19. MICROTEAM – INSIGHT

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19.1 Introduction

In life threatening situations, it is highly desirable to be able to explore terrains and buildings before entering them. Small rooms, narrow entrances and enemies are a few examples of the many challenges during such a mission. The perfect solution for this problem is using Micro Aerial Vehicles (MAVs) to explore the buildings.
The objective of this design project was to design a vehicle, called Insight, capable of performing these tasks. The big challenge was competing in the MAV08 competition in India and acting as member of a MicroTeam. This team consists of a Grover which transports the vehicle to the building of interest, and RoboSwift, which functions as an eye-in-the-sky.
The biggest challenge for the design project was to meet the large amount of requirements, which followed from the customer, the competition and governmental regulations.

Based on the mission scenario, a Mission Need Statement was defined, which served as a guideline for the project and is formulated as follows:

Take off from a ground vehicle, fly through a window, perform perch and stare and deliver live streaming video from within a room.

After ten weeks of intensive work, the team came up with the following design: a quadrotor concept capable of flying the mission. This summary gives some basic information on the design project for this quadrotor.

19.2 Project objectives, requirements and constraints

The design project to come up with a solution for the challenge mentioned in the introduction, had to be performed within 10 weeks of design, by 9 students, within a budget of 10,000 euro for 3 vehicles and a ground station.
Besides the requirements, which follow directly from the Mission Need Statement, a large list of additional requirements was given to the project team.

The design team made a distinction between killer, driver and less important requirements to streamline the design progress. The most important requirements on the design were:

- Enter through a 1x1 m window and perform flight in a 3x3x3 m room including furniture
- Be non-line-of-sight controllable with a limited number of control variables
- Be able to observe the whole room for minimal 30 min
- Stick to the ceiling for 48 hrs
- Fly for 20 min, hover for 4 min and provide live streaming video of the room while attached for minimal 30 min

Constraints on the design were:

- Fit in a sphere of 30 cm diameter
- May not be heard from 20 m distance

19.3 Design concepts

After setting up Design Option Trees and running through the first trade-off process, in which most design options were eliminated, four candidates remained for the final design, these can be seen in figure 19.1.

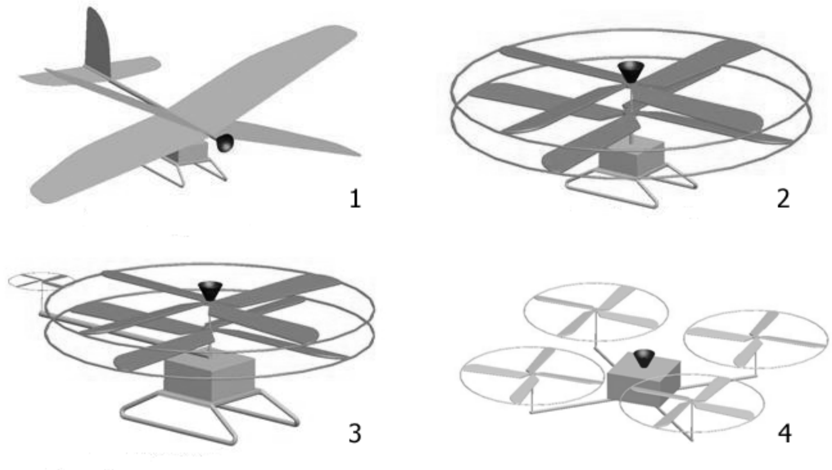

Figure 19.1: Design Concepts

Concept 1, flapping wing biplane

The flapping wing biplane concept has four wings, placed in pairs above each other. The vehicle is controlled by changing the blade flapping frequency and by changing the direction of the control surfaces at the tail.

Advantages of this configuration are the better flight endurance and the feasibility of the design. A main disadvantage is that this concept has a difficult switch between forward flight and hover.

Concept 2, conventional co-axial

This coaxial helicopter has two main, counter rotating rotors placed above each other to counteract the torques. The direction of the thrust can be changed by applying a centre of gravity shift to the vehicle. Yawing is done by changing the main rotor speeds with respect to each other.

