AN ANALYSIS OF THE STABILITY AND PERFORMANCES OF ROTARY WING MICRO AERIAL VEHICLES

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***Abstract**: Micro aerial vehicles are small objects dedicated to a new set of D3 missions (dull, dirty, dangerous missions) not capable for the classic UAV solutions. First we present the benefits of rotating wing micro aerial vehicles (RW-MAVs) and a classification of the mission scenarios. According to the new missions we define the basic requirements that RW-MAV that should be satisfied in order to successfully complete urban and indoor missions. We define the new 4RW-MAV architecture and we propose a comparative analysis with the characteristics and performances of different classic configurations. Based on a better maneuverability, portability and agility, the 4RW-MAV architecture is promising but depending on the geometry there are some differences regarding the performances, stability and the payload capacity. In urban or indoor missions the maneuverability is crucial and thus the new architecture should provide better movement capabilities. The 4RW-MAV configuration is effective in indoor narrow space with a capability to maneuver in a very fast and effective way, impossible for other configurations. The net effect relevant for control during autorotation landing is analyzed by adding a vertical offset relative to the vertical position predicted in the absence of ground effect. This vertical offset is estimated from flight data and taken into account accordingly.*

***Keywords**: micro aerial vehicle (MAV), rotary wing MAV (RW-MAV), flight dynamics.*

1. INTRODUCTION

Autonomous RW-MAV flight represents a challenging control problem with high dimensional, asymmetric, nonlinear dynamics. RW- MAVs are widely regarded to be significantly harder to control than fixed-wing micro air vehicles. At the same time, RW-MAVs provide unique capabilities, such as in place hover and low-speed flight, important for many applications. Recently, there has been considerable progress in autonomous RW-MAV flight. Examples range from basic upright hovering and forward flight to inverted hovering, and even to extreme aerobatic maneuvers. All of this prior work pertains to helicopters operating with normal engine power.

The starting point for this kind of research is based on a new definition, a new classification of scenarios and missions proposed for the smallest category of UAVs. Based on the new technologies and the downsizing of the payload and sensors, the effective envelope of civil applications for UAV systems (UAS) is extended and the research is focus on the ways to find new architectures, new solutions for reducing the costs of missions. According to their special capability to hover, there are different types of missions for RW- UAVs: urban law enforcement, special operations and information gathering; coastal patrol, on-shore border patrol and maritime surveillance; civil security (search & rescue and avalanche survivor search); fire brigade; civil security and police (contamination measurement and natural disaster monitoring); environmental (crop monitoring and local science mission); flight services (training, terrain mapping, photography and monument inspection). The aim of the analysis of scenarios and the capability to respond to different possible profiles of the mission is to obtain new solutions, more robust and more effective. The main obstacles in the development of small size rotary wing vehicles are related to the following aspects: it is very difficult to develop control laws in an environment in which the flow induced by rotors in the vicinity of walls generates strong nonlinear aerodynamic ground effects; the problem of obstacle avoidance is difficult for small size objects; the autonomous navigation in a GPS-denied environment is not very accurate for small systems; the design of an airframe that can protect the vehicle against collision is possible only for dedicated configurations (ISAE concept). There are made of course new steps in video compression and real time monitoring, in navigation and control of micro vehicles. It is also necessary to reduce the weight, size and power consumption of payload (analyzing sensors technology, optics, housing and cabling and connectors), to adopt innovative sense and avoid systems, to test some new platform configurations that allow an extended envelope of operation for such miniaturized systems.

The basic performance parameters are presented in the following list:

- **Maximum Take Off Weight**: it represents the overall value of the vehicle mass. It is calculated considering the whole RW-MAV with every kind of device or instrument installed on it at the moment of the start of the mission (take off).
- **Payload:** for this parameter different definitions can be found. In our case, considering the modular conception of the platforms that will be designed, the payload can be seen as the maximum weight of the module applied to the vehicle. The difference between maximum take off weight and payload represents just the weight of the vehicle with the only devices strictly needed to make it fly.
- **Maximum speed**: this is the highest value of speed that the RW-MAV can reach during the fly.
- **Endurance**: it represents the time that the air vehicle can spend flying before a new landing is required (for changing batteries, refueling, recharging, downloading collected data).
- **Range**: it represents the maximum distance from the starting point that the vehicle can reach considering that it must come back and land. This parameter could change depending on the mission. In fact if it is not required the RW-UAV to come back, the maximum range could be theoretically double.
- **Ceiling**: due to the changing of the air characteristics with the altitude with respect to the sea level, the RW-UAV can reach a maximum height depending on its characteristics (power, efficiency, etc.).

