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From the Test Benches to the First Prototype of the muFly Micro Helicopter

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Abstract The goal of the European project muFly is to build a fully autonomous micro helicopter, which is comparable to a small bird in size and mass. The rigorous size and mass constraints infer various problems related to energy efficiency, flight stability and overall system design. In this research, aerodynamics and flight dynamics are investigated experimentally to gather information for the design of the helicopter's propulsion group and steering system. Several test benches are designed and built for these investigations. A coaxial rotor test bench is used to measure the thrust and drag torque of different rotor blade designs. The effects of cyclic pitching of the swash plate and the passive stabilizer bar are studied on a test bench measuring rotor forces and moments with a 6–axis force sensor. The gathered knowledge is used to design a first prototype of the muFly helicopter. The prototype is described in terms of rotor configuration, structure, actuator and sensor selection according to the project demands, and a first version of the helicopter is shown. As a safety measure for the flight tests and to analyze the helicopter dynamics, a 6DoF vehicle test bench for tethered helicopter flight is used.

Keywords MAV · Test bench · Coaxial · Aerodynamics · Stability · Design · Flight test

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1 Introduction

The state of the art in aerial robotics has moved rapidly from simple systems based on RC models, only able to do basic hover or cruise flights using inertial sensors, to robotic vehicles able to navigate and perform simple missions using GPS and/or vision sensors. In terms of fixed wing aircraft, this state of the art evolution concerns UAVs as large as 3 m like the Sky–sailor solar airplane [1], as well as vehicles as small as the Procerus MAV [2] or the Aerovironment's Black widow MAV [3]. Rotary wing systems also follow this state of the art evolution, with the largest available MAVs like the quadrotor developed at Cambridge university [4]. However, the research focus for palm size helicopters is still on vehicle design and flight stabilization. Here, examples are the muFR helicopter [5], the CoaX developed at EPF Lausanne [6] and the MICOR developed by the University of Maryland [7]. These MAV's are among the most advanced, but their capabilities are still limited to automatic hovering or human aided navigation. The European project muFly was launched in July 2006. Its project consortium consists of six partner institutions working on different fields as sensors, actuators and power supply. The goal of the project is the development of a fully autonomous micro helicopter, comparable in size and mass to a small bird. At this scale, a lot of challenges arise, such as the low efficiency of the rotor system [8] or the low thrust to weight ratio. The muFly project tackles these problems by investigating the different components of the system. Therefore, test benches are built to acquire experimental data. Together with simulation results, this data is used to design the actual helicopter. But even before these problems can be attacked, the general concept for the helicopter has to be chosen.

Today there exist many different configurations of rotary wing aircrafts, such as quadrotor, conventional single rotor, axial and coaxial helicopters (Fig. 1), and each one possesses advantages and drawbacks. Thus, a careful evaluation of each of them is necessary before the rotor configuration for muFly can be chosen. This includes important criteria like compactness, mass, power consumption and payload. Those criteria are listed, weighted and used for grading the different configurations in Table 1. Note that the two first criteria are muFly specific. *Compatibility 1* constrains the selection to the system specifications defined in the project proposal, while the *Compatibility 2* constrains the selection to the technology available from the project partners.

All these five different configurations are virtually designed at a scale comparable to that of muFly, and their respective masses and power consumptions are calculated. Every criterion is graded on a scale from 1 (worst) to 10 (best), only mass, power consumption and index indicator are calculated quantities. They are scaled to fit into the grading range. While the coaxial and axial concept mainly convince with their compactness and compatibility with the muFly specifications, the tandem and quadrotor achieve a high payload. The conventional helicopter configuration suffers from a lack of compactness and the fact that not all the power is used for propulsion (tail rotor). The evaluation shows that a coaxial setup is the best choice for the muFly application.

Next question is how to steer the helicopter, so different steering concepts are evaluated such as moving the center of gravity [6] or using flaps to change the orientation of the down wash [7]. For our project, a simplified swash plate mechanism

