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Design and Development of a Novel Spherical UAV

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Abstract: This paper presents the design and system integration of a novel coaxial, flap actuated, spherical UAV for operations in complex environments, such as buildings, caves or tunnels. The spherical design protects the inner components of the vehicle and allows the UAV to roll along the floor if the environment permits. Furthermore, the UAV can land and take-off from any orientation and come into contact with objects without putting the propellers at risk. Flaps at the base of the sphere will generate roll and pitch moments as opposed to conventional swash plate designs while the coaxial setup will provide the necessary yaw moments and increase in thrust to volume ratio of the system. The flaps, placed below the propellers allow for decoupled roll and pitch control in a thrust vectoring manner. The final result of this design is a well-protected, compact, easily controlled, flexible and agile UAV for operations in complex environments. The spherical UAV was successfully flight tested on a number of occasions with various PD and μ-synthesis robust control systems and was observed to be easily stabilised and resistant to external disturbances to certain extent.

Keywords: Complex environments, spherical frame, robust control, μ-synthesis, contra rotating propellers, ultra-sonic sensor,test bench, coaxial rotor.

1. INTRODUCTION

1.1 Background

Over the past couple of decades the areas of applications of Unmanned Aerial Vehicle (UAV) have rapidly grown with platforms being tasked with increasingly more complex missions. More precisely, multi-rotors and small aerial vehicles have attracted considerable attention from the civil as well as military market because of their size, agility, cost of operation and ownership etc.

Nowadays, small aerial vehicles are used for example for surveillance and aerial monitoring, surveying and climate change research. Examples of the use of UAVs in commercial application are presented in Microdrones (2015), where quadrotors for industrial inspection, precision agriculture, surveying & mapping, remote sensing, and photogrammetric applications, were covered. Another example is given in Alpha (2015), where a small fire-fighting unmanned helicopter with an integrated Ground Control Station, is presented. Aeryon (2015) proposed quadrotor platforms for environmental sensing, private security, and tactical operations.

Indoor environments present other type of operational challenges such as restricted space for manoeuvring, GPS coverage, and the number of obstacles present in the operational environment. Several researchers have focused their research interest on fabricating smaller and more adaptive UAV designs to minimise the collision impact and increase the mission effectiveness in an indoor environment. However, another approach is to investigate and research the development of more innovative aerial vehicle designs and configurations. Parrot (2015) and Kalantari and Spenko (2013), presented two UAVs with similar design concepts that have a special frame, which allows the platform of performing both aerial and terrestrial locomotion in challenging terrains.

A spherical UAV, developed by the Japanese Defence Technical Research and Development Institute, was reported by Jonsson (2011). This vehicle is capable of flying in cramped and cluttered environments. There is no risk of propeller damage, since they are protected inside the structure.

1.2 Motivation

In this paper a spherical UAV, is proposed. The platform was designed to operate mainly in indoor complex environments such as buildings, caves, pipes, and sewerage systems. The design and size of the UAV was made, to be suitable for multiple operations such as monitoring & surveillance, pipeline inspection, mapping etc.

In order to navigate indoors, the aerial vehicle is equipped with ultrasonic sensors and an Inertial Measurement Unit (IMU). The spherical frame, which has an inner diameter of 22.6 cm, was developed in order to protect the propellers and the inner components in case the vehicle makes contact with a wall or a surface. Furthermore, the spherical design of the UAV allows the vehicle when the environment permits to roll along the ground. This could potentially be very useful for operations in very narrow spaces, for example, collapsed buildings following a disaster. Furthermore,

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this could potentially also be a more energy efficient way to operate, hence increasing the operational endurance of the vehicle. Finally, the agility and manoeuvrability are guaranteed by the simulated model and control architecture of the system.

2. SYSTEM DESIGN AND STRUCTURE

The physical shape of the aerial vehicle, the choice of control actuators, the choice of hardware and electrical/electronic design are a vital step to ensure that the final aerial platform is one that is capable of supplying enough thrust to lift-off, enough control authority for stabilisation, enough computational power for control/sensor fusion and can supply the required voltage and current to all components at the same time. This section is subdivided into two main parts, namely: the mechanical design part; and the system integration part.

2.1 Mechanical Design

The light-weight and rigid mechanical structure of the system is shown in Fig. 1. It was designed such that it could provide maximum protection but also allow the aerial vehicle to manoeuvre freely and efficiently in a challenging environment. The compact size of the vehicle was achieved by the appropriate selection of components such as the ultra-nano-size servos and the 3-blade propellers. The most challenging part was the selection of the propulsion system.

