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Design and Development of Modular Autonomous Flying Vehicle

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Abstract**—**In recent years, Vertical Take-off and Landing vehicles (VTOL) have gained popularity among researchers due to their capabilities of vertical stationary flight and maneuverability. As the consequences, many beneficial and unique applications of this type of vehicle can be found for both military and civilian purposes. Despite heightened interest in VTOL vehicles, research in this area until now has focused almost exclusively on rotorcraft platforms such as quadrotors. Very little research has been performed in extending the design of VTOL vehicles to a multi-rotor platform consisting of individual flight modules using distributed control. In this project, a multi-rotor platform consisting of modular flight vehicles using distributed control has been designed. The individual modules are able to communicate and coordinate with each other to fly in a variety of flight formations either as individual units flying in formation in a coordinated fashion or as larger units by physically combining and docking with each other. A distributed strategy for hover control based on the physical parameters of the distributed flight array (DFA) formed the basis of the flight control of the vehicles. The analysis of the prototype showed that the roll and the pitch angles achieved stabilization in the hovering state.

Keywords**—**Distributed flight array, VTOL vehicles, UAV, multi-rotor platform, distributed UAV flight formation control.

I. Introduction

In the past decade, Unmanned Aerial Vehicles (UAVs) have gained immense popularity within the aerial vehicles community, in particular the Vertical Take-off and Landing vehicles (VTOL). A particular advantage they have over the majority of aerial vehicles is their ability for vertical stationary flight. Furthermore, they provide an excellent opportunity for exploiting and testing advanced sensor technology, increasing the limits of energy storage, and developing techniques in automatic control. VTOL vehicles are finding applications in many different and diverse areas ranging from military applications to traffic surveillance. They are increasingly used for many civil applications such as firefighting, surveillance of pipelines, disaster relief, pollution monitoring, and remote aerial mapping. They can also very accurately and efficiently perform tasks that would pose significant risks for a human pilot to perform. Moreover, they also possess an advantage of maneuverability due to their inherent dynamic nature.

With the increasing interest in VTOLs in the last decade, the algorithms developed to control them have also increased substantially in number and complexity. Various control structures ranging from basic PID controllers [1], Linear Quadratic (LQ) control technique [1] to more complex systems such as Backstepping control scheme [2], collision avoidance control system [3], Differential-Evolution based Robust Control [4], Hybrid Algorithm using Differential Equation and prediction error modelling [5], hybrid of conventional back propagation training algorithm for the NARX network and multiobjective differential evolution [6], layered architectural framework control strategy [7], robust hybrid control design [8], stability augmentation system and a modern control approach [9], robust H-infinity attitude controller [10], [11], [12], [13], Model Predictive Control Scheme [14], Sliding-Mode control technique [15], Neural Networks [16], [17], [18], Fuzzy Control scheme [19] and Real Time Fuzzy Control Technique [20] have been developed to stabilize UAVs in-flight while formation control techniques such as using a cascade controller [21], PID controller incorporating a Kalman Filter [22], formation control technique using 3D Potential Field [23], [24] and Neural Network based formation control [25] have been developed for in-flight formation control of multiple UAVs. Recent progress in sensor technology, data processing and integrated actuators have made the development of small scale miniature robots fully possible. This opens the way to several, complex and highly important applications for both military and civilian use. Significant research has also been performed in developing autonomous VTOL vehicles [24], [25].

The heightened interest in VTOL vehicles has also led to the introduction of many novel design architectures to more efficiently perform the on-board sensing, communication and computation requirements such as the development of the path planning to facilitate the autonomous landing of an unmanned helicopter on a moving platform [26], achieving autonomous control of a rotorcraft using Fuzzy Control [19], mounting thrust vectoring nozzles on a quad ducted fan helicopter to maintain a horizontal attitude [27], mounting of a tilting mechanism for rotors on an autonomously controlled quadrotor helicopter to maintain a horizontal attitude [28], mounting extra thruster rotors to maintain the position and horizontal attitude of the quadrotor helicopter [29], development of a ducted flying object equipped with normal and reverse rotation ducted fan to cancel Gyro moment effect [30], development of a vision based

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altitude control strategy for a rotorcraft [31], the development of a 6-DOF Inertial Measurement Unit with the capability of measuring the angular acceleration [32], to significantly improve the safety of rotorcraft platforms by incorporating ducted fans instead of rotor blades [33], development of a layered architectural framework incorporating a novel fault detection and identification method [7] and the development of the mathematical model of a fixed-pitch unmanned co-axial rotorcraft using a multi-body dynamics modelling technique [34].

Despite the widespread popularity of VTOL vehicles and significant research being carried out in this area, researchers until now in this area have focused primarily on quadrotor platforms. Very little research has been performed in the design of multi-rotor platforms known as distributed flight arrays which consist of individual flying modules that are able to fly as individual units in a coordinated fashion or as a larger flying unit by physically combining and docking with each other. They feature rich dynamics and challenging design problems, and will undoubtedly provide a platform for developing distributed estimation and control.