2. INNOVATIVE RW-MAV PLATFORMS, DIFFERENT FROM THE CONVENTIONAL ONES

The basic requirements to satisfy in order to successfully complete an urban mission are:

- **Safety**: is for sure the most relevant topic when any kind of vehicle, especially if it is a flying vehicle, has to operate near to human beings. In case of accident, due to an external factor (system failure, too strong wind, etc.) or a mistake during the mission (wrong manual maneuver, bad mission definition to the autopilot, etc.), the contact between any rotating part of the vehicle and people in the surrounding has to be prevented and avoided.
- **Agility**: in urban environments it is common to find buildings very close one to each other, with different height, trees, electric cables, poles and a huge number of other fix or moving obstacles. For this reason, once took for granted that any "urban-UAV" must have its own collision avoidance system, the vehicle needs a great agility in terms of rapidity in changing speed, direction or altitude. The controllability must be improved as the speed of the platform increases as at high speed there is less time for decision and command of escape maneuvers. This characteristic would be probably more relevant than other, like the maximum speed value, because in narrow spaces it can become strictly necessary. Form this point of view the best platform would be the smallest and lightest one (for instance a small 4 rotors) or in general the one with the higher power/mass ratio.

- **Autonomy**: in order to satisfy this particular requirement, the general platform layout or shape is not so relevant. More relevance has to be given to all the vision sensors (cameras, IR, thermal or sonar sensors, etc) and the flight control software (autopilot, collision avoidance, etc.). So during the design phase of an UAV for urban applications, all these devices must be taken into account and must be developed very carefully.

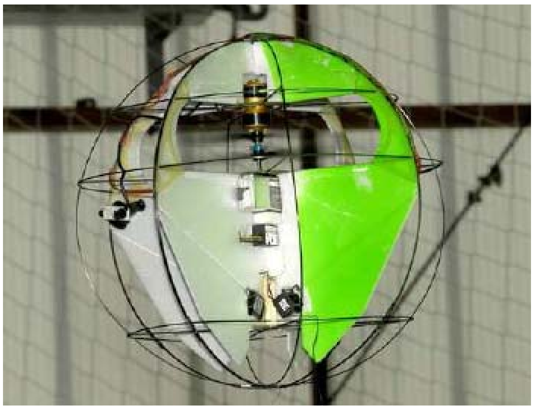

Fig. 1 Concept from ISAE

a)Vision concept from ISAE (Fig. 1) is a new tilt body bi-rotor concept based on two propellers facing each other and surrounded by a series of circular carbon rods. Each propeller is driven by a simple out runner brushless motor which has the advantage to avoid the complexity of a hollow shaft system. Speed control of both motors is carried out through a pair of speed controllers electrically connected through the carbon rods.The ultimate goal of the Vision is to be used as a hand-launch projectile which could be thrown through a window, roll on the floor and take-off to complete its indoor spying mission.

b) AirRobot (Fig. 2) is a micro UAV with autonomous flight and navigation capabilities and modular payloads for use in reconnaissance, surveillance, search and rescue, documentation, inspection and also other scenario.

Fig. 2 AirRobot

AirRobot AR family is a concept based on quadro-rotor solution and has a compact size of only 700 mm in diameter and utilizes a new (patented) propulsion system.

Fancopter (Fig. 3) is a close range aerial reconnaissance micro- system. The compact dimensions and collision avoidance system enable this RW- MAV to be used even inside buildings.

Fig. 3 Fancopter

The Small Quad-rotor **4RW-MAV** (Fig. 4a) is suited for very small payloads and can eventually fly inside buildings. Due to the small size of the platform part of the structure or internal components can be shared with model aircraft industry, this allows the widespread utilization of COTS for the design and development of such systems. Quad-rotors can be up scaled to higher maximum take off weight mass and payload mass to fulfill payload requirements for other missions, such as those coupled with the small shrouded rotor platform (Fig. 4b).

SIERRA Cargo Plus allows the utilization of bigger sensors for missions inside buildings. It results a capability to perform some missions that involve surveillance thanks to the availability of professional camera and video camera in the new payload range.

a) b)

Fig. 4a - SIERRA Concept , b - Classic and 4RW Cargo Plus

3. AN ANALYSIS OF THE DYNAMICS OF A CONVENTIONAL 4RW-MAV

4RW-MAVs are well-known to have complex dynamics. For instance, to completely capture the state of the "4RW-MAV system" one would have to include the state of the air around the 4RW-MAV into the dynamics model. However, various prior work done on a conventional RW-MAV has shown it is possible to build a sufficiently accurate model for control by treating the 4RW-MAV as a rigid-body, possibly including the blade-flapping dynamics and the main rotor speed.

