural Framework

The geometry of an aerodynamic structure plays an important role in hovering and VTOL applications. For achieving high performance, the framework has been developed in quadrature configuration. This not only improves maneuverability but also assist in attaining the stable drifting response. The experimental platform for carrying out the current research is shown in Fig.1

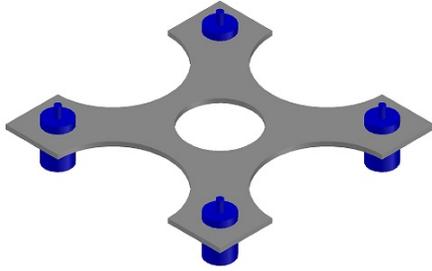


Fig. 1. Mobile Platform Structure

The nozzles are the critical part of jet propulsion systems. The four blocks of multi-nozzles have been fixed on the mobile setup to displace the maximum surrounding air and generate enough thrust to lift the platform. The nozzles are properly designed in accordance to specifications and requirements by utilizing the isentropic relations given by [48], [49], [51]:

Mass Flow Rate of Fluid at Nozzle Exit:

$$\dot{m} = \frac{A p_i}{\sqrt{T}} \sqrt{\frac{\gamma}{R}} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (1)$$

Nozzle Pressure Ratio:

$$\frac{P_e}{P_i} = \left(1 + \frac{\gamma - 1}{2} M_e^2 \right)^{\frac{\gamma}{\gamma-1}} \quad (2)$$

Density of Fluid:

$$\rho = \frac{P}{RT} \quad (3)$$

Nozzle Exit Velocity:

$$V_e = M_e \sqrt{(\gamma RT)} \quad (4)$$

Nozzle Area Ratio:

$$\frac{A_e}{A_i} = \frac{1}{M_e} \left[\left(\frac{2}{\gamma + 1} \right) \left(1 + \frac{\gamma - 1}{2} M_e^2 \right) \right]^{\frac{\gamma+1}{2(\gamma-1)}} \quad (5)$$

Thrust Generated by Nozzle:

$$F = \dot{m} V_e - (p_e - p_o) A_e \quad (6)$$

In the above equations,

F= Nozzle Output Thrust , \dot{m} =Mass Flow Rate,
 p_i = Nozzle Inlet Pressure , p_e = Nozzle Exit Pressure,
 p_o =Free Stream Pressure , ρ =Density of Air at a Point,
R=Real Gas Constant , T=Total Nozzle Exit Temperature,
 A_i =Nozzle Inlet Area , A_e = Exit Area,
 M_e =Mach Number of Fluid at Nozzle Exit,
 γ = Specific Heat Ratio.

After designing process, the block of multiple nozzles undergo the testing procedure. Small scale nozzle trial setup is made to verify the output thrust in response to the variable pressure input. This validates the results obtained from the testing phase and also provides the information related to dynamics of the operational process.

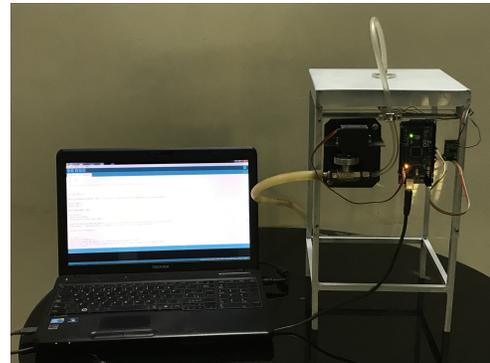


Fig. 2. Experimental Setup for Determining Thrust Response

The mounting of the nozzle blocks and the sensors is another aspect that can impart instability to the system. These components are adjusted in a suitable position far away from the center of gravity thus reducing the jittering effect.