This paper presents the design and development of a modular autonomous flying vehicle, i.e. a multi-rotor platform consisting of modular VTOL vehicles that are able to fly as individual units or dock with each other to form a larger flying unit as required. A distributed flight array is implemented to achieve such purpose. The modular flying vehicle gives many advantages over conventional rotorcrafts such as significantly greater resilience to catastrophic on board failure, greater optimization and flexibility, and considerably lower maintenance costs as each module can be combined or released to suit the flight condition and task. The significance of the study lies in the fact that it will be a significant contribution to research and development in the area of VTOL vehicles. Furthermore, this project will provide a very useful platform for developing distributed estimation and control. The design challenges resemble those of modular reconfigurable robots and micro aerial vehicles which include electromechanical interconnection, inter-module communication, and energy storage.

II. Methodology

The following methodology has been adopted to describe the development of such flying vehicle.

1. *Designing the 3D model of the Distributed Flight Array and the modular VTOL vehicles:* This enables us to visualize the Distributed Flight Array's mechanical structure and aid in its modeling. The existing designs are studied thoroughly and an indigenous design is proposed adopting necessary modifications and improvements.
2. *Flight Dynamics and Mathematical Modeling of the Distributed Flight Array:* This step is essential in understanding the flight dynamics of the Distributed Flight Array and developing an appropriate controller for it. A large number of factors have been taken into consideration such as the required generated thrust during take-off, hovering and landing, total flight time and flight altitude.
3. *Hardware and Sensor selection:* It involves selection of suitable hardware to meet the various requirements of the Distributed Flight Array such as the propulsion system which can generate the required thrust. It also involves selection of various sensors such as the gyro, accelerometer, barometer, GPS and compass unit which will be able to send data in real time to the flight controller which along with the input from the ground station will determine the output thrust generated by the propulsion system. The various sensors available are studied properly and a decision is made keeping in view the cost constraints as well as precision and reliability.
4. *Controller design:* The various controller designs implemented for existing distributed flight array of flying vehicles are examined and compared followed by selection of the most appropriate distributed control algorithm for this project.
5. *Hardware and software integration:* The various hardware such as the on-board flight controller and the various sensors are interface with the appropriate software so as to implement the designed distribute control algorithm on the flight controller.
6. *Finalizing the design followed by fabrication of the prototype:* The physical frame and structure of the Distributed Flight Array is finalized and modeled using AutoCAD and SolidWorks software.
7. *Testing of the system and analysis of its performance:* Various tests are performed on the Distributed Flight Array to gauge its performance and suitable modifications and changes are introduced as necessary.

III. The Distributed Flight Array

This section introduces and describes in detail the design of the Distributed Flight Array which builds upon the aerodynamics of multi-rotor crafts to fly in various flight formations of individual modules. This section explains the characteristics and advantages of the DFA over conventional rotorcrafts, the core functions the DFA is required to perform, the design of the DFA and describes a flight control strategy for the Distributed Flight Array available in the existing literature.

Distributed Flight Array (DFA) is defined as an extension of the design of the VTOL (Vertical Take-Off and Landing) aircraft configuration to a multi-rotor platform with distributed control. The DFA consists of individual units that are able to operate and assemble with each other. Each module can generate enough thrust using a single fixed-pitch propeller to lift itself into the air, but is unstable in flight. But when they are joined together, these units become a complex multi-propeller system which has the capability to perform coordinated flight.

The individual modules will be able to communicate and coordinate with each other to fly in a particular flight formation to carry out a specific task. The DFA has highly complex research dynamics and poses challenging research & control problems.

A. Advantages of the DFA

The DFA has many advantages over conventional rotorcrafts. They are:

1. Unlike in conventional rotorcrafts where the failure of even one motor or a physical failure of one of the arms of the rotorcraft in-flight generally leads to a failure of the whole aircraft, in the proposed design of flying these agents in formation with ducted fan architecture of the individual agents, catastrophic failure of one or more than one critical components in-flight would generally not lead to a failure of the whole system since other agents in the flying formation would be able to compensate for the change in generated thrust and payload by changing their speed and orientation using a feedback control system.

2. Since these drones are capable of performing in a wide variety of flying formations – either combining and merging together to form a bigger flying unit or flying in smaller coordinated formations, these drones will be able to decide and change their flying formation to best suit the task at hand, thus greatly enhancing their optimization and flexibility. When they need to carry a heavier payload, they could merge together and fly in a larger formation to increase the generated thrust and thus make them more agile. On the contrary, if they need to spread out over an area for example, for navigation & topographic mapping, identifying victims stuck during a natural disaster, they could separate from each other and fly in a coordinated fashion in smaller flying units.

3. Since the individual flying agents will require only two sets of motors and propellers to fly compared to the higher numbers for conventional quadrotors, their maintenance costs will be significantly lower. Moreover immediate repairs of individual agents due to failures in-flight will not need to be performed immediately since as explained above, failure of individual agents will generally not lead to a failure of the whole formation.

4. Reference [35] stated that since the DFA is a multi-propeller which has the unique characteristic of being a high altitude wind turbine, the fact that it possesses modularity and high-redundancy is desirable since it will allow it to handle multiple points of failure while still remaining airborne which gives rise to many interesting and unique applications.

B. Requirements of the DFA

The requirements that a DFA should satisfy are [35]:

1. Each module must be optimized for weight, strength, and durability

2. Modules must be able to drive and dock reliably with peers using a minimum number of sensors in favour of reducing design complexity and energy usage; and

3. The DFA must be able to fly in a coordinated fashion regardless of the array's configuration.

C. Design of the DFA

When considering the design of the DFA, the design and the control mechanism of each of the individual agents will have to be taken into consideration. Also, the communications protocol to establish communication among the modules will also be an important component of the design process.