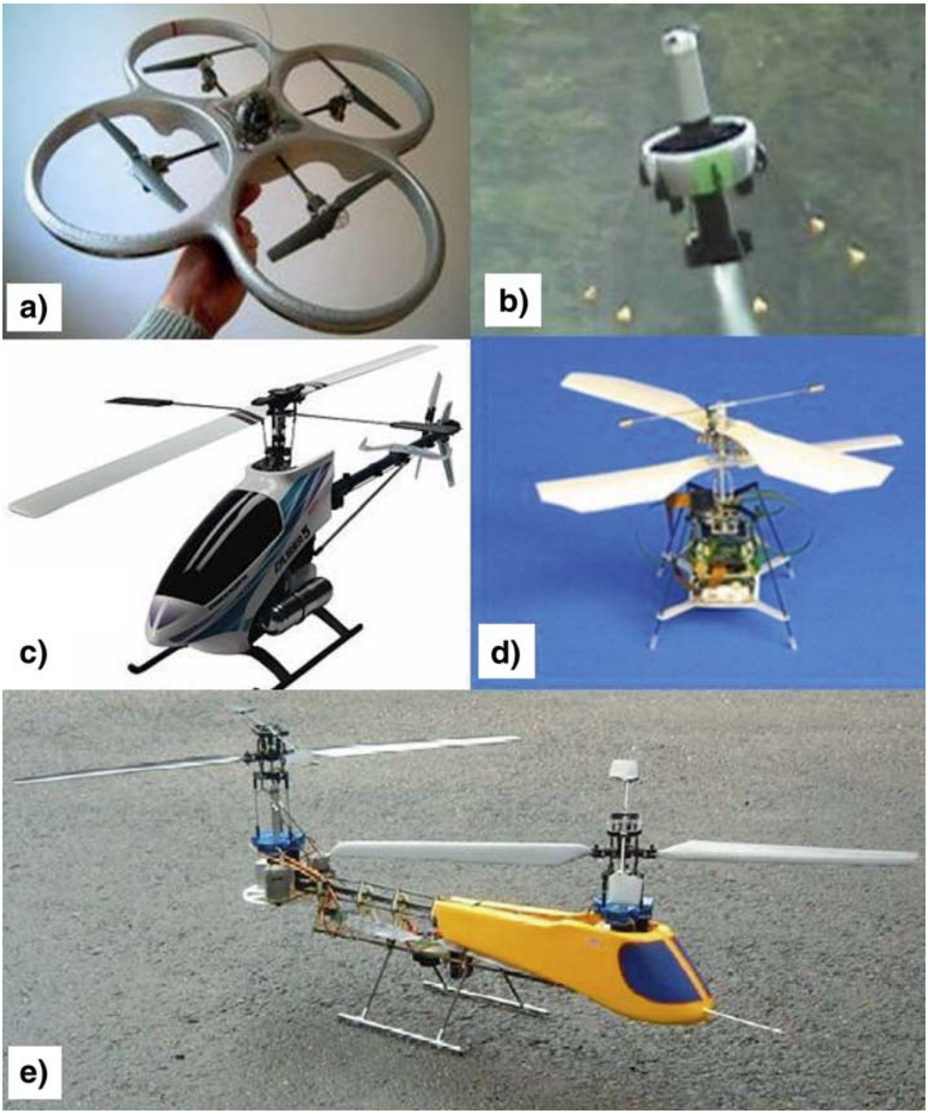


Fig. 1 Different helicopter configurations: a) Quadrotor, b) Axial, c) Conventional, d) Coaxial and e) Tandem

allowing only cyclic pitch is chosen. This is mainly due to its fast response to steering inputs.

The focus of this paper is how to build a micro helicopter from scratch by first designing different test benches for understanding the different problems affecting the design and then using this knowledge to design the helicopter itself. Designing an MAV is a very challenging task. There are many important aspects to look at, such as having an efficient propulsion group to achieve high thrust and high maneuverability

Table 1 Evaluation summary. Compatibility 1: Compatibility with the system specifications, Compatibility 2: Compatibility with the available technology

Criteria	Weight	Conventional	Axial	Coaxial	Tandem	Quadrotor
Compatibility 1	5	7	9	9	5	4
Compatibility 2	6	5	8	9	5	6
Compactness	8	5	10	10	4	3
Mass (/10)	8	5.96	6.26	6.45	6.45	7.99
Power consumption (/2)	8	5.54	5.75	6.21	6.21	7.95
Index indicator (×10)	7	8.81	8.17	7	7	4.28
Realization simplicity	5	6	8	7	6	10
Control simplicity	5	6	7	8	7	9
Payload	4	6	4	6	8	8
Maneuverability	4	9	7	7	6	7
Reliability	6	5	4	7	6	7
Total		214.67	277.11	**295.76**	191.76	179.44

with a low power consumption. For a first estimation and layout of the different components, calculations and simulations are useful, but at the end the calculations have to be verified by experimental data. Therefore building test benches prior to designing the MAV itself is important at this state of the art, where a lot of research problems are still open.

The paper is organized as follows: in Section 2 the problem of low rotor efficiency is investigated using a coaxial rotor test bench to measure the resulting thrust and torque for different rotor blade design parameters. Section 3 is investigating the resulting forces obtained by the steering mechanism and furthermore the effects of the stabilizer bar used on the helicopter to obtain passive stability. After investigating the aerodynamical effects, the design of the first prototype is presented in Section 4, and a test bench for safe flight tests and for analyzing the helicopter dynamics is shown in Section 5. Finally the conclusion of the work and an outlook are given in Section 6.