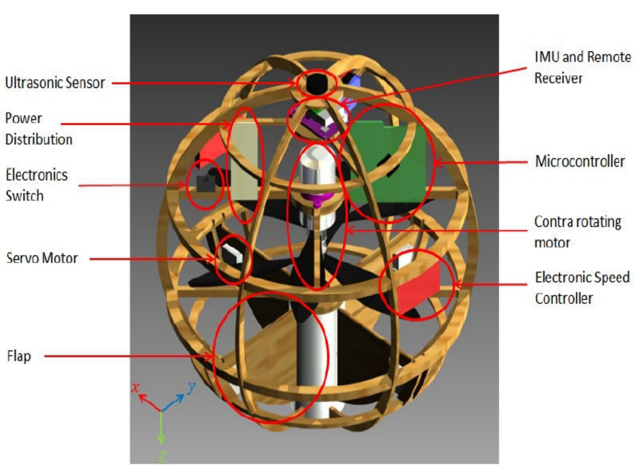

Fig. 1. CAD model of the spherical UAV showing the components' configuration in the vehicle.

According to references Koehl et al. (2012), Schafroth et al. (2010) and Bouabdallah et al. (2006) it was decided to select a contra-rotating motor. This type of motors could provide higher thrust, are compact, while having counter-rotating propellers cancel out the torque effect. The aerial vehicle light-weight structure was made from plywood. The material was used in the construction of the vehicles frame and flaps. The parts were designed in a 3D Computer-Aided Design (CAD) software and produced by a Computer Numerical Control (CNC) router. The total weight of the aerial vehicle is 0.59Kg.

It is worth mentioning that the key role of the four individually controlled flaps-surfaces, is to control the vehicle during flight. They have a 90^o separation around the inner circumference of the vehicle, and are located below the propellers along the vehicles x and y-axis. Therefore, a roll moment can be generated by constraining the flaps along the x-axis to move together whilst a pitch moment can be generated by constraining the flaps along the y-axis to move together. The yaw moment can be produced by the differential propeller speed.

2.2 System Integration

The hardware integration of the system, which is illustrated in Fig. 2, was proposed in order to provide sufficient attitude and altitude control of the vehicle. The hardware architecture is composed of an embedded system, sensors, communication modules, servos, and electronic speed controls (ESCs).

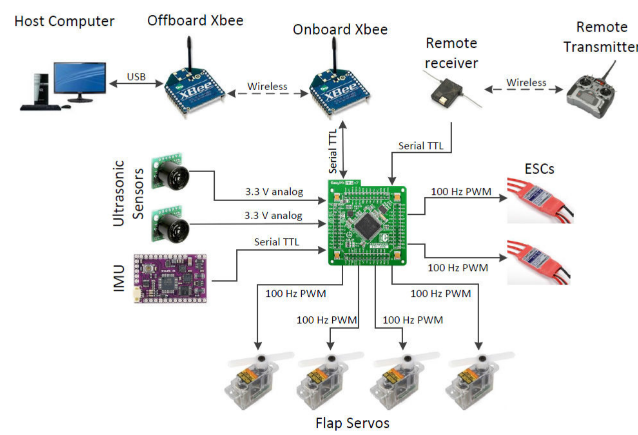

Fig. 2. Interconnections between the micro-controller and the hardware components on-board and off-board the UAV.

The micro-controller used on the spherical UAV is an STM32F407VG micro-controller made by ST Microelectronics. It runs at 168MHz and has 1MB of flash memory. It runs the control algorithms, for configuring flaps orientations and propellers angular velocity. The orientation of the flaps is regulated through the ultra-nano servos, while the propellers revolutions via the ESC-motor system. Each (18 Amps) ESC receives a PWM signal and supplies an individual motor of the contra rotating system with a three phase voltage. The micro-controller is connected with all the peripherals for receiving measurements or pilot commands and transmitting control signals to the control modules. Ultrasonic sensors are used to measure the distance to the ground and ceiling. The IMU provides attitude, acceleration and heading information. The IMU is running at a rate of 100 Hz, it consists of 3-axis gyroscope, 3-axis accelerometer and 3-axis magnetometer and it has a GPS port. A small and light receiver was selected that can accept direct pilot commands and feed them to the processing unit. Furthermore, the processing board has a bidirectional communication through an XBee module, operating at 2.4 GHz on the IEEE 802.15.4 physical radio specification, for real-time data acquisition. The Contra Rotating system, which consumes a maximum of 375 W, comprises two coaxial motors that are fixed with