Advantages of this configuration are the high flight endurance and the stability. A large disadvantage is that it is sensitive to disturbances, which is undesirable for outdoor flight in windy conditions.

Concept 3, coaxial with tail rotor

The coaxial with tail rotor helicopter also has two main rotors above each other. Attitude control is done by changing the main and tail rotor power settings.

This concept also has a high flight endurance and stability, but is also very sensitive to disturbances and is less manoeuvrable in small rooms, because of the tail rotor.

Concept 4, quadrotor

A quadrotor has four rotors in the same plane. Attitude control is done by changing the rotor speeds.

The main advantage of this concept is the good manoeuvrability. Disadvantages are the reduced flight endurance and the fact that this concept is unstable and need to be actively stabilized, imposing a big challenge on the design.

19.4 Trade-off

After establishing these concepts, trade-off criteria were set-up to compare the different concepts. These trade-off criteria are based on the list of requirements. The criteria are: observation, controllability, stability, mission feasibility, noise, and flight endurance.

The corresponding weight factors were established by applying a risk assessment to the different requirements.

All four design concepts were extensively evaluated on the trade-off criteria to be able to do the final trade-off as objective and qualitative as possible. The flight endurance is calculated for two different observation system options: a 2 camera option with servo ‘Combi’, and a 3 camera option, which has a reduced field of view, but lower power consumption and weight and hence increases the flight endurance. The final trade-off table is shown in table 19.1.

From this table, it became immediately clear that the *quadrotor* with the combined camera system is the best concept.

Main challenges for the detailed design are the Control and Stability of the vehicle, because designing the active stabilization system is a great challenge. Besides, improving the Flight Endurance will also require much effort during the detailed design phase.

Configuration	Camera	Observation	Controllability	Stability	Feasibility	Noise	Endurance
		Trade-off criteria					
Weight factor		25	20	18	16	10	8
Co-axial with COG shift	Combi	+	O	O	-	-	+
Coaxial with Tail Rotor	Combi	+	-	O	-	-	+
Quadrotor	Combi	+	+	+	O	O	-
	3 Cameras	-	+	+	O	O	O
Flapping Wing Vehicle	Combi	+	O	-	O	+	O
	3 Cameras	-	O	-	O	+	+

Table 19.1: Trade-off table

19.5 Final design

During the detailed design phase, the quadrotor was extensively elaborated on the fields of *Aerodynamics and Performance*, *Structures and Integration*, *Observation System* and *Control and Stability*. The design team was subdivided in groups covering these aspects of the vehicle. This section presents some results from these groups and gives an overview of the final design, which is shown in figure 19.2. Some characteristics of the final design are presented in table 19.2.

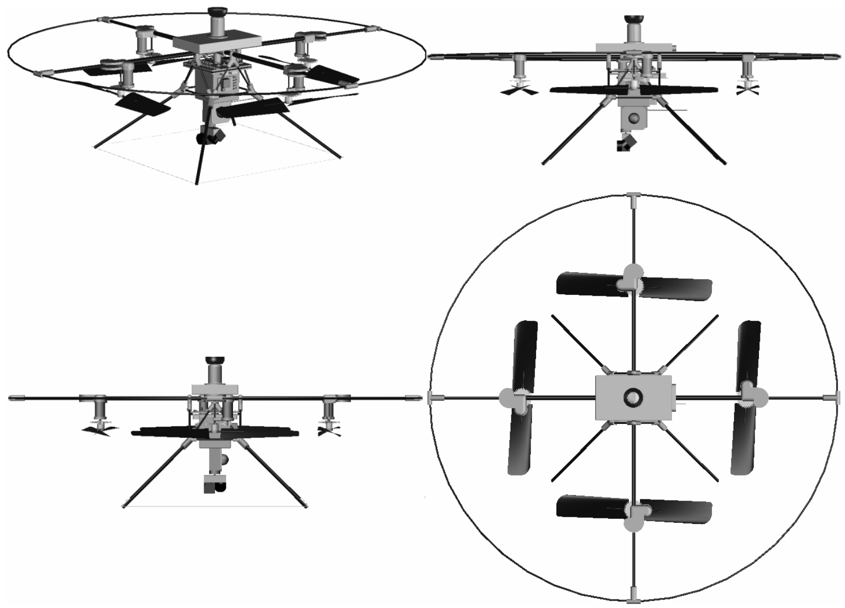

Figure 19.2: 3D (top left), side views (top right, bottom left)
and top view (bottom right)