The design challenges of a DFA are very similar to that of modular reconfigurable robots and micro aerial vehicles, which consist of electromechanical interconnection, energy storage and inter-module communication.

The main components of a DFA are [35]:

1. Chassis & Docking Mechanism
2. Flight Unit
3. Drive Unit
4. Sensing, Communication & Computation (p. 601)

An important design requirement for the chassis is that it must be light enough to facilitate flight and should be durable enough to withstand repeated drops from at least two meters. An arrangement of permanent magnets on each side of the modules help to keep the modules attached to each other. A design requirement of the magnets is that they are chosen to be strong enough to keep the modules attached to each other and to withstand the stresses of flight, but they can be de-magnetized to such that each module can be separated from each other when sufficient current is applied to them.

The drive unit consists of custom-made omni-wheels with rollers orthogonal to the axis of the wheel mounted to the chassis and a brushed DC motor with integrated encoder for velocity feedback drives each wheel. The flight unit consists of a brushless DC motor with an off-the-shelf electronic speed controller, a 3-blade propeller and a Lithium-ion Polymer battery embedded in the chassis. All the modules contain identical flight units. However, the direction of the propeller from each unit can be either clockwise (CW) or counterclockwise as required to cancel the aerodynamic torques in trimmed flight.

For the sensing, communication and computation requirements of the individual modules, custom designed electronics were used to meet all the on-board sensing, communication, and computation requirements. Each module consists of its own three axis rate gyro, infrared transceivers, pressure sensor and a microcontroller.

D. Flight Control Strategy of the Distributed Flight Array of Autonomous Flying Vehicles

A simple distributed strategy for hover control based on the physical parameters of the Distributed Flight Array (DFA) was implemented and presented here. The control strategy presented here is generalized and assumes full state feedback of the system. An estimator was used to obtain the state of the system.

The full flight dynamics of the Distributed Flight Array could be quite complex if effects like the flexibility of the propellers, aerodynamic effects of the propeller duct, and the forces that kept the modules together were considered. The system was thus simply modeled as a rigid body without any compliant inter-module connections, incorporating a force and torque generation process at each module around the hovering equilibrium. This was proven to be adequate for the purpose of hover control.

The DFA's body coordinate frame B coincided with the array's center of mass and was aligned with its principal axes of rotation. A sequence of three rotations described by the Euler angles acting along the respectively and in that order described the orientation of the DFA's coordinate frame with respect to the inertial coordinate frame [35].

The coordinate location of the module with respect to the DFA's body coordinate frame was represented by $(x_i,\ y_i)$. The altitude and the attitude of the DFA could be controlled by varying the force (or thrust) and torque produced by each module [25].

The total thrust generated by N modules was the sum of all the thrusts produced by each module [35],

$$F = \sum_{i=1}^{N} f_i \tag{1}$$

The rolling torque was the sum of all the thrusts acting along the moment arm y_i [25],

$$T_\gamma = \sum_{i=1}^{N} y_i f_i \tag{2}$$

The pitching torque was the sum of all the thrusts acting along the moment arm x_i [35],

$$T_\beta = -\sum_{i=1}^{N} x_i f_i \tag{3}$$

The yawing torque was the sum of all the reaction torques produced by each module. In the case, the torque could be accurately modelled as a linear function of thrust. Therefore, the yawing torque could be expressed as [35],

$$T_\alpha = \sum_{i=1}^{N} c_i f_i \tag{4}$$

where the sign of c_i depended on the propeller's direction of rotation, i.e. positive when the propeller rotated CCW and negative when the propeller rotated CW.

To simplify the control strategy for the DFA, the array configuration was assumed to be disk-like. The following are the equations of motion which have been linearized about hover and were normalized in order to gain some intuition about how the number of modules N in the array affected the flight dynamics:

The following equations were developed for the DFA [36]:

$$\ddot{z}\ (normalized\ vertical\ acceleration) = \frac{1}{N}\sum_{i=1}^{N} a_i \tag{5}$$

$$\hat{I}_x\ddot{\gamma}\ (normalized\ rolling\ torque) = \frac{1}{N}\sum_{i=1}^{N} \hat{y}_i a_i \tag{6}$$

$$\hat{I}_y\ddot{\beta}\ (normalized\ pitching\ torque) = -\frac{1}{N}\sum_{i=1}^{N} \hat{x}_i a_i \tag{7}$$

$$\hat{I}_z\ddot{\alpha}\ (normalized\ yawing\ torque) = \frac{1}{N}\sum_{i=1}^{N} \hat{c}_i a_i \tag{8}$$

where: a_i is the normalized control input in units of acceleration, $(\hat{x}_i,\ \hat{y}_i)$ are the normalized position coordinates written as,

$$\hat{x}_i = \frac{x_i}{\frac{\ell\sqrt{N}}{2}}\ ,\ \hat{y}_i = \frac{y_i}{\frac{\ell\sqrt{N}}{2}}, \tag{9}$$

$\hat{c}_i = c_i / \ell$ is the normalized force to torque conversion constant, $\hat{I}_x,\ \hat{I}_y,\ \hat{I}_z$ are the principal mass moments of inertia given as,

$$\hat{I}_x = \frac{\in_x \ell\sqrt{N}}{8}, \quad \hat{I}_y = \frac{\in_y \ell\sqrt{N}}{8},\ \hat{I}_z = \frac{\in_z \ell N}{8}, \tag{10}$$

where $\in_x, \in_y, \in_z$ are statistical parameters capturing the mass distribution of the array and are expected to be close to 1 for a disk-like array.