B. Selection of Sensors & Actuators

To design a precise control system, sensors and actuators are the critical components that contribute in enhancing the performance of dynamic processes. These vital elements are selected on the basis of several considerations including the size, cost and operational complexity. The main requirement of the sensors in the present research is to detect the attitude and altitude of the mobile platform. For monitoring the stability level low cost Inertial Measurement Unit (MPU 6050) consisting of 3-axis accelerometer and 3-axis gyros are employed. Besides the advantages of small size of MEMs based MPU 6050 modules, these are highly prone to systematic and stochastic errors. Systematic errors include DC offsets, scalability factor, cross coupling and g-dependent disruptions [43–45]. Such type errors can easily be mitigated through proper calibration and sensor position adjustments on the mounting surface. The stochastic errors on the other hand cause perturbations in the measurement due noisy accelerometer signal and the drifting values obtained from the gyros. The accelerometer or gyro alone is not capable to detect the tilt of airborne structure. To cope up with this discrepancy multi-sensor fusion filtering technique (utilizing Kalman Filter) is adopted to get reliable Euler values [41], [46], [47]. The height of the aerodynamic platform is measured by the set of four economical infrared sensors (model: GP2Y0A41SK0F) giving the output as analog signal that is processed interpreted to give dependable/reliable results. These sensors require external low pass filters with software driven signal conditioning to attenuate the noise and enhance the signal integrity. The calibration technique of the height sensor is comprehensively discussed in [32].

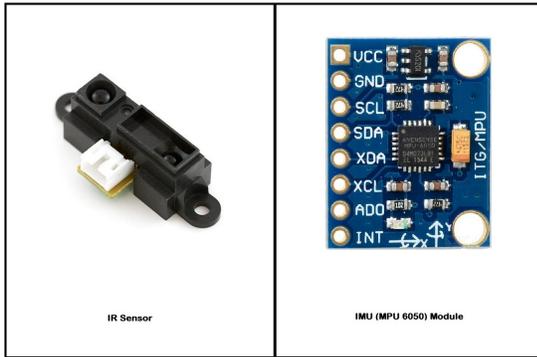


Fig. 3. Altitude and Attitude Sensor Modeules

The electromechanical valve actuators are used to adjust the thrust generated by the multi-nozzle block. The actuators are chosen on the basis of simple construction, cost effectiveness, smooth operation and easy calibration. For the experimental setup, customized electromechanical ball valve actuators are designed to achieve the smooth operation through servo feedback mechanism providing accurate robust control. This would allow the synchronized control of thrust to balance and stabilizing the motion of aerial frame.

To improve the quality of system response, extra sensors and actuators are incorporate to the platform enabling to perform the functional requirements under fail safe conditions.

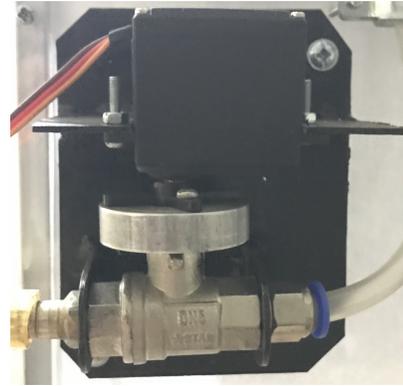


Fig. 4. Electro-Mechanical Ball Valve Actuator

C. ANFIS Based Control

The commonly used ANFIS technique is Type II architecture which is based on T-S rule structure. T-S type ANFIS has priority over other types due to its enhanced controllability and adaptability features. It is a five layered process that acts in accordance to the triggered rules. Each layer consists of square nodes (containing variable parameters) or circular nodes (containing fixed parameters). Typical representation of rules involving two inputs and single output is given by [38], [39]:

$$\begin{aligned} \text{if } x_1 \text{ is } R_{x_1} \text{ and } x_2 \text{ is } R_{y_1} \text{ then } f_1 &= p_1(x_1) + q_2(x_2) + r_1 \\ \text{if } x_1 \text{ is } R_{x_1} \text{ and } x_2 \text{ is } R_{y_2} \text{ then } f_2 &= p_2(x_1) + q_2(x_2) + r_2 \\ &\vdots \\ \text{if } x_1 \text{ is } R_{x_N} \text{ and } x_2 \text{ is } R_{y_N} \text{ then } f_N &= p_N(x_1) + q_N(x_2) + r_N \end{aligned}$$

where x_1 and x_2 are the inputs while f_N is the rule output.

The choice of shape for the membership function is a critical part of working scheme that varies with the type of selected application [40]. The number of rules are based on the relationship between number of inputs and membership functions are defined as [50]:

$$\text{Number of Rules} = (M)^n$$

where "M" represents number of membership functions and "n" shows the number of inputs to the controller.

