Design and Development of an Agile Single-engine Holonomic Multicopter UAV

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Design of a novel agile holonomic multicopter UAV using only one main motor to turn all the rotors is presented followed by a review of its specifications and capabilities compared to that in the existing systems. An overview of some major existing multicopter UAVs that were targeted to achieve a better performance in any of these 3 categories: agility, holonomy, and power distribution, is presented in this paper. These systems are then scored using a Weight Decision Matrix (WDM). The following design parameters were considered in the WDM: weight, size, mechanical/control complexity, agility, 3D trajectory tracking ability, and flight endurance. A comparison among all the existing designs and ours is provided. Our proposed system out scores the existing multicopter UAVs cited in the literature by a large margin.

I. Introduction

Despite the fact that non-holonomic multicopters are omnipresent, due to their simplicity, they render themselves as under-actuated systems. However, the emergence of the civilian applications such as conducting close-up inspection of infrastructure, and object delivery and manipulation, would require the development of a new generation of multicopter UAVs capable of hovering at any desired pose, moving at any orientation and also translating in any direction, ability to exert a force wrench at any desired direction, and enduring long flight times. Our proposed design is a timely response to the world wide need for the development of this class of multicopter UAVs. We considered the following factors in our design:

1) Agility: how fast the system can re-plan its trajectory towards a goal when needed.
2) Holonomy: the ability to fly in any orientation and translate in any direction (aka, 3D trajectory tracking capability) and correspondingly being able to exert force/moment on external objects at any given direction/orientation.
3) Flight endurance: by centralizing the power distribution to the blades, one will be able to use high-endurance engines such as gas-type and/or fuel cells.
4) Mechanical complexity: to bring the number of actuators to the minimum without compromising the aforementioned features.

In short, in our design, we propose a holonomic tricopter with tilting rotors and variable-pitch blades, where all the rotors are powered by a central engine for high flight endurance. This renders an optimal design in terms of the power requirement and the number of actuators needed to operate the system. In total, the proposed system would require one main motor, three actuators (one for each baled) to change the pitch angle of them through a variable-pitch mechanism, and three actuators (one for each rotor) to generate the tilting motion in each rotor. Also, a novel mechanism is proposed through which one can maintain the rotational speed of the blades, using a central motor, at constant while tilting the rotors.

Before expanding on the technical specifications of our proposed system further, we would provide a literature survey on the existing multicopter UAVs that would have satisfied at least one of the design factors listed above. In particular, we will study the following multicopters (they are listed by the name of their developers):

A) Gareth Roberts, David Langkamp and William Crowther at University of Manchester, UK (2011)
B) Mark Cutler and Jonathan P. How at MIT, USA (2012)
C) Mohamed Kara Mohamed and Alexander Lanzon at University of Manchester, UK (2012)
D) Markus Ryll, Heinrich H. Bulthoff, and Paolo Robuffo Giordano at Max Planck Institute, Germany (2014)

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E) Michalis Ramp and Evangelos Papadopoulos at National Technical University of Athens, Greece (2015)
F) Dario Brescianini and Raffaello D'Andrea at ETH, Switzerland (2016)

After introducing the enlisted vehicles, a feature score matrix is used to rank them. A score of 0 to 5 was used, with 0 meaning the vehicle either does not have the desired feature listed above or has very low performance in that regard, 5 meaning the vehicle either has the feature or has a very high performance in that regard. The features investigated in this report are: holonomy, power, weight, size, mechanical complexity, 3D trajectory traceability, and flight endurance.

The paper is organized as follows: section II presents a review of the existing designs. A new design of an agile single-engine holonomic multicopter UAV is presented in section III. Finally, the paper concludes with presenting some of the outlooks in section IV.

II. Review of The Existing Designs

This section introduces the details of the existing designs and presents their specifications and features.

A. Gareth Roberts, David Langkamp and William Crowther at University of Manchester, UK (2011)

In this design, six fixed non-coplanar motors are used as shown in Fig. 1. Each rotor has a variable-pitch blade. Using this non-coplanar design and being able to reverse thrust direction through variable-pitch blades, one can decouple translational and rotational motions yielding a fully holonomic flying vehicle. A total number of 12 actuators, 6 motors for turning the rotors and 6 servo motors for changing the pitch angle in the blades are used. Table 1, provides feature score matrix.

As seen in Table 1, this design scores low in the following criteria: power, weight, mechanical complexity and flight endurance. However, this vehicle provides holonomic motion and the capability to track 3D trajectories. Due to the huge mass/inertia, the system is not very agile.