The normalized and linearized equations of motion about the equilibrium which have been presented in equations (5) to (8) can be written as equation (11):

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \hat{I}_x & 0 & 0 \\ 0 & 0 & \hat{I}_y & 0 \\ 0 & 0 & 0 & \hat{I}_z \end{bmatrix}\begin{bmatrix} \ddot{z} \\ \ddot{\gamma} \\ \ddot{\beta} \\ \ddot{\alpha} \end{bmatrix} = \frac{1}{N}\begin{bmatrix} 1 & \hat{y}_1 & -\hat{x}_1 & \hat{c}_1 \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \hat{y}_N & -\hat{x}_N & \hat{c}_N \end{bmatrix}\begin{bmatrix} a_1 \\ \vdots \\ \vdots \\ a_N \end{bmatrix} \tag{11}$$

The following control strategy was implemented on the distributed flight array:

$$a = Qf(z, \dot{z}, \gamma, \dot{\gamma}, \beta, \dot{\beta}, \alpha, \dot{\alpha})$$

where

$$Q = [q_z, q_\gamma, q_\beta, q_\alpha]$$

$$f = [f_z(z,\dot{z}),\ f_\gamma(\gamma,\dot{\gamma}),\ f_\beta(\beta,\dot{\beta}),\ f_\alpha(\alpha,\dot{\alpha})]^T$$

and where $f.(\cdot)$ are arbitrary functions to be determined.

IV. CONCEPTUAL DESIGN

In this section, the conceptual design of the distributed flight array is presented. The proposed distributed flying array will be composed of individual flying agents who will have the capability of coordinating and collaborating with each other in-flight to carry out and perform a variety of tasks. Depending on the specific requirements of the task to be performed and to fully exploit the capabilities of these flying agents, these agents will be able to fly in a number of different flight formations – the individual flying agents will be able to come together and physically combine with each other and merge to form a large flying unit composed of many individual flying agents when required as well as be able to separate from each other and spread out and fly as smaller flying units or as individual agents when necessary.

A. Design

There will be a paradigm shift in the design and construction of these flying agents. Their design is based not on the current conventional design of rotorcrafts such as quadcopters and hexacopters. Each individual agent is a twin-rotor rotorcraft which has a diamond shaped structure. The diamond shaped structure and the twin rotor arrangement is achieved by attaching two equilateral triangular shaped frames side by side with a ducted fan mounted on each frame.

As mentioned earlier, these individual agents would be able to fly in various flight formations depending on the specific requirements of the task to be performed. The individual flying agents could physically combine with each other to merge together to form a larger flying unit when required. The diamond shaped structure of the individual agents permits the individual agents to combine with each other in a number of possible different patterns which could be replicated infinitely in any given direction. A few possible patterns which could be generated are illustrated in **Figure 2**.

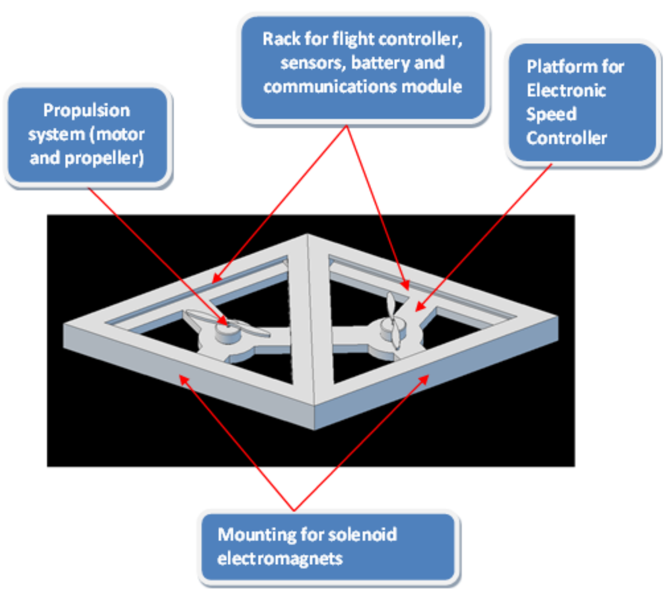

Figure 1 Conceptual design of the agent

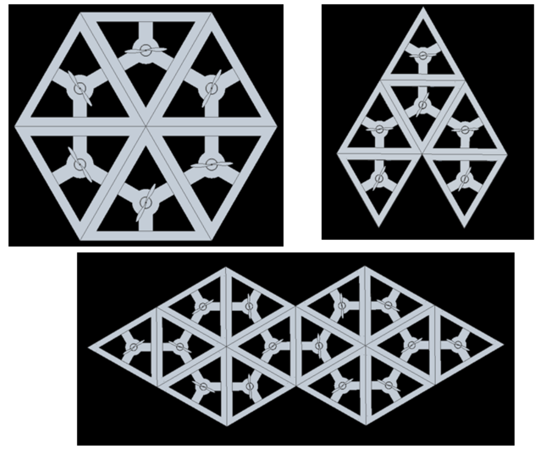

Figure 2 A few possible flying formation patterns that could be generated using the diamond shaped individual agents

B. Dimensions

The dimensions of the individual agent are illustrated in **Figure 3**.