The rules are composed of two sets of variables $\{S_1, S_2\}$ including premise and consequent parameters. For each rule, the premise parameters constitute the membership function while consequent parameters are related to output bilinear funtion. These parameters are modified by utilizing different learning algorithms to adapt the varying input due to physical and environmental changes to achieve precise robust output response. The Anfis structure for two inputs (each having two membership funtions) can be described in five layers:

1) *Layer 1*: In this step the degree of membership is calculated for each input variable against the number of triggered rules. The rules are associated to the membership functions

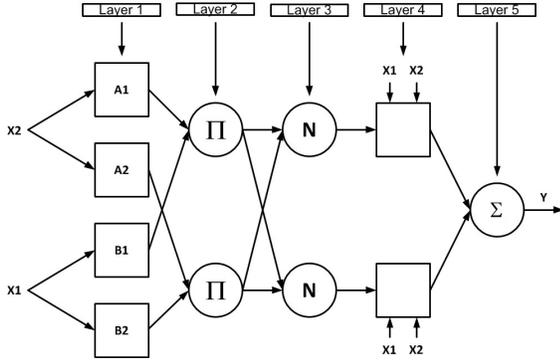


Fig. 5. ANFIS Structure

distributed over the universe of discourse whose shape (triangular, s-type, trapezoidal, bell, Gaussian) is defined by the premise parameters. The commonly used shape especially for nonlinear systems is Gaussian function that can be given by:

$$\mu_{i,j}(x) = \exp^{-0.5(x-c_{i,j})^2/a_{i,j}^2}$$

2) *Layer 2*: It determines the firing strength of each triggered rule correlating the inputs by taking T-Norm (product, min, max, union, complement etc.). T-S ANFIS utilizes the product of membership values for the given inputs for the evaluation process.

$$w_k = \mu_i(x_1) \cdot \mu_j(x_2)$$

3) *Layer 3*: It is a stage in which the normalized firing strength of activated rule is found by the ratio of individual firing strength of each rule to the sum of strengths of all firing rules.

$$\bar{w}_k = \frac{w_k}{w_1 + w_2 + w_3 + \dots + w_n}$$

4) *Layer 4*: The product of individual normalized firing strength and the conditional function gives the output of each triggered rule. The conditional functions comprise of the consequent that interpolates and scales the output response.

$$\bar{w}_k f_k = \bar{w}_k (p_w x_1 + q_w x_2 + r_w)$$

5) *Layer 5*: The resultant output is obtained by combining the outputs of all the activated rules.

$$O = \sum_k \bar{w}_k f_k$$

The ANFIS parameters are adjusted by self learning algorithms. The classic way to modify these parameters is to employ the hybrid approach combining the Back Propagation (BP) and Least Square Estimation (LSE). The BP changes the premise parameters during the backward pass while LSE varies the consequent parameters through forward pass. Advance learning algorithms have been proposed by the researchers for tuning ANFIS to get the optimized results.

D. GA Based ANFIS Parameters Updation

GA's are the evolutionary search and optimization algorithms based on the process of survival of the fittest inspired by darwins theory of evolution. The concept of GA's was proposed by John Holland in 1970's. These are well suited for the various practical problems in many fields. Some of the applications of GA's include optimization, machine learning, automatic programming, economics, gene selection etc [31], [34–36]. The basic components of GA involved in solving the optimization problems are :

1) *Population Size*:: The population size is represented by number of chromosomes. Each chromosome defines a candidate solution. Set of chromosomes represent the number of possible range of solution space.

2) *Fitness Function*:: It is the objective function that provides a selection criterion for the fittest solution. This means the fitness function with high fitness value would have high probability of being selected as candidate solution for next proceeding operations. The selection must be made in each iteration to evolve most fit next generation and knock out the rest of the solutions.

3) *Offsprings*:: A new generation is produced with better solutions than the preceding one based on the selection criteria of the fittest solutions.

4) *Cross Over*:: In this stage the superior solutions in pairs start to intermingle with each other to give new pairs containing hybridized characteristics of mating pairs.

5) *Mutation*:: Mutation adds up new information to the GA search to form the next generation. It causes changes in the solutions making it different from the solutions of the previous generations to maintain the genetic diversity.

