Design and Development of a Holonomic and Power Efficient Multi-rotor UAV

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INTRO

Current multi-rotor UAVs offer a simple mechanical enterprise with remarkable flight stability and VTOL with in-place hovering capability. However, the current research trend is going through a quantum leap of making them: (1) endure longer flights, and (2) move holonomically.

GOAL

The simplest mechanical design (i.e., having the lowest number of actuators) and the most energy efficient holonomic configuration for a multi-rotor UAV.

APPLICATIONS

- Able to hover at any posture and to fly along any trajectory at any desired orientation with applications in object grasping and delivery in confined spaces is addressed.
- Furthermore, this can lead to the design of UAVs that can exert a force wrench at any desired direction.

WHAT IS INCLUDED?

- a comprehensive review of the state of the art
- a novel design that surpasses other existing multi-rotor UAVs in terms of holonomy, power consumption, weight/size, mechanical complexity, controllability, and flight endurance.
- A comparison chart on parallels between our proposed design and the existing systems via a Weighted Decision Matrix (WDM)

THE PROPOSED DESIGN

- Holonomy in motion is achieved by changing the thrust in each individual rotor by incorporating variable-pitch blades.
- Thrust vectoring, is carried out individually at each rotor by controlling their tilting angles w.r.t the fuselage.
- Individual rotor thrust vectoring via tilting facilitates for the use of a single centralized motor as well, since there will be no need to turn the rotors at different speeds.
- Central gas or even fuel-cell engines, with a much better power to mass ratio and endurance, can be used.
- power consumption can be further optimized by adding a dihedral angle between the rotors and the fuselage and also moving the COM of the UAV below the rotors plane. Readers are encouraged to read our paper on this topic accepted in IROS2017 [6].

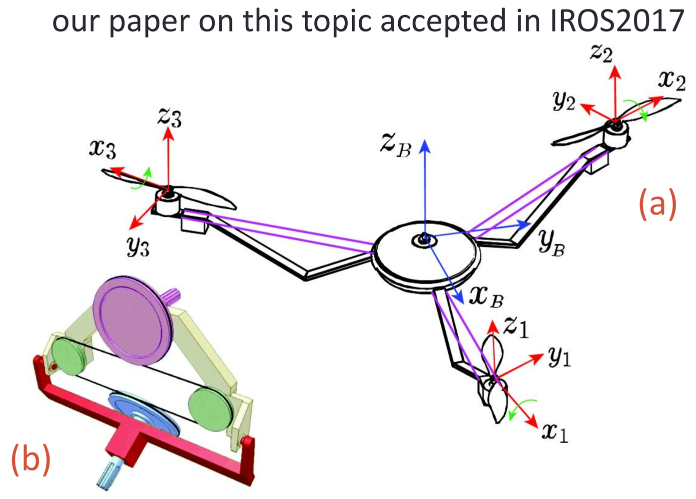


Figure 1. (a) The proposed design with a central motor and three variablepitch tilting propellers. Each rotor can tilt about the x-axis of its corresponding frame as shown in red. The positive direction of tilting is shown by green arrows. (b) The proposed pulley-belt mechanism to tilt the rotors. Propellers are attached to the blue shaft and the red bar can tilt.

The proposed UAV consists of:

- One central motor turning all the rotors at the same speed,
- Three servo-motors for tilting the rotors w.r.t the fuselage,
- And three servo-motors for changing the pitch angle of each propeller attached to each individual rotor.

These would suffice to hover the UAV at any desired pose, to move it along and desired trajectory, and to exert a force wrench at any desired direction.

REVIEW OF THE STATE OF THE ART

A. **A. Gareth Roberts, David Langkamp and William Crowther at University of Manchester, UK (2011)**
In this design, six fixed non-coplanar motors are used. 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.

B. **Mark Cutler and Jonathan P. How at MIT, USA (2012)**
They have used four variable-pitch blades in a quadcopter-type structure. 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.

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. 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.