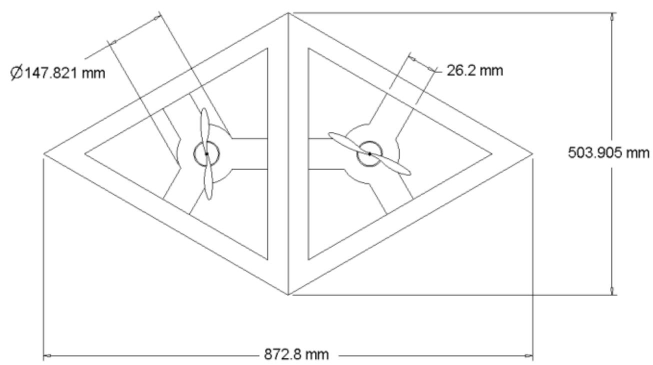

Figure 3 Top view of the agent

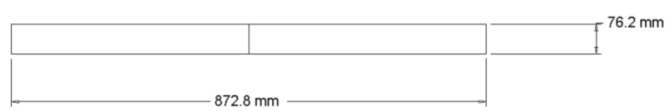

Figure 4 Front view of the agent

C. Propulsion System

The propulsion system of the agent would be provided by two motor-propeller combinations each of which would be placed at the centre of each of the two equilateral triangular frames. The motor-propeller combination was chosen such that the total thrust generated by the propulsion system was approximately 2.3 times the weight of the agent during take-off so as permit vertical acceleration and a control algorithm was implemented so that the generated thrust was equal to the weight of the agent during hovering.

In order to calculate the required generated thrust at take-off and during hover mode, the weight of the individual agent was calculated first. A summary of the mass of all the components of the agent is shown in **TABLE I**.

TABLE I SUMMARY OF THE MASS OF THE AGENT

No.	Component	Unit Weight (in grams)	Quantity	Total Weight (in grams)
1	ArduPilot Mega APM 2.6 + Ublox 6M GPS w/ compass DIY Drones APM2.6	31	1	31
2	ESC 30A Brushless Electronic Speed Controller for Quadcopter	40	2	80
3	Turnigy 2836 Brushless Outrunner 1000kv	78	2	156
4	LiPo 3200 mAh - 35/55C	225	1	225
5	Xbee-PRO 802.15.4 (Series 1) and Xbee Shield	3	1	3
6	Frame	900	1	900
7	9 x 4.5" 9045 Carbon Fiber Propeller Props	4.5	2	9
8	Solenoid Electro-magnet	20	4	80
9	Miscellaneous	120	1	120
	Total mass			1604

Therefore, from weight of the individual components of the agent above, the total mass of the agent is equal to 1,604 grams.

Since during take-off it is desired that the generated thrust should be equal to 2.3 times the weight of the agent, required generated thrust during take-off, $T_{desired}$ is equal to,

$$\begin{aligned} T_{desired} &= 2.3 \times \text{weight of the agent} \\ &= 2.3 \times 9.81\, m/s^2 \times 1.604\, kg \\ &= 36.191\, \text{Newtons} \end{aligned} \quad (12)$$

By performing iterations using various combinations of brushless motors and propellers to acquire the desired generated thrust using the Blade Element Momentum Theory, the required motor-propeller combination was determined to be:

Motor: Turnigy 2836 Brushless Outrunner 1000kV

KV rating (without torque): 1000 rpm/V

No-load current = 1.2 A at 11.1 V

Maximum current limit (upto 15s) = 28 A

Resistance $= 0.059\,\Omega$

Number of magnetic poles = 10

Mass = 78 grams

Propeller: 9" x 4.5" Carbon Fiber Propeller

Material: Carbon Fiber

Angle of twist $= 0^\circ$

Diameter = 9 inches = 0.2286 meters

Pitch = 4.5 inches = 0.1143 meters

Number of blades = 2

Propeller constant (K_p) = 1.18

Gear ratio = 1:1

From experimental results, current of the motor at maximum power dissipation = 21.05 A; voltage of the motor at maximum power dissipation = 13.59 V; Input electrical power $= current \times voltage = 21.05\,A \times 13.59\,V = 286.1\,Watts$, output mechanical power (measured) = 244 Watts; efficiency = 85.3 %

According to the Blade Element Momentum Theory, the static thrust produced by a propeller, T, in Newtons, is given by,

$$T = \left[\frac{\pi}{2} D^2 \rho P^2\right]^{1/3} \quad (13)$$

where T, D, ρ, and P are the static thrust produced by the propeller (N), propeller diameter (m), density of air (1.225 kg/m^3), power absorbed by the propeller from the motor (W), respectively.

For the chosen motor-propeller combination, the above parameters were found to be:

D = 9 inches = 0.2286 meters

$\rho =$ density of air $= 1.225\ kg/m^3$

P = 244 *Watts*

Therefore, the static thrust produced by the propeller, *T*, is equal to

$$T = \left[\frac{\pi}{2} \times (0.2286\,m)^2 \times 1.225\,kg/m^3 \times (244\,Watts)^2\right]^{1/3} \quad (14)$$

$$T = [5{,}986.707924]^{1/3} = 18.158\ Newtons \quad (15)$$

Since each agent will contain two propellers to generate the required thrust, the static thrust generated by an agent T_{agent}, is given by,

$$T_{agent} = 2 \times 18.158\ Newtons = 36.316\ Newtons \quad (16)$$

Since these agents will perform at relatively low speeds compared to the earth, the calculations of the static thrust can be applied to a wide range of flight conditions. Since the static thrust produced by the agent for the chosen motor-propeller combination $T_{agent} = 2 \times 18.158\ Newtons = 36.316\ Newtons$ is approximately equal to the required generated thrust during take-off $T_{desired} = 36.191\ Newtons$, the chosen motor-propeller combination would satisfy the flight conditions for the given agent.