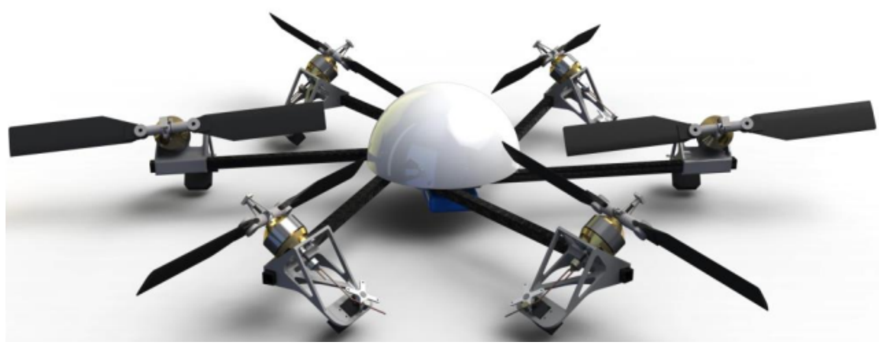

Fig. 1 Omni-directional aerial Vehicle [1].

Table 1 Feature Score Matrix for Design A.

Holonomy	Power	Weight	Size	Complexity	3D Trajectory Traceability	Endurance
5	1	1	2	2	5	2

B. Mark Cutler and Jonathan P. How at MIT, USA (2012)

They have used four variable-pitch blades in a quadcopter-type structure, as shown in Fig. 2. Although their system is not capable of achieving holonomic motion, but it is very agile. They are using variable pitch propellers to reverse the direction of thrust. Reversing thrust's direction is helpful for aggressive maneuvers, especially for maneuvers that would require instant change in the altitude, and also for fast flip/barrel and inverted flights. The total number of actuators are eight, four motors plus four servos, [2]. Table 2, provides the feature score matrix.

As seen in Table 2, this design scores low in terms of holonomy. It also has a moderate power efficiency due to its small weight and size. The most important feature of this design compared to a regular quadcopter with fixed-pitch blades is the ability to change the thrust vector for each blade on the fly. This setup will keep the motors turning at a constant speed all the time, which would require less power to operate.

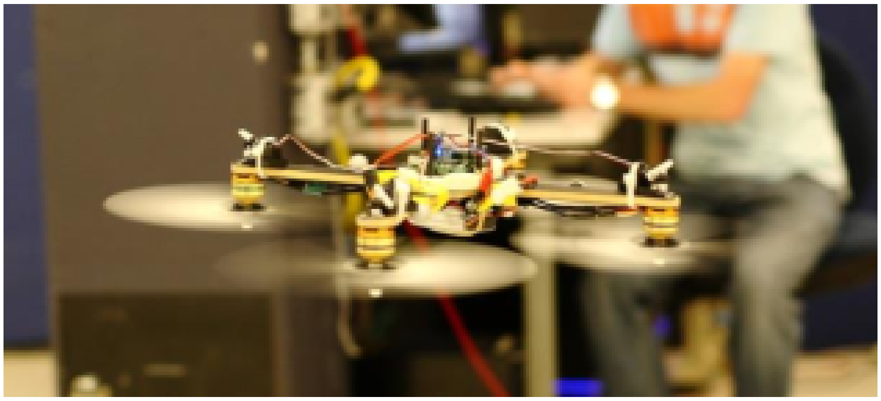

Fig. 2 Variable-pitch quadcopter developed at ACL at MIT [2].

Table 2 Feature Score Matrix for Design B.

Holonomy	Power	Weight	Size	Complexity	3D Trajectory Traceability	Endurance
0	3	3	4	4	4	3

C. Mohamed Kara Mohamed and Alexander Lanzon at University of Manchester, UK (2012)

They represent a holonomic tricopter UAV. The vehicle has a triangular shape with three arms as shown in Fig. 3. At the end of each arm a motor, which can be titled about the arm's axis, is used. The propellers used in this design are fixed-pitch. Thrust vectoring in each propeller can be then achieved by changing the speed of the motors and also tilting them. Number of actuators are as follows: three motors to turn the propellers, and three servos for tilting the rotors, adding up to the total number of six actuators. Table 3, provides feature score matrix.

This design scores reasonably high in almost every aspect of the desired design factors. However, it would score lower in terms of the mechanical complexity and power requirement. The power is not centralized, so the possibility of using gas-type and/or fuel cells in place of electromechanical actuators remains questionable.