Let $\{e_N, e_E, e_D\}$ the inertial axes and $\{x_B, y_B, z_B\}$ the body axes. Euler angles of the body axes are $\{\varphi, \theta, \psi\}$ with respect to the e_N, e_E and e_D axes (roll, pitch, yaw). Let *r* the position vector from the inertial origin to the vehicle center of gravity and ω_B the angular velocity. The current velocity direction is referred to as e_v in inertial coordinates.

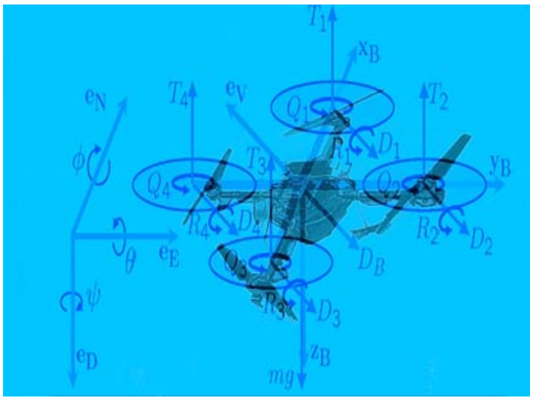

Fig. 5 Diagram of a quad-rotor aircraft

The rotors, numbered 1−4, are mounted outboard on the x_B , y_B , $-x_B$ and $-y_B$ axes, respectively, with position vectors r_i with respect to the CG. Each rotor produces an aerodynamic torque, Q_i, and thrust, T_i, both parallel to the rotor's axis of rotation, and both used for vehicle control. Here,

$$T_i \approx u_i \frac{k_t}{1+0.1s} \tag{1}$$

where u_i is the voltage applied to the motors, as determined from a load cell test. In flight, T_i can vary greatly from this approximation. The torques, Q_i, are proportional to the rotor thrust, and are given by $Q_i = k_r T_i$. Rotors 1 and 3 rotate in the opposite direction as rotors 2 and 4, so that counteracting aerodynamic torques can be used independently for yaw control. Horizontal velocity results in a moment on the rotors, R_i, about $-e_v$, and a drag force, D_i, in the direction, $-e_v$. The body drag force is defined as D_B, vehicle mass is m, acceleration due to gravity is g, and the inertia matrix is $I \in R^{3x3}$. A free body diagram is depicted in Fig. 2. The total force, F, and moment, M, can be summed as,

$$\begin{aligned} F &= -D_B e_v + mg e_D + \sum_{i=1}^{4}\left(-T_i z_B - D_i e_v\right) \\ M &= \sum_{i=1}^{4}\left(Q_i z_B - R_i e_v - D_i\left(r_i \times e_v\right) + T_i\left(r_i \times z_B\right)\right) \end{aligned} \tag{2}$$

The full nonlinear dynamics can be described as,

$$\begin{aligned} m \cdot \ddot{r} &= F \\ I\dot{\omega}_B + \omega_B \times I\omega_B &= M \end{aligned} \tag{3}$$

where the total angular momentum of the rotors is assumed to be near zero, because they are counter-rotating. Near hover conditions, the contributions by rolling moment and drag can be neglected in Equations (1) and (2). Define the total thrust as $T = \sum_{i=1}^{4} T_i$. The translational motion is defined by,

$$m\ddot{r} = F = -R_\psi \cdot R_\theta \cdot R_\varphi T z_B + mg e_D \tag{4}$$

where R_φ, R_θ, and R_ψ are the rotation matrices for roll, pitch, and yaw, respectively. Applying the small angle approximation to the rotation matrices,

$$m\begin{bmatrix} \ddot{r}_x \\ \ddot{r}_y \\ \ddot{r}_z \end{bmatrix} = \begin{bmatrix} 1 & \psi & \theta \\ \psi & 1 & \varphi \\ \theta & -\varphi & 1 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ -T \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} \tag{5}$$

Finally, assuming total thrust approximately counteracts gravity, $T \cong \overline{T} = mg$, except in the e_D axis,

$$m\begin{bmatrix} \ddot{r}_x \\ \ddot{r}_y \\ \ddot{r}_z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix}\begin{bmatrix} 0 & -\overline{T} & 0 \\ \overline{T} & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} + \begin{bmatrix} \varphi \\ \theta \\ T \end{bmatrix} \tag{6}$$

