Micro Aerial Vehicle (MAV) "Quadrocopter Garmisch 2005"

1. Overview

1.1 Braun Modelltechnik MAV family

Braun developped during the last 6 years a couple of vertical take off and landing MAVs with 3 and 4 rotors. Here are some examples:

- TriBelle (fig. 1)
- Quadrocopter Summer 2001 (fig. 2)
- Quadrocopter Winter 2001 (fig. 3)
- Quattrocopter EADS (fig. 3)
- Quadrocopter XL (fig. 4)
- Quadrophony (fig. 5)
- MAV Bundeswehr (fig. 6)
- Quadrocopter overlapping (fig. 7)
- Quadrocopter Garmisch 2005 (fig. 8)
  This helicopter was designed for the 1st US European MAV Competition at Garmisch-Partenkirchen (Germany) in the year 2005. It is the main topic of this report.
- TriBelle plug-and-fly (fig. 9)
- Quadrocopter fold-up (fig. 10)

1.2 Components of the system

The MAV Quadrocopter Garmisch 2005 consists of the following components:

Radio controlled 4-rotor-helicopter (fig. 11):
- Carbon fiber plastic framework (fig. 21)
- 4 propulsion systems (coreless motor, gearbox, carbon rotor) (fig.12)
- electronic device (RC-receiver, microcontroller, 3 gyros, 4 speed controller) (fig. 13)
- 4 lithium polymer batteries (fig. 14)
- Camera with video transmitter (fig. 15)
- Removable collision protection system (carbon fiber plastic ring)

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Ground station (fig. 16)

- RC transmitter
- Video receiver (mounted on photo tripod)
- Video glasses
- Laptop for recording video signal (option)

1.3 How it works

The MAV is manually radio controlled by the pilots transmitter via 4 functions (left stick: roll, up and down; right stick: pitch, yaw).

The flying platform is controlled and stabilized by the speed of the 4 propulsion systems (fig. 17, 18). Each motor has its own speed controller. He gets the control information from the microcontroller which processes receivers and gyros signals.

The pilot wears video glasses which displays the video signal from the MAV. So he can watch MAVs surrounding as if he sits in it. There is no need of any direct sight to the MAV. Piloting the MAV in that way is very similar to flying a manned helicopter.

The camera is mounted on the top of the helicopter, view to the front with an angle of about 15° downwards (fig. 15). So the pilot can see the surrounding in front of the MAV and the bottom as well, even the MAV is standing on the ground. Sight to the bottom is important for estimation flight height.

1.4 Technical data

Weight of Quadrocopter Garmisch 2005 [g]

propulsion systems	4 motors	80	
	4 gearboxes	14	
	4 rotors	22	
	4 coverings	3	
4 lithium polymer batteries		94	
electronic device	main board	15	
	receiver	8	
	4 speed controller	6	
	wiring and plugs	19	
	covering	3	
carbon fiber plastic framework		14	
payload	video camera	16	
	video transmitter	24	
	covering	2	
		320	sub-total
removable collision protection system		11	
		331	total

MAVs dimensions:
Length: 495 mm (with collision protection system: 600 mm)
Width: 495 mm (with collision protection system: 600 mm)
Height: 338 mm

Rotor dimensions:
Diameter: 242 mm
Pitch: 110 mm

Used frequencies:
Radio control: 35.010 MHz
Video transmission: 2.430 GHz

Number of battery cells: 3 x 4 = 12 (3 connected in series, 4 in parallel)

Nominal battery capacity: 4 x 310 mAh = 1240 mAh

Battery voltage:
Nominal voltage: 3 x 3.7 V = 11.1 V
Range during flight: 9 - 12.6 V, average due to internal battery resistance:
3 x 3.3 V = 9.9 V

Electric power:

Camera with video transmitter: 0.1 A x 9.9 V =	1 W
Propulsion systems and electronic device: 2.8 A x 9.9 V =	28 W
Total:	29 W

Flight time: 20 minutes

Maximum cruise speed: 15 m/s

Deployable radius: 500 m

2. Systematic process of development in 4 steps

The question to answer was: Which technical concept is the best for close-up surveillance (500 m radius)? This task had been performed systematically. The process of development the MAV Garmisch can be divided into 4 steps:

2.1 Comparison of possible solutions

Possible solutions for surveillance in close-up area are discussed in fig. 19. The helicopter is the winner. Main advantages: monoeuvrability to all directions, ability to hover, suitable even under windy conditions.

2.2 Comparison of different rotary wing configurations

Two aspects have to be taken into account: energy efficiency and control system. The 4 rotor concept solves both criteria: There is no need of any tail rotor which wastes energy (high energy efficiency). Torque moments are balanced due to two clockwise and two anticlockwise rotors.