General Vehicle Characteristics		
Maximum dimension	0.3	m
Total mass	72.2	grams
Cost per Insight	2618	euro
Total cost: 3 Insights + ground station	9732	euro
Performance Characteristics		
Flight endurance, incl. 30 min. observation during 48 hours attachment	20	min
Flight endurance, excl. 30 min. observation	24	min
Maximum forward velocity	4	m/s
Maximum thrust-to-weight-ratio	1.5	-
Maximum rate-of-climb	7.4	m/s
Maximum vertical wind handling	2.6	m/s
Rotor speed in hover	5534	RPM
Motor spin-up time from to	2.0 / 0.6	sec
Motor spin-up time from to	0.6	sec
Controllability Characteristics		
Transmitter range ('Field Force 9')	1200	m
Maximum oscillation amplitude	2.6	°
Delay for ramp input of 10	0.9	sec
Power Supply Characteristics		
Battery: 2 cell Lithium-Ion Polymer, 7.4 V, 480 mAh		

Table 19.2 Overview of Insight properties

Propulsion System & Rotor Design

The quadrotor has been optimized to fly as efficient as possible in hover, since during the mission, the vehicle will be hovering most of the time. From research it was found that certain airfoils which are thin, have strong camber and have a sharp leading edge still perform well at low Reynolds numbers. For Insight the NACA 4402 airfoil was chosen, which complies with these requirements and in tests showed excellent performance at very low Reynolds numbers. The blades used for the rotors have been twisted such that they deliver the highest possible lift-to-drag ratio. Furthermore it was found that having two blades requires the least amount of power. The rotor design was fitted with a motor and gearbox, which resulted in the propulsion system, optimized for hover, as shown in figure 19.3 (top right).

The performance of the vehicle was evaluated by analyses of its forward and vertical flight characteristics. This resulted in the performance characteristics as shown in table 19.2.

The expected noise generation of the vehicle was evaluated by testing the noise production of certain MAVs outdoors. From this it was concluded that using high quality gearboxes the requirement that it may not be heard at 20 *m* distance can be met.

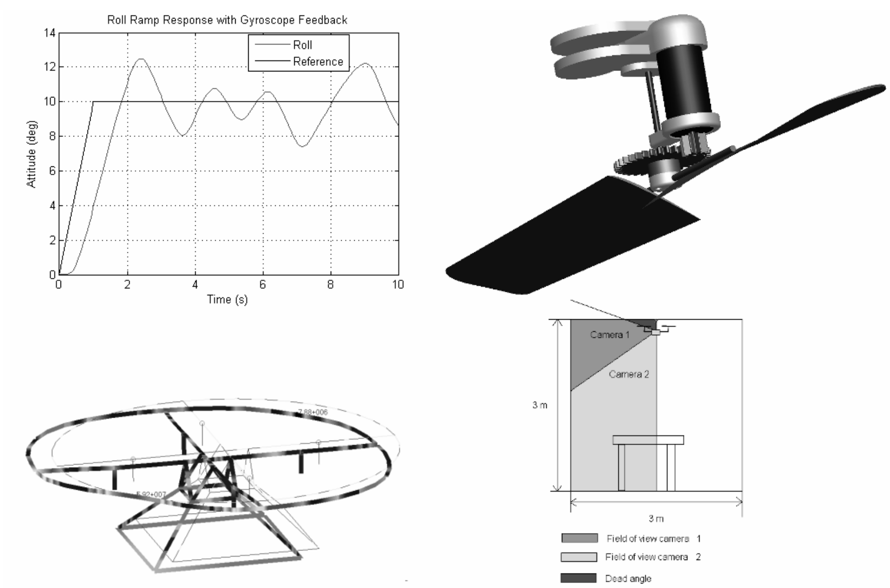

Figure 19.3 Final Design Results

Structure and Component Integration

The *Structures and Integration* group designed the integration of all components in the vehicle and did a thorough structural analysis of the resulting structure for critical load cases occurring during the mission, resulting in a final structural design.