D. Flight Mechanism of an Individual Agent

By rotating the two propellers of an agent at the same speed but in opposite directions, it would cancel out the rotational torque and moment of each propeller but would enable the generated vertical thrust of each propeller to be added up which would create a net vertical thrust for the agent. By changing the propeller speed of both the propellers by the same amount, the lift force could be varied which would generate motion in the vertical direction. Increasing or decreasing the speed of both the propellers by the same amount would make the agent move upwards or downwards in the vertical direction respectively as shown in **Figure 5**.

By increasing the speed of rotation of one propeller relative to the other, roll rotation coupled with lateral motion is produced as illustrated in **Figure 7**.

E. Flight Mechanism of the Distributed Flight Array

When docked together, bi-directional inter-agent communication between the agents will enable them to determine the centre of mass of the distributed flight array and the number of agents in the array which will enable the individual agents to generate the required thrust so that the array can hover. Moreover, each individual agent will determine the direction of its propeller rotation (clockwise or counter-clockwise) so as to eliminate the aerodynamic torques generated in the array in-flight. Using distributed control, the individual agents will vary the amount of thrust generated so as to achieve roll, pitch and yaw rotation coupled with lateral motion so as to achieve in-flight maneuverability as illustrated in **Figure 8**.

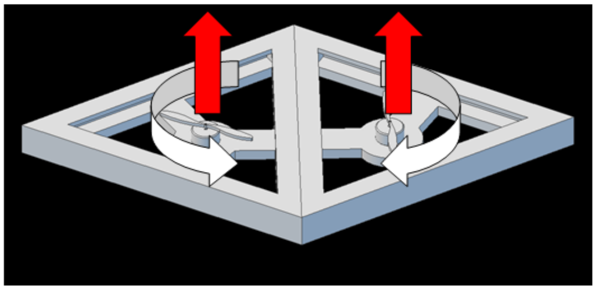

Figure 6 Increasing the speed of both the propellers by the same amount but in opposite directions would generate vertical motion

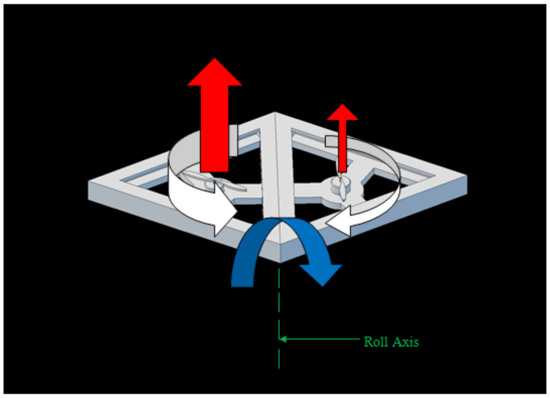

Figure 7 Roll rotation is achieved by increasing the speed of one propeller relative to the other (the width of the arrow is proportional to the propeller speed)

V. ANALYSIS AND RESULTS

A. Final Assembly of the Agent

An agent which would satisfy the requirements of the Distributed Flight Array (DFA) was successfully constructed. The detailed views of the final assembly of the agent are illustrated in **Figure 9**.

B. Flight Data

The Mission Planner was used to obtain all the in-flight data from the on board Flight Controller ArduPilot Mega (APM) 2.6. For this purpose the Mission Planner was installed in the Ground Station and was used to obtain all the in-flight data and telemetry logs from the on board Flight Controller by connecting it to the Ground Station using a USB cable.

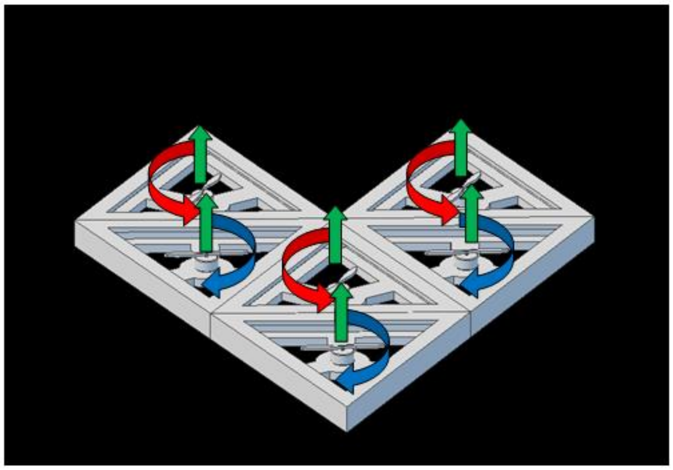

Figure 8 Each agent within the array will determine the speed of propeller rotation and the direction of propeller rotation so as to achieve the desired flight maneuver