In order to understand the process of optimization of ANFIS by GA, let us consider a set of ANFIS variables (S_1, S_2). Components of the set contain the parametric vectors defining the premise and consequent parameters. The variables are initialized and are then randomly generated to define the structural framework. The inputs are applied to the ANFIS and the feasibility of the output is checked by evaluating the fitness function. Based on this, series of processes including offspring generation, crossover and mutation in the parameters are carried out maximize the fitness function. If the required results are not achieved, the above mentioned processes are repeated to get the desired response. The steps involved in optimizing ANFIS parameters can be represented by the figure given below:

E. Proposed ANFIS Control Strategy

The trial setup under consideration is a complex nonlinear system with highly uncertain behavior. The main objective of the control strategy is to maintain the height and inclination level of mobile platform by regulating/adjusting the air flow

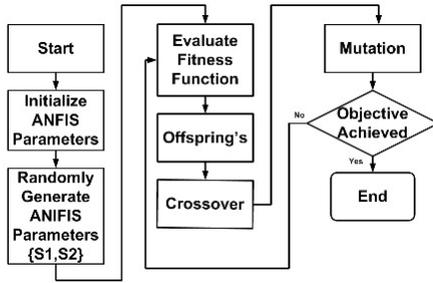


Fig. 6. ANFIS-GA Algorithm

through each BMZ to get stable output thrust response. Such systems require robust automatic reconfigurable controller design to achieve smooth, efficient and high performance operation. The techniques adopted are used to reduce the overshoot response and oscillatory effects to attain smooth balanced maneuvering of air lifted platform.

The proposed strategies incorporate two main approaches for the implementation of ANFIS-GA based control algorithm. The first scheme consists of separate controller architecture for measurement of each altitude and attitude parameters. The vertical position of the hovering structure is determined by infrared sensor. The estimated level is compared with the desired set point that becomes the basis of scalable controller action for the main electro-mechanical ball valve actuator resulting in regulated air flow to achieve desired elevation response. The orientation of the airborne structure is estimated by two IMU's (MPU 6050). The information is processed and then interpreted by the ANFIS control whose parameters are tuned by genetic algorithm to trigger the four actuators for modulating the air flow. The synchronized motion of air supplied to the multi-nozzle blocks from the actuators results in stabilizing the mobile platform. This methodology can be further divided into two subcategories. In method (1a), each of the control signal is sent to complementary pair of actuators that accept the inputs having the same magnitude but with opposite sign.

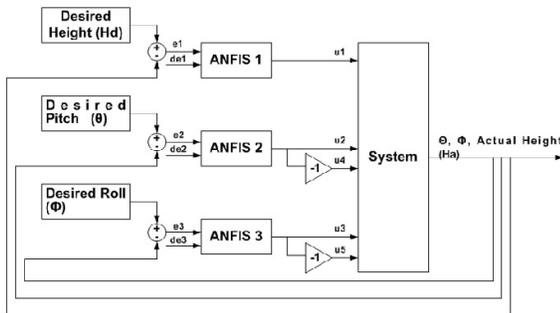


Fig. 7. Method(1a) for Elevation and Stability Control

The other method (1b) involves the fixing of the valve position of two actuators located at right angle to each other. Only the two other actuators are utilized for producing the regulated thrust from MNB. To enhance the performance of the model system, multiple sensor modules are adopted. This

not only provides the better assessment of the system but also adds more resilience towards disturbance and changing environments. The other advantage of using this approach is that it makes the system more redundant and fault tolerant under dynamically variant conditions.

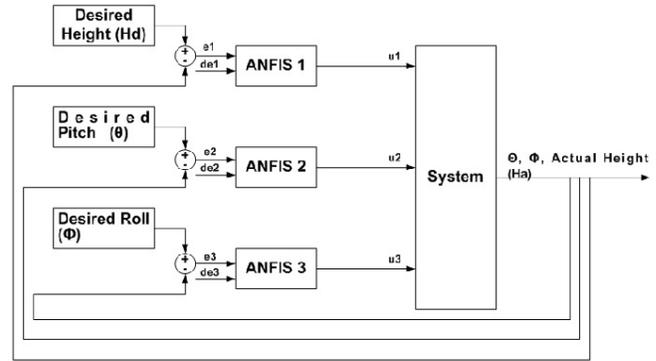


Fig. 8. Method(1b) for Elevation and Stability Control

The second scheme uses combine controller architecture employing only the IR sensors for carrying out the monitoring of height and tilting level. Like first scheme two methodologies are adopted. In Method (2a), the measurement obtained from each sensor is averaged. The difference between the average height and the localized elevation measured from each corner of the platform generates the error signal which is then accepted by ANFIS-GA based controllers responsible for sending the control signal to the actuators. The selected routine is dependent on two controllers that have been employed to accomplish desired balanced position. It is only applicable where hovering level is achieved over plane surface without obstacle.