A four rotor helicopter can be controlled only by speed of the 4 rotors. The MAV does not include any mechanics, except rotating axles. That keeps the construction design very simple and lightweighted. So the 4-rotor-machine is the first choice.

2.3 Technical preparation of the best solution 4-rotor-helicopter

A lot of tasks had to be solved to transfer the basic idea 4 rotors: rotor aerodynamics, calculation and testing of propulsion systems, design of lightweight structure, optimization of gyro stabilization etc. Some of these aspects are focussed in the following chapters.

2.4 Customization according to specification of MAV demonstration at Garmisch-Partenkirchen

Garmisch specification requires maximum dimension in flight of 500 mm. Former 4 rotor prototypes had to be customized according this restriction.

3. Rotor design

Rotor design of Quadrocopter Garmisch is based on blade element theory. Therefor, an excel sheet had been programmed. The program is valided with measurement data of rotors from 80 mm up to 36 m diameter (recalculation of human powered helicopters). Fig. 22 shows an example of rotor calculation for Quadrocopter Garmisch. Results had been validated with a rotor test stand.

As you can see at fig. 14 MAV Garmischs rotors work on two levels of height. With this solution rotor diameter can be bigger (242 mm) without passing over the restricted outside dimension (500 mm). More rotor area can be implemented. Lower rotor area load increases energy efficiency. The rotor overlapping area (degree of overlapping) of MAV Garmisch is close to an optimum, as measurements demonstrated.

If overlapping is too much, efficiency drops. This was the result of testing an other prototype platform (fig. 7). This 4-rotor-MAV shows rotors with a diameter of 370 mm, which is ever so much in view of the outside dimension of 500 mm. The reason for efficiency losses is aerodynamic interaction of the rotors. Especially the lower rotors work in turbulent conditions due to the downwash of the upper ones. In the middle of the MAV the air has to pass 4 rotor levels. Result: 40 % lower efficiency than Quadrocopter Garmisch.

A disadvantage of overlapping rotor areas is higher noise emmission especially if the gap between the rotating blades is very small. Nevertheless, MAV Quadrocopter Garmisch is still quiet due to low revolution speed.

A step to arise efficiency while the outer diameter is narrowed is the use of 4 blades at each rotor instead of 2 which are applied generally. This effects an economy of 5 % (fig. 23).

Another important aspect of rotor design is maximum reference cruising speed. If the rotors are optimized for hover flight, maximum cruising speed is limited strongly. It can fly only walking speed and cannot operate in windy conditions. To increase maximum speed the rotors must have more pitch, but not too much. Rotor design of Quadrocopter Garmisch (242 x 110 mm) is a compromise to achieve a cruising speed of about 15 m/s on one hand and an acceptable hover efficiency on the other hand. The price to pay for this range of speed is a loss of efficiency in hover flight of about 10 % (fig. 24).

Development MAV aerodynamics always has to do with Low Reynold's numbers. Reynold's number of Quadrocopter Garmischs rotor blades is round about 50000, which is under the critical Reynold's number of commonly used airfoils. Under these conditions aerodynamic resistance is higher whereby efficiency drops. I found out that under these conditions a simple shaped airfoil is more efficient than most other airfoils: This is a circular arc segment with an airfoil thickness around 6 %. The airfoil diagram shows lower aerodynamic resistance than a standard airfoil. Furthermore, circular arc segment rotor blades are much easier to manufacture.

Another important influence on efficiency is the shape of the wing tips. The rotor blades a designed with round tips. This is a good compromise of energy efficiency and simple design.

4. Energy efficiency

Due to low energy density of electrical power sources compared to fuel of combustion engines energy efficiency aspects have to care about during design process of electric driven MAVs.

To enable long duration flights with enough payload while MAVs dimensions are not too big, two factors have to be taken into account:

4.1 Ensure enough energy on board

This requirement means that the battery has to have high energy density and its mass should have a relative high portion of the total weight (more than 25 %, better more than 50 %). Lithium polymer batteries are the best choice right now, if rechargeability is required.

4.2. Keep energy losses small

In the previous chapter a few aerodynamic aspects refering to efficiency had been discussed. There are a couple of more influences. Flight weight is the most famous influence. As a first approximination demand for power output grows quadratically with the weight. Lightweight construction is mandatory.

To get a picture of the competitive requirements "small dimensions, long flight time, high payload" look at fig. 20.

5. Framework

The framework of Quadrocopter Garmisch is built out of carbon fiber plastic. This material has a high specific strength and a high specific stiffness (rough rule of thumb: strength and stiffness like steel, but only a quarter of mass).