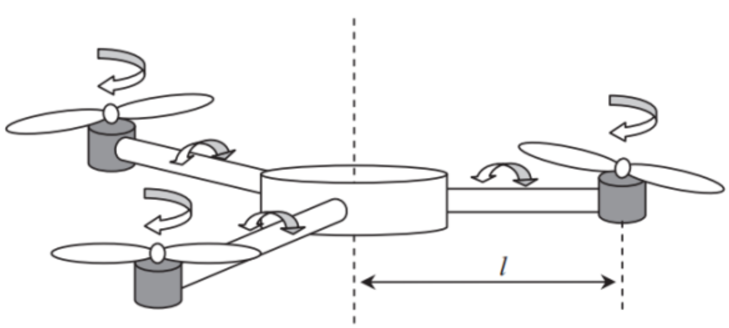

Fig. 3 Holonomic tricopter from the University of Manchester [3].

Table 3 Feature Score Matrix for Design C.

Holonomy	Power	Weight	Size	Complexity	3D Trajectory Traceability	Endurance
5	4	4	4	3	5	4

D. Markus Ryll, Heinrich H. Bulthoff, and Paolo Robuffo Giordano at Max Planck Institute, Germany (2014)

This vehicle is very similar to the previous design. Four rotors are used instead of three, however. This renders itself as a quadcopter with four arms as shown in Fig. 4. At the end of each arm a motor which can be tilted about the arm's axis is employed. Fixed-pitch propellers are used in this design. Number of actuators would boil down to: four DC plus four servo motors, adding up to the total number of eight. Table 4, provides the feature score matrix.

The performance of this design is close to the performance of that in design C. However, since there are more motors used in this design, the power, weight, size and endurance scores have dropped. This design is over actuated, thus, not yielding an optimal configuration in terms of spatial maneuverability and power consumption.

Fig. 4 Holocopter [4].

Table 4 Feature Score Matrix for Design D.

Holonomy	Power	Weight	Size	Complexity	3D Trajectory Traceability	Endurance
5	2	3	3	3	5	3

E. Michalis Ramp and Evangelos Papadopoulos at National Technical University of Athens, Greece

This is similar to that in design C, except, it provides an over-actuated system with additional redundancy in terms of the 3D maneuverability. In this design, the rotors can tilt along two axes of rotations, one being along the arm's axis and the other perpendicular to that. By this, one can do the thrust vectoring for every single rotor in virtually every possible direction (see Fig. 5). No report is provided on a working prototype. Research remains at the study level only. Table 5, provides feature score matrix.

As seen in Table 5, the major weakness of this design is the mechanical complexity. It is not surprising that no working prototype under this design is cited in the literature. Adopting a double-axis tilting rotor, in order to point the thrust vector in any arbitrary direction in space, while maintaining a stable flight would be a challenge.

F. Dario Brescianini and Raffaello D'Andrea at ETH, Switzerland

They used eight fixed-pitch blades along with reversible brushless DC motors as shown in Fig. 6. It decouples translational and rotational motions, thus, fully holonomic. A prototype is made that can hover at any desired

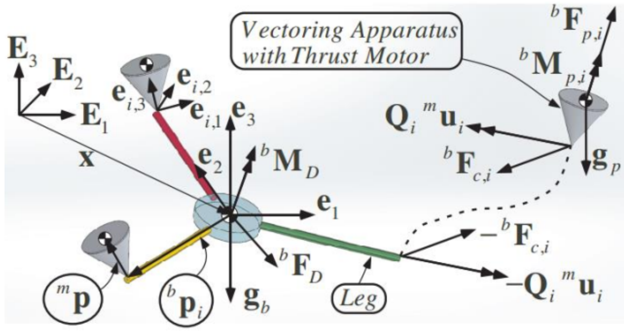

Fig. 5 Holonomic Tricopter [5].

Table 5 Feature Score Matrix for Design E.

Holonomy	Power	Weight	Size	Complexity	3D Trajectory Traceability	Endurance
5	4	4	4	1	5	4

altitude/attitude and also accelerate in any arbitrary direction. Table 6, provides feature scores matrix. This design would not score very high in terms of power management, weight/size, and flight endurance. Furthermore, the size and shape of the vehicle, i.e., a cuboid, makes it difficult to get close to the objects required in object-grasp and delivery tasks.