To cope with the attachment requirement, a fail safe attachment system was designed which uses microspines and adhesive bonding.

During the structural design, finite element models were made of the structure, which was subsequently tested for the load cases *transport*, *take-off* or *maximum thrust conditions*, *collision*, and *landing*. The structure was designed to survive all load cases. To reduce the decelerations during impact, the electronics are connected to the structure via a rubber connection. One result of the finite element calculations is shown in figure 19.3 (bottom left) for a collision.

Observation System

The observation system consists of two cameras and a customized servo, which makes it possible to rotate the cameras for 360° and see the whole room (see figure 19.3 bottom right). The cameras and the transmitter are attached to the servo, which is attached at the bottom of the structure. An analogue signal is used to transmit the video images via Grover to the ground station.

Control System

A simulation has made it plausible that it is possible, but difficult to control the quadrotor non-line-of-sight indoors with the help of an onboard PD control system. Therefore, the Insight should be steered by a skilled pilot.

The simulation deviates from reality. Examples of omitted effects are the aerodynamic effect dependence on flight speed, internal and external electro-magnetic interference and vibration of the vehicle. Consequently, the results should be verified by real-life tests, which will be time consuming. Before the required performance for the competition can be obtained, a lot of time and effort will have to be put in testing and tuning the vehicle. Also the pilot will need prolonged training. This will all take a considerate amount of time, which is accounted for in the time-planning.

19.6 Conclusions and recommendations

During the concept selection, it was found that a quadrotor Micro Aerial Vehicle is the most appropriate vehicle to perform the Insight's mission. In the detailed design phase this quadrotor crystallized into a design that is now ready to be built immediately. The most significant results of the design include:

- The structure has been optimized, such that a lightweight solution is reached. From the thorough structural analysis it is obtained that the vehicle maintains structural integrity during flight.
- Understanding the possibilities and restrictions of conventional helicopter theory, a good approximation is done on the aerodynamic performance of the rotors.
- The observation system can deliver good vision during flight. Also the Insight is capable of supplying full coverage of a room after attachment to the ceiling.
- Choosing the quadrotor design the challenge of controlling the vehicle has arisen. Therefore, this controllability was the centre of our design and its difficulties have been understood. It is difficult, but possible to control the quadrotor non line-of-sight indoor, the simulation showed. A skilled pilot should steer the Insight.

The design resulted in a vehicle that is able to meet all the requirements stated by the customer. The MicroTeam is therefore confident that the design will definitely be a likely candidate to win the MAV '08 competition in India. This however will only be possible when enough experts and enthusiast students are found willing to help producing the Insight.

After detailing the design still several future challenges remain:

- The greatest challenge will be controlling the vehicle. The onboard controller will need to be tuned for perfection to secure mission success. Furthermore, the pilot will need prolonged training to control the vehicle.
- More research on the filtering of the sensors is recommended. It was evaluated that the sensor noise will have an important influence on the performance of the controller. Also, the simulation should be improved by including more effects. Different advanced control methods could be explored, as currently is performed with LQ (Linear Quadratic), sliding mode and adaptive control. Other applicable control methods would be LPV-control or model predictive control.

- Use of embedded systems and sensor information is difficult, therefore the question whether the IMU will fulfil the manufacturer' specifications remains.
- Good approximations have been carried out, when using conventional helicopter theory on MAV scale. However still little is known about the actual aerodynamic performance of rotorcraft in this flow regime. Therefore bank testing of the suggested rotor should reveal, whether it delivers the lift as calculated and the resulting endurance of the vehicle should be verified by flight testing.

The main advantage is that, when the model is built, it can easily be adjusted and tuned. Therefore the design will certainly be able to fly and its performance will grow over time.