The main part of the framework (fig. 21) is made of carbon tubes with an outer diameter of 7 mm and a wall thickness of 0.5 mm. They consists out of carbon fiber hoses with epoxy resin matrix. Details of manufacturing these tubes are written down in [1]. Orientation of carbon fibers is adapted to torsion and bending stresses (plus/minus 25° to longitudinal axis of the tube). Total mass of the main part of the framework is 14 g.

The different tubes are sticked together with epoxy resin and superglue (cyano acrylat basis). In addition the splices are compounded with carbon rovings which are winded around.

The electric wires are cabled inside the carbon tubes.

To protect the MAV from collision damage a removable carbon ring can be attached. This ring includes 4 plug-in mounts for assembling. The ring itself is a flexible 1.5 mm carbon rod. Rings mass is 11 g.

To get adequate clearance underneath the gearcase the MAV comes with an undercarriage in the form of carbon stilts. They are composed of 2 mm carbon rods, that can be plugged undernearth the framework. In case of breakdown they can be replaced.

The framework has to sustain static and dynamic loads. This had been tested in flight. Mechanical vibrations occured: A former version showed critical vibrations of the on-top camera. This problem was solved with a thicker holder tube and a shock mount of the camera. Thus the frequence response system could be put out of tune.

6. Flight stability

The higher flight stability the easier the MAV is controlled. Flight stability of Quadrocopter Garmisch is based on electronic gyro stabilization. Three gyros are attached, each for one of the three axis (roll, pitch and yaw axis) (fig. 13).

Stabilization mechanism is designed to compensate every rotary motion of the MAV about the three axis, which does not come from the pilot.

Example: If the MAV is caught by a gust from the left, it tends to rotate to the right. The roll gyro detects this movement and outputs a signal to the control electronic. The microcontroller generates new signals for two speed controllers: Revolution speed of the right propulsion system increases. The left one decreases. Thus creates a roll torque to the left. The MAV keeps its flight position. It is nearly untouched by the gust. All that happens within about 5 ms. The very quick control cycle guarantees best flight stability.

To achieve such a quality of stability control parameters have to be adjusted. Testing of a prototype showed that flight stabilization affects to a resonance vibration, if weight moment of inertia of MAV is too small. That's why the battery of MAV Garmisch is devided into 4 single batteries, which are plugged at the four edges of the framework, far away of the center of gravity (fig. 14).

Another crucial point is the height of MAVs center of gravity. A popular fallacy is, that the center of gravity should be low lying. Instead of that the best position is close to the rotor level. Thus moment of a torque is reduced to a minimum as a result of forces of intertia and lifting forces. The MAV accelerates and decelerates without building up.

For this reason the camera, the video transmitter and the control electronic are mounted on the top of the MAV. Therewith the mass of the motors and batteries undernearth the rotor level is compensated.

7. Practical experience

Field tests indicated that the MAV concept of Quadrocopter Garmisch can be used for surveillance in close-up area. This, however, requires that the pilot is familiar with the system, because the MAV is controlled manually. Enough flight training is a precondition. The pilot has to learn to interprete cameras pictures and to transfer it into the right control commands. Therefor, he has to handle 4 functions simultaneously without "thinking of that". Furthermore, the pilot should fly the MAV never backwards to prevent collision with anything behind the MAV, which cannot be seen in the camera picture. Controlling the MAV is more difficult when it's windy and when the available space capacity is modest. Flying through an open window or door can be an enormous challenge under turbulent air conditions.

The big advantage of a manually controlled MAV is its variability during the flight. The pilot can change the flight direction within a second. Visual interpretation of the surrounding by a human being is so far much better than any automatic image processing. To avoid collision with an obstacle by flying around is no problem for a trained human pilot.

9. Further development

Nevertheless, the use of a manually controlled system is limited due to required high experience of the staff. Further development should be focussed on reducing control commands. There is a need of more automatic processing to increase ease of use. An important step towards automatic flight is done by stabilization the platform with gyroscopes. By adding tri-axial accelerometers the MAV can be stabilized better. Location locking can be implemented with the use of a global-positioning system (GPS). Therefor, it may be helpfull to apply more sensor technics: image processing via optical flow, magnetometers for detection earths north direction, ultrasonic sensors for obstacle detection, air pressure sensors for height calculation etc. So an autonomous waypoint navigation can be realized as well.

Literature:

[1] Stefan Dolch, 1995: Rippenflügel aus Faserverbundwerkstoffen - Leichtbau mit Rohrholmen in Theorie und Praxis (fin wings made of composite materials - lightweight structures with tube spars - theory and practice)
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