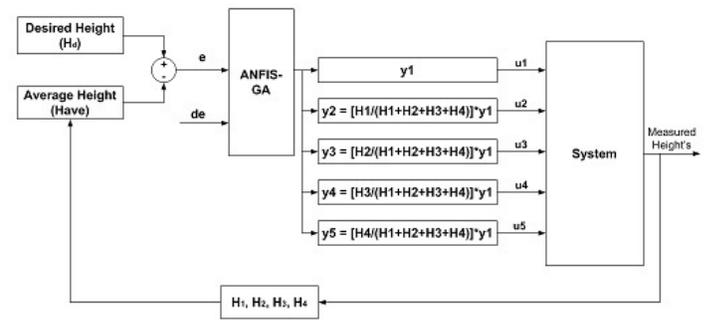
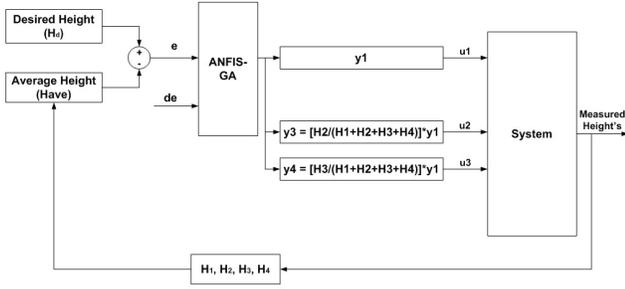


Fig. 9. Method(2a) for Elevation and Stability Control

Similarly Method (2b) combines the the characteristics of methods 3 4. It utilizes only two complementary actuators with multi IR sensors. The control structure of this routine is given as follows:

h]



Method(2b) for Elevation and Stability Control

F. Software Development

In engineering field, software is a programming domain that acts as mode of communication for monitoring and supervision of system integrated devices. The basic criterion for developing a reliable software is to design an interactive and customizable software with modular approach that satisfies all the operational and functional requirements. The testing software for the automated jet propulsion applications has been developed in LabVIEW environment. The libraries and sub-libraries are formed to carry out the tasks including system initialization, configuration, sensor actuator calibration, data acquisition, control, performance analysis and data logging.

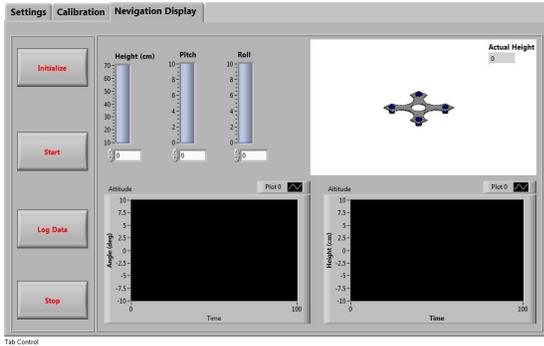


Fig. 10. Software Interface for Operational Control and Stability of Mobile Platform

III. EXPERIMENTAL SETUP & PROCEDURE

The trial setup consists of a test stand having a static base located 0.25 m above the ground that acts as launching pad for the quadrature UAV configuration. Four multi-nozzle blocks (MNB's) are fixed on the movable frame at the corners that are utilized to convert the air pressure (from the compressor) into kinetic energy to generate thrust for lifting the mobile platform. MNB's are connected to electromechanical ball valve actuators through soft tubes. Each actuator is attached to (1 to 4 way) distributor joined to the main actuator fixed to compressor supply line providing the regulated pressure. The airborne structure freely moves in vertical direction within height range of 0.25-4 m allowed partially restricted translational movement to judge the orientation level. The four infrared height sensors and two inertial measurement units (IMU's) are mounted at specified positions.