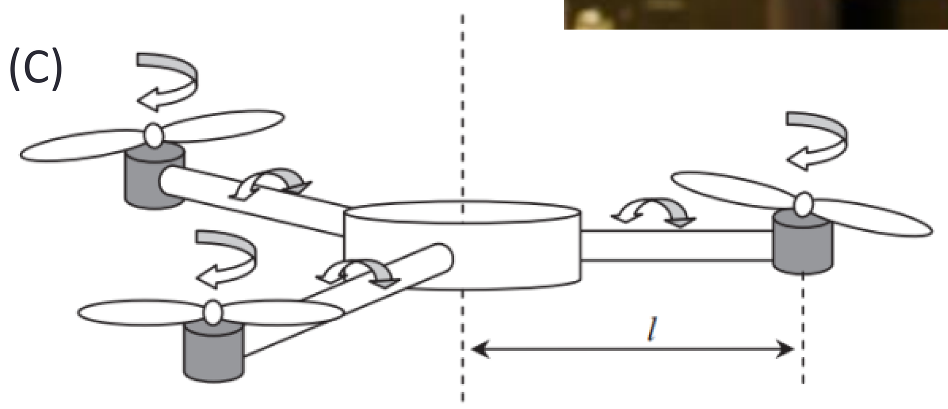
D. **Markus Ryll, Heinrich H. Bulthoff, and Paolo Robuffo Giordano at Max Planck Institute, Germany (2014)**
This vehicle is very similar to the previous design. Four rotors are used instead of three, however. This renders itself as a quadcopter with four arms. At the end of each arm a motor which can 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.

E. **Dario Brescianini and Raffaello D'Andrea at ETH, Switzerland**
They used eight fixed-pitch blades along with reversible brushless DC motors. It decouples translational and rotational motions, thus, fully holonomic. A prototype is made that can hover at any desired altitude/attitude and also accelerate in any arbitrary direction.

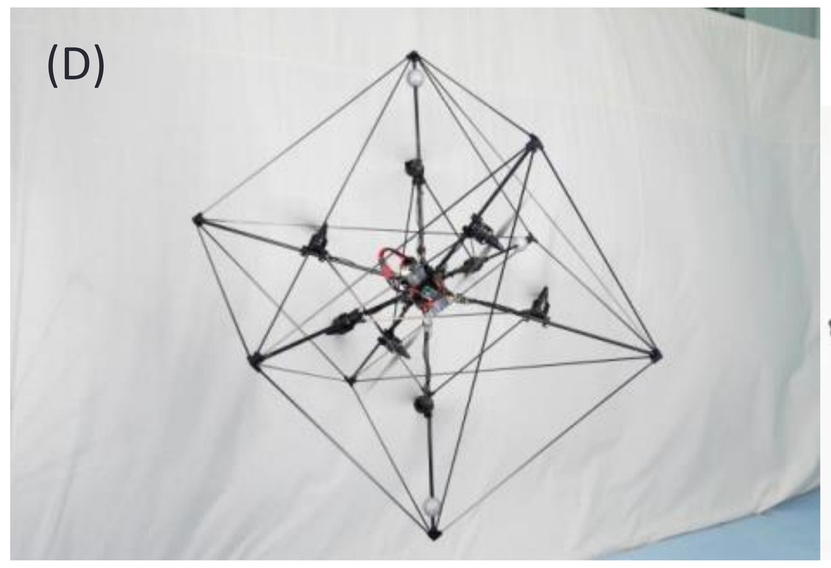
(A)

(B)

(C)



(D)



(E)

WDM MATRIX

	Holonomy	Power	Weight	Size	Complexity	3D Trajectory Tracking	Endurance	Total
Weights	5	5	4	4	2	3	5	-
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	1	1	1	3	5	1	64
Our Design	5	5	5	5	2	5	5	134

It can be seen that our proposed design scores higher than the competition in almost every aspect of the desired features. However, complexity is the only feature in which our proposed design would not score high.

*Zero is the lowest (worst) weight and five is the highest (best) weight.

SUMMARY OF THE FEATURES

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.
- Complexity is the only feature in which our proposed design would not score high.

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