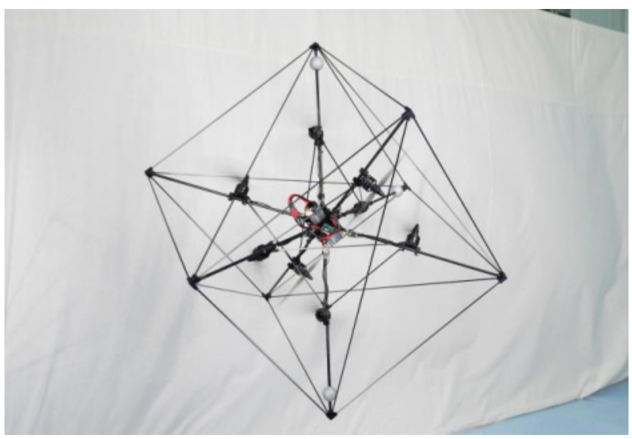

Fig. 6 Omni-directional aerial vehicle developed at ETH [6].

III. OUR PROPOSED DESIGN

In the previous section, we presented a review of the existing agile and holonomic multicopter UAVs. We mentioned some of the shortcomings of each design by providing a feature score matrix. In this section we present our proposed design in further details and compare it against the aforementioned multicopters.

Our design objective was to make a holonomic multicopter while having the minimum number of actuators with lowest weight, size and power consumption factors and correspondingly the highest flight endurance.

Our design entails three arms (120 degrees between every two arms) as shown in Fig. 7a. There is only one main motor installed on the center point of the fuselage for turning all three propellers at the same speed. The power is transferred to the variable-pitch propellers via a pulley and belt drive mechanism. Further details of this drive mechanism is depicted in Fig. 7b. All the three rotors will be spinning at the same speed. However, the thrust in each rotor can change by either changing the pitch angle of the blades through the variable-pitch actuation mechanism and/or via

Table 6 Feature Score Matrix for Design F.

Holonomy	Power	Weight	Size	Complexity	3D Trajectory Traceability	Endurance
5	1	1	1	3	5	5

change in the rotational speed of the rotors via the main rotor, and also by tilting the rotors individually. This way, one can do the control via thrust vectoring in any desired direction in the 3D space.

Another novelty introduced in this design is a tilting mechanism for the rotors without compromising the torque received from the main motor mounted on the fuselage. In the drive mechanism shown in Fig. 7b, it is noteworthy that the movement of the rotor's driving pulley (in purple) and idle tensioners (in green) will not pose unwanted twisting force on the main motor driving pulley (in blue), simply because the rotational axis of the tilting mechanism is aligned with the direction through which the belt from the main motor is tensioned.

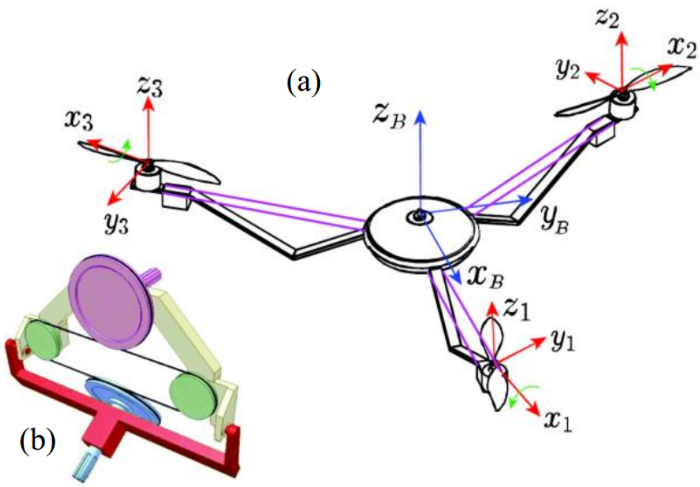

Fig. 7 A schematic of our proposed design

At the end of each arm, as shown in Fig. 7a, one of these tilting mechanisms is installed. A variable-pitch propeller is connected to the bracket in red color (details not shown). The blue pulley attached to the red bar, as shown in Fig. 7b, can be tilted using a servo motor. One should note that the propellers can tilt only a fraction of 360 degrees in order to achieve spherical holonomic motion (i.e., hovering at any desired attitude). The required maximum tilting angles for the rotors for spherical holonomy would depend on the arms' length on the tricopter. In general, 180-degree tilting in rotors would suffice to achieve spherical holonomy by adopting variable pitch control of the propellers (from -90 degrees to +90 degrees with zero being the case when thrust force vector is perpendicular to the x-y plane of the body frame and is pointing in the positive z direction of the body frame). Also we are assuming that we can reverse the direction of the thrust force of a single propeller almost instantaneously, which is physically realizable with quick-dynamic servo motors.