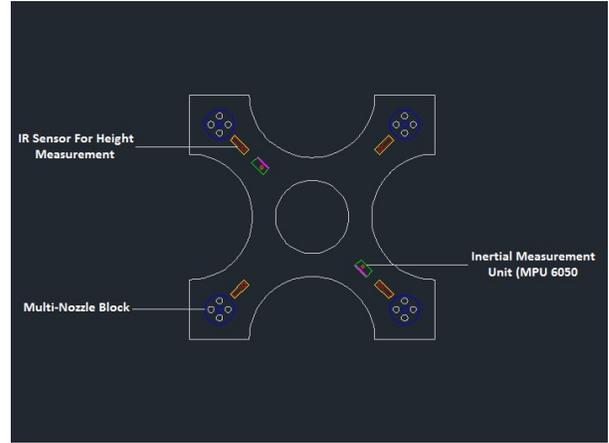


Fig. 11. Mounted Components on Mobile Platform (Bottom View)

To monitor the height and Euler Angles (only pitch and roll), multi sensor fusion strategy has been employed. The purpose of the using group of sensors is to achieve precise measurement and at the same time imparting redundancy to the system in case of failure of any detecting module. The data collected from the sensors are filtered to get the reliable readings.

The electromechanical actuators are operated by pwm signal to adjust the globe valve position for pressure regulation. The main actuator is used to control the height while four subactuators are used to stabilize the platform.

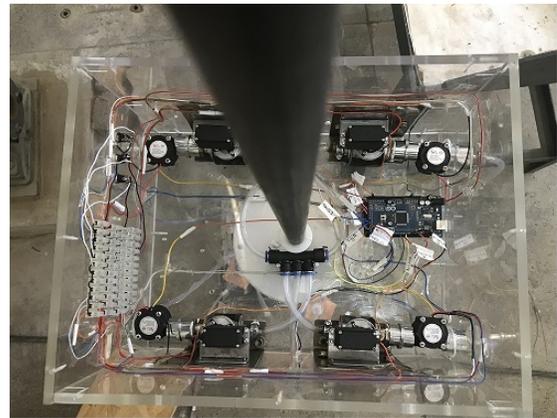


Fig. 12. The Control Unit Panel Box

The acquired information from two transducers (detecting the height and inclination level) are transmitted to data acquisition & control unit Arduino Mega 2560. To get the reasonably high Signal to Noise Ratio (SNR), signal conditioning is carried out to attenuate the noise and reasonably scaled output signal. From here the signals are received by the computer where it is analyzed, interpreted, displayed and stored in a datalogging file. Based on the data obtained, the control output is generated by utilizing the ANFIS control algorithm. The control signal regulates the electro-mechanical actuators for adjusting the mass flow rate of compressed air to achieve the desired thrust response.



Fig. 13. Main Experimental Setup

IV. EXPERIMENTAL RESULTS & ANALYSIS

The comprehensive testing has been carried out on the experimental setup against three different control frameworks to check their efficiency and viability for the selected application. The performance parameters for the altitude including settling time and final steady errors are evaluated. For the Attitude control, only RMSE values for the Euler angles (pitch, roll) are calculated as the set-point for attaining the stable tilt level is not varied throughout the investigation process. The Mobile Platform is allowed to hover over the smooth surface for the trial procedure. The response for each adopted techniques are briefly discussed below:

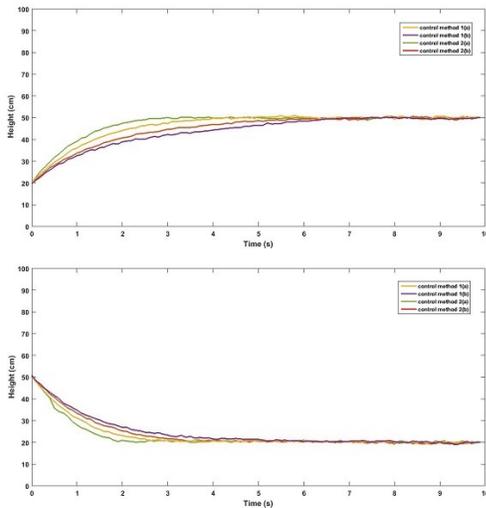


Fig. 14. Response of Different Controllers

Fig 15 gives the comparison of the output response of different control methods for positive and negative setpoints. It is observed that by triggering all the actuators, fast and robust action is achieved for attaining the desired height. Actuation

of only two actuators results in the slow control action.