For small angular velocities, the Euler angle accelerations are determined from Equation (3) by dropping the second order term, $\omega \times I\omega$, and expanding the thrust into its four constituents. The angular equations become,

$$\begin{bmatrix} I_x\ddot{\varphi} \\ I_y\ddot{\theta} \\ I_z\ddot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & -1 \\ 1 & 0 & -1 & 0 \\ K_r & -K_r & K_r & -K_r \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} \tag{7}$$

The 4RW-MAV control is based on a 4-dimensional action space: the cyclic pitch controls i_{lon}, i_{lat}, which cause the 4RW-MAV to pitch forward/backward or sideways; the tail rotor (rudder) control i_{rud}, which affects tail rotor thrust, and can be used to yaw (turn) the 4RW-MAV; the main rotors collective pitch control i_{col}, which changes the main rotors thrust by changing the pitch of the rotor blades. The interest is to use a dynamics model with a relatively small number of parameters to be estimated from flight data. In this case we first subtracted the effects of inertia and gravity, and then learn a model from data to predict accelerations in a coordinate frame attached to the 4RW-MAV. We integrate the accelerations over time to obtain position, velocity, orientation, angular rate and main rotor speed. The simplified dynamics uses the following parameterization:

$$\dot{u} = v \cdot r - w \cdot q - g_u + C'_u \cdot [u] \tag{8}$$

$$\dot{v} = w \cdot p - u \cdot r - g_v + C'_v \cdot [v] \tag{9}$$

$$\begin{aligned} \dot{w} &= u \cdot q - v \cdot p - g_w + \\ & C'_w \cdot \left[1; w; i_{col} \cdot \Omega; \sqrt{u^2 + v^2} \right] \end{aligned} \tag{10}$$

$$\dot{\Omega} = C'_\Omega \cdot \left[1; \Omega; i_{col}; w; \sqrt{u^2 + v^2}; \left(i_{lat}^2 + i_{lon}^2 \right) \right] \tag{11}$$

The velocities (u, v, w) and angular rates (p, q, r) are expressed in the 4RW-MAV's reference frame. Here g_u, g_v, g_w refer to the components of gravity in the 4RW-MAV's reference frame; is the main-rotor speed.

4. CONCLUSIONS AND FUTURE WORK

The 4RW-MAV architecture has similar characteristics to the traditional shrouded configuration. The main differences are in the payload entity, the maneuverability and the portability. The payload, instead of being from 3 to 20 kilograms, is less than one kilogram. In this way it is the best choice for scenarios whose payload is an optical camera or a simple IR camera. In this case the maneuverability is crucial and thus the configuration must provide a very high level of movement. The 4RW-MAV architecture is able to maneuver in a very fast and effective way, moving in a way not possible for the other configurations. The portability can fulfill the needs of a typical mission, in which the rotorcraft should be carried on by a single person and should become operational in a very short time. The weaknesses of the 4RW-MAV configuration are the low speed, low endurance and short range. We found that the net effect relevant for control during a quad rotor autorotation landing was sufficiently well captured by adding a vertical offset relative to the vertical position predicted in the absence of ground effect. This vertical offset was easily estimated from flight data and taken into account accordingly.

REFERENCES

1. Bagnell, J., Schneider, J. *Autonomous helicopter control using reinforcement learning policy search methods*, International Conference on Robotics and Automation, IEEE, 2001;
2. La Civita, M., Papageorgiou, G., Messner, W.C., *Design and flight testing of a high-bandwidth H1 loop shaping controller for a robotic helicopter*, Journal of Guidance, Control, and Dynamics, 29(2):485–494, March-April 2006, 10,5;
3. Ng, A.Y., Coates, A., Diel, M., Ganapathi, V., *Autonomous inverted helicopter flight via reinforcement learning*, In ISER, 2004;
4. Seddon, J., *Basic Helicopter Aerodynamics*, AIAA Education Series, America Institute of Aeronautics and Astronautics, 1990;
5. Boşcoianu, M., Pahonie R., *Some Aspects Regarding the Cooperative control problem for flying wing micro aerial vehicles*, 10th WSEAS Int. Conf. on Math. Methods and Computational Techniques in Electrical Engineering, Sofia, May 2008;
6. Pahonie, R, Cîrciu, I., Boşcoianu, M., *An Analysis of Different Rotary Wing Micro Air Vehicles Solutions*, Metalurgia Internațional vol XIV, no.7 Special ISSUE;
7. Roberts, J.M., Corke, P.I., Buskey, G., *Low-cost flight control system for a small autonomous helicopter*, In IEEE Int'l Conf. on Robotics and Automation, 2003.