As an alternative, another novel mechanism using spur gears for tilting the rotors without compromising the torque received from the main motor is introduced (Figure 8). The small gear, as shown in Fig. 8, is fixed and is receiving torque from the central motor, while the larger gear is connected to the fixed gear and it can be tilted using a servo mechanism while still being engaged with the fixed gear. The tilting gear goes through two motions: one is due to the torque received from the fixed gear and the second is due to the rotation caused by a servo motor. Just like that in the previous design, a tilting range of up to 180 degrees would suffice to achieve spherical holonomy. This design would be advantageous over the pulley-and-belt in terms of overall weight, since a lower number of rotary units would be required. Furthermore, this design would be more reliable and less susceptible to failure because of omitting the belt, which can be subjected to wear and tear.

The closest design, cited in the literature, to our proposed system would be design C. However, there are some fundamental differences, which are explained here. Seven motors are used in our system, one as the main power source, three servo motors for tilting rotors, and three servo motors for controlling the pitch angle in the variable-pitch blades. The proposed vehicle will be spherically holonomic making it capable of tracking 3D trajectories in space. Weight, size, and mechanical complexity is favorable due to a lower number of actuators. Finally, our design would outperform all of the existing designs in terms of power consumption and flight endurance since it is using only one main motor that turns at constant speed. Table 7, provides feature score matrix.

Table 7 Feature Score Matrix for Our Design.

Holonomy	Power	Weight	Size	Complexity	3D Trajectory Traceability	Endurance
5	5	5	5	2	5	5

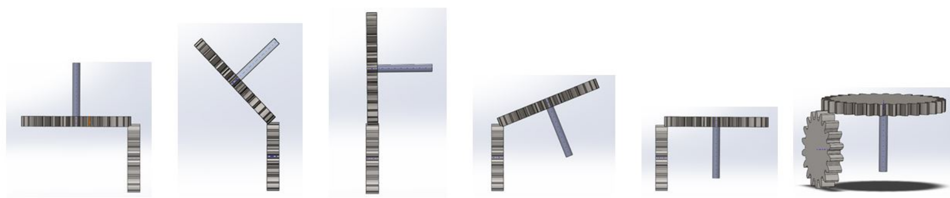

Fig. 8 Tilting mechanism using spur gears. From right to left, tilting from 0 to 180 degrees.

Complexity is the only feature in which our proposed design would not score high. It is also important to note that since we are using only one main motor on the fuselage turning at constant speed, it can be a gas-powered and/or fuel cell type motor, through which a much better flight endurance can be expected as opposed to that when using electromechanical actuators powered by batteries. How the power is distributed from a central point on the fuselage to all three rotors is a work in progress. Pulley and belt and also gear trains have been favored by far due to their simplicity and flexibility, though.

To summarize, main features of our proposed design are listed below.

- Using only one main motor centrally located on the fuselage.
- The main motor turns at constant speed.
- The main motor can be gas powered and/or operated via fuel cell technology.
- Exceptional flight endurance due to the use of one single centralized motor.
- Light weight, therefore, power efficient.
- Optimized design in terms of number of actuators.
- Full spherical holonomy, which is required for 3D trajectory tracking.

A comparison among all of the presented designs is done using a Weighted Decision Matrix (WDM) in Table 8.

IV. Conclusion

Six different designs of agile and holonomic multicopter UAVs developed in the research groups from around the world were presented first. Detailed specifications of those designs were introduced and ranked through a scoring matrix including factors such as: holonomy, power consumption, weight, size, mechanical complexity, 3D trajectory tracking, and flight endurance. Our proposed vehicle was then explained and compared against these existing designs. It was shown that it scored higher than the competition in almost every aspect of the desired features.

References

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Table 8 Weighted Decision Matrix.

	Holonomy	Power	Weight	Size	Complexity	3D Trajectory Traceability	Endurance	Total
Weights	5	5	5	5	2	5	5	1
Design A	5	1	1	2	2	5	2	71
Design B	0	3	3	4	4	4	3	78
Design C	5	4	4	4	3	5	4	118
Design D	5	2	3	3	3	5	3	95
Design E	5	4	4	4	1	5	4	114
Design F	5	1	1	1	3	5	1	64
Our Design	5	5	5	5	2	5	5	134

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