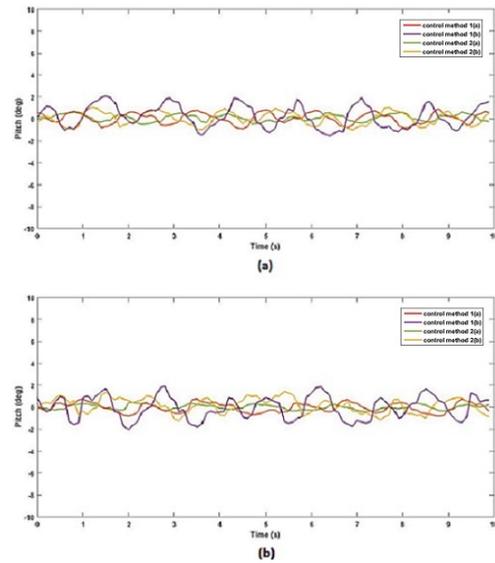


Fig. 15. Pitch Angle Error

To determine the performance of hovering stability of the mobile structure, the persisting error for the euler angles (pitch and roll) are analyzed. In Fig 16 it is noticed that there is more deviation of pitch angle when using the MPU6050 module rather than the IR sensors for different control methods. The reason is that IMU's are more vulnerable to noise and disturbance. But this discrepancy can be removed by using multiple sensors and multiple actuators. This is evident from the given figure that the control method 3 using the four actuators and two IMU's show better control response.

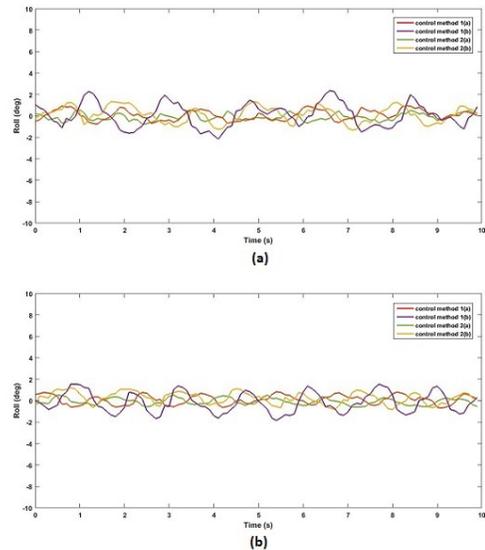


Fig. 16. Roll Angle Error

Similar trend has been detected in Fig 17 when examining the roll angle error of the drifting platform. The overall performance is evaluated and is shown in the table 1.1:

Table 1.1

Method	Increasing Height and Stability Control			
	Settling Time (s)	Height Level RMSE	Pitch Angle RMSE	Roll Angle RMSE
1(a)	2.89	0.63	0.31	0.28
1(b)	5.53	0.95	0.43	0.35
2(a)	2.45	0.19	0.02	0.07
2(b)	4.76	0.54	0.14	0.13

Method	Decreasing Height and Stability Control			
	Settling Time (s)	Height Level RMSE	Pitch Angle RMSE	Roll Angle RMSE
1(a)	2.61	0.49	0.39	0.3
1(b)	3.78	0.61	0.48	3.38
2(a)	1.63	0.27	0.05	0.11
2(b)	3.25	0.32	0.21	0.17

V. CONCLUSION

This paper focuses on mechatronics approach in the development of aerodynamic platform with hovering and VTOL capability. The research has been carried on model jet propulsion system with multiple nozzles mounted in quadrature configuration, generating enough thrust to lift the mobile structure. The reason of using multiple nozzle blocks instead of single nozzle is that it improves the performance by displacing more surrounding air imparting smooth hovering capability and reduced jittering effects. Multiple sensors are used for measuring the tilt level and the elevation of the aerial framework to increase the resilience against the varying dynamic conditions. Multi sensor multi fusion techniques are applied to enhance the quality of the acquired signal leading to precise estimation of the required parameters. To achieve high stability and smooth vertical motion of the drifting setup, ANFIS-GA based controllers have been utilized with two different approaches. The first strategy is further subdivided into two sub methodologies. In method one all the actuators are triggered to modify the air flow through multi nozzle blocks while the other methods modulates only two actuators keeping the rest in fixed open position. The second technique adopted used only the IR sensors for monitoring the position and inclination level that is only applicable when hovering over even surface without obstacles. The recorded average height is fixed as set point that is compared with the localized heights from the four corners generating the stimulus for the synchronized regulatory action of the fluid flow through actuators. It can be seen that by the adopting proper design consideration, the proposed schemes show reasonably good control response. Furthermore it is revealed that method (1a) gives remarkable control response with robust characteristics under variable dynamic environment when moving over smooth surface. Otherwise the method (2a) is the reasonable option that can adopted for all operating conditions.

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