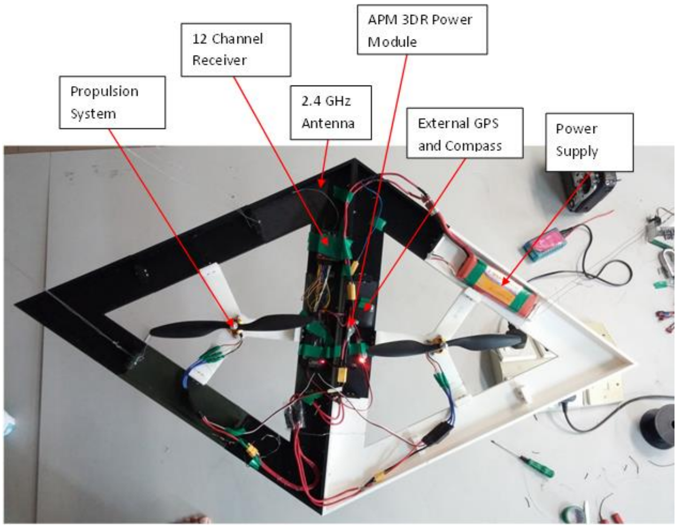

Figure 9 Top view of the agent

C. Mapping and Navigation

The external GPS and compass module was used to track the movement of the agent by plotting the coordinates of the agent on a map of the Earth using the Mission Planner software.

D. Flight Telemetry Data

The Flight Telemetry data of the agent at hovering condition was recorded in the Ground Station using the Mission Planner software.

E. Tuning the various control parameters of the agent

The various control parameters of the agent: Roll, Pitch and Yaw were tuned by implementing the controller described in the conceptual design.

F. Tuning of the Roll Controller

The tuning of the Roll Controller was done by implementing the following steps:

1. A rapid bank angle demand was inserted into the model when it was in the FBW-A mode, it was held in that position for a few seconds and then it was released. The same procedures were also carried out in the other direction.
2. The value of RLL2SRV_D was increased in steps of 0.01 until the agent started to oscillate, after which it’s value was decreased by half.
3. The integrator gain was then slowly increased in increments of 0.05 from its initial value of zero until the bank angle started to oscillate following which it was decreased by half.

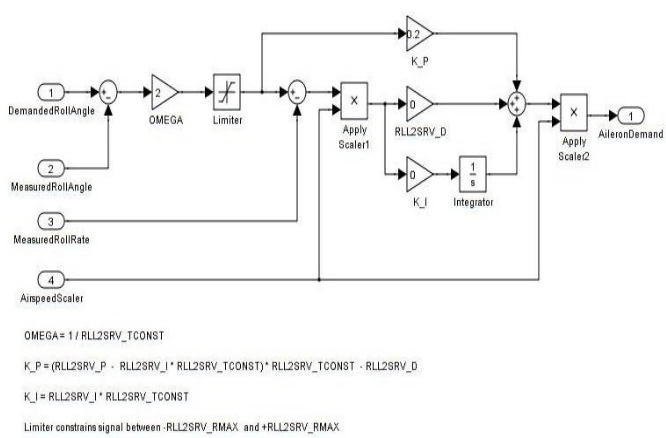

Figure 10 The roll controller implemented on the agent

G. Tuning of the Pitch Controller

The tuning of the Pitch Controller was done by implementing the following steps:

1. A rapid pitch angle demand was inserted into the model when it was in the FBW-A mode, it was held in that position for a few seconds and then it was released. The same procedures were also carried out in the other direction.
2. The model was then rolled to achieve the maximum bank in each direction.
3. The PTCH2SRV_RLL was decreased in small steps of 0.05 from the default value of 1 until the model stopped gaining height.

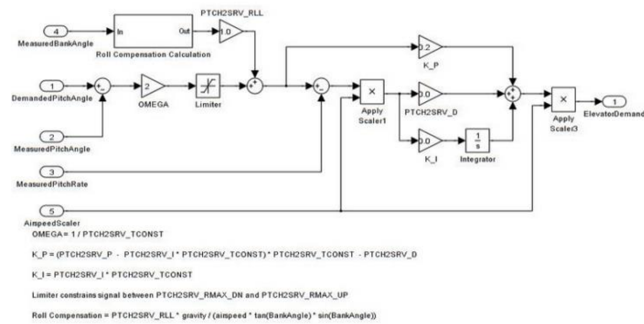

Figure 11 The pitch controller implemented on the agent

H. Tuning of the Yaw Controller

The Yaw control loop was setup as a simple Yaw Damper since it had inadequate fin area. The tuning of the Yaw Damper was done by implementing the following steps:

1. It was ensured that the YAW2SRV_SLIP and YAW2SRV_INT gains had a value of 0, the YAW2SRV_RLL gain had a value of 1 and the YAW2SRV_DAMP gain term had a value of 0.
2. The agent was very quickly rolled from the maximum value of the banking angle in one direction to the maximum value of the banking angle in the opposite direction.
3. The YAW2SRV_DAMP was slowly increased in small steps of 0.05b until it was noticed that the Yaw angle started to oscillate. The value of the gain was decreased by half from the value that caused the oscillation.
4. The agent was the rolled into and out of turns in both the directions. The value of the YAW2SRV_RLL gain term was increased in steps of 0.05 from it’s default value of 1 until the agent stopped yawing the nose to the outside of the turn.

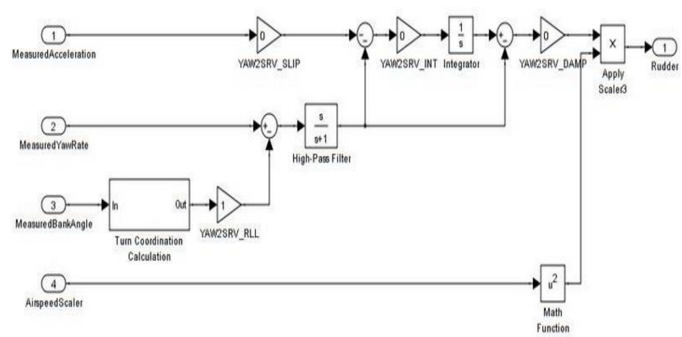

Figure 12 The yaw controller implemented on the agent

I. Flight Analysis and Discussion

The flight analysis of the agent was carried out by plotting the various control surfaces of the agent – the roll, pitch and yaw angles of the agent – against time after the tuning of the implemented controller parameters was performed 250 times.

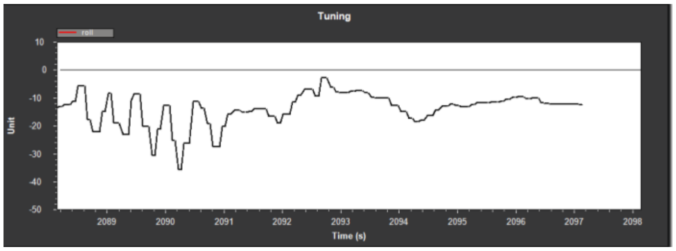

Figure 13 Plot of the roll angle of the agent against time

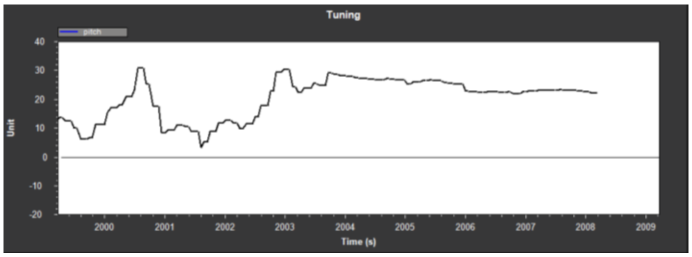

Figure 14 Plot of the pitch angle of the agent against time

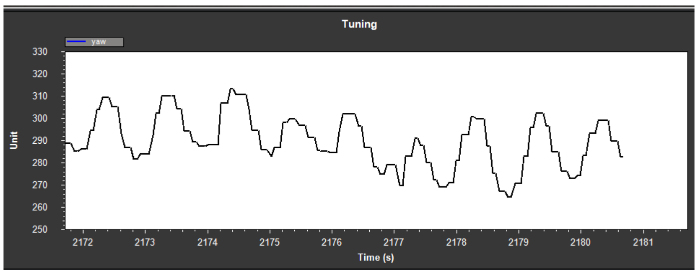

Figure 15 Plot of the yaw angle of the agent against time

From the roll, pitch and yaw angles of the agent measured as the agent approached the hovering state, it was found that the roll angle of the agent exhibited significant fluctuations initially which the controller was able to successfully diminish over time as the agent approached the hovering state. The pitch angle of the agent exhibited moderated fluctuations which the controller was also able to successfully diminish over time as the hovering state was achieved. The yaw angle of the agent however exhibited significant fluctuations which the controller could not diminish and it continued to fluctuate even in the hovering state.

This behavior of the yaw angle of the agent could be attributed to the fact that the flight controller found it difficult to null the net moment which was generated as the agent produced differential thrust using the propulsion system to achieve the desired hovering altitude. Besides, with two rotors and the current diamond shape, the agent is highly underactuated.

When the agent eventually achieved the desired hovering altitude, significant oscillations in the net generated moment of the agent persisted due to the differential thrust continuously produced by the flight controller to make continuous minor adjustments to the coordinates of the agent so as to remain at the desired hovering altitude.

This oscillation in the net generated moment of the agent in the hovering state doesn't exist on conventional multirotor platforms such as quadrotors and hexacopters owing to the fact that they have a higher number of motors to generate the required differential thrust as a consequence of which minor adjustments to the differential thrust generated by the multirotor doesn't lead to significant moments being generated which the flight controller finds difficult to cancel out.

VI. DISCUSSION

In this paper, a multi-rotor platform with distributed control has been designed. The design challenges of the DFA were very similar to those of modular reconfigurable robots and micro-aerial vehicles which included electromechanical interconnection, inter-module communication, and energy storage. The design of the DFA gives it many unique advantages over conventional rotorcrafts such as significantly greater resilience to catastrophic on board failure, greater optimization & flexibility, and considerably lower maintenance costs. The propulsion system was determined so that it could generate the required thrust to achieve the desired vertical acceleration during take-off. The efficiency of the motor was also taken into account when determining the propulsion system.

The constructed agent is capable of taking off and landing employing a propulsion system consisting of only two motors and propellers. The controller implemented was able to successfully eliminate the oscillatory behaviour of the roll and pitch angles as the agent approached the hovering state although significant oscillatory behaviour of the yaw angle of the agent continued even in the hovering state which the controller couldn't diminish. This could be reduced by combining many such agents in coordinated flight so as to reduce the net moment generated in the hovering state.

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