2 Understanding the Propulsion

Aerodynamics is one of the major challenges faced in MAV design. In fact, the power required for the propulsion of a micro helicopter is more than 90% of the total power consumption and is the most limiting factor of the flight duration. It is important to understand the aerodynamic effects to have an efficient propulsion group and moreover to achieve appropriate control.

In the low Reynolds number regime the muFly rotors are operating in (about $Re \approx 60000$), viscous effects start to play an important role. Phenomena like laminar separation bubbles strongly affect the aerodynamic efficiency, which is much lower than for full scale helicopters. Their Figures of Merit (FM, ratio between induced power and total power) can reach up to 0.8, while for an MAV the FM is up to 0.5 [9]. Unfortunately, there is not a lot of literature and experimental data available for this range, one exception is [10]. The lack of trustful aerodynamical data makes it very important to have an own rotor measurement setup. Therefore, a coaxial rotor test bench has been designed and built for measuring thrust and torque of different parameter combinations on the rotor blades. Aside from the experimental investigation, simulation models are developed. Three common approaches are used for a better understanding of the problem:

1. Blade Element Momentum Theory (BEMT) using X–Foil software [11],
2. Free Vortex Wake Approach [12],
3. Computational Fluid Dynamics (CFD).

The complexity of the approach is increasing in the order of appearance. The BEMT simulation is used as a very fast first layout tool. The free vortex approach simulates the rotor wake which is not included in the BEMT and gives more information on the velocity field in the down wash, which strongly affects the lower rotor. The CFD simulation is then used for simulating all the 3D effects. Here, the commercial CFD code Ansys CFX is used.

The rotor test bench setup and its components are shown in Fig. 2, and its block diagram is shown in Fig. 3. The whole system is controlled by a PC through the Virtual Com Ports (VCP), which are connected to the motor controllers and to the data acquisition module. Thus, the rotor can be run at any desired angular velocity, and the respective thrust and torque are measured. The rotor heads on the test bench are designed such that the blades can be mounted rapidly and precisely at any pitch angle. For the experiments, it usually ranges from 10° to 20°. The motor controller module provides information about the motor current, which relates to the motor load torque. The rotor blades are designed in CAD and are directly manufactured on a rapid prototyping machine. This provides flexibility in testing the desired profiles and is only limited by the strength of the material. However, since the aerodynamic and centrifugal forces are relatively small, material strength

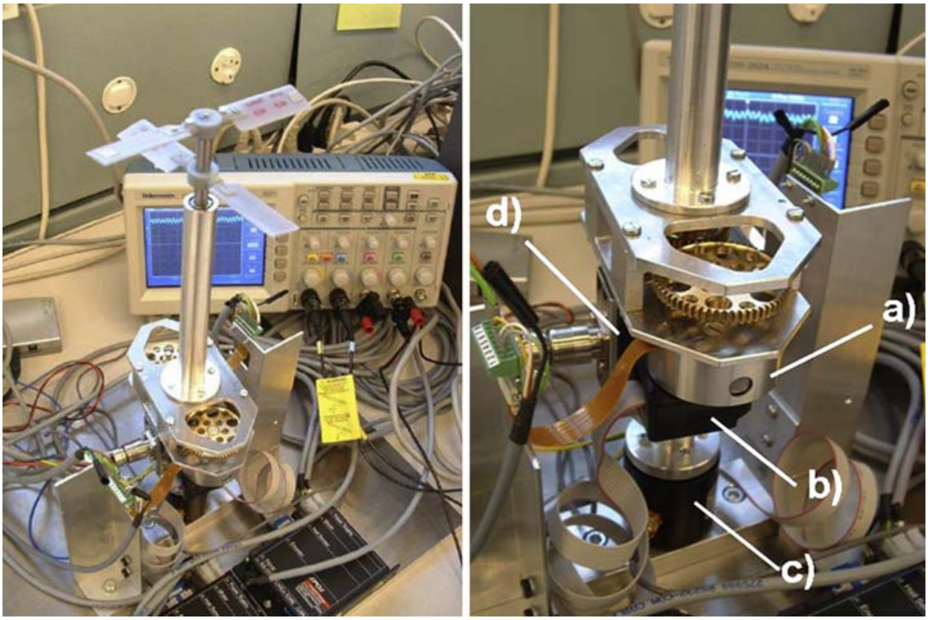


Fig. 2 Test bench for rotor blade testing: a) 2× Maxon EC 45 flat 30 W motor, b) 2× optical encoders, c) RTS 5/10 torque sensor, d) FGP FN 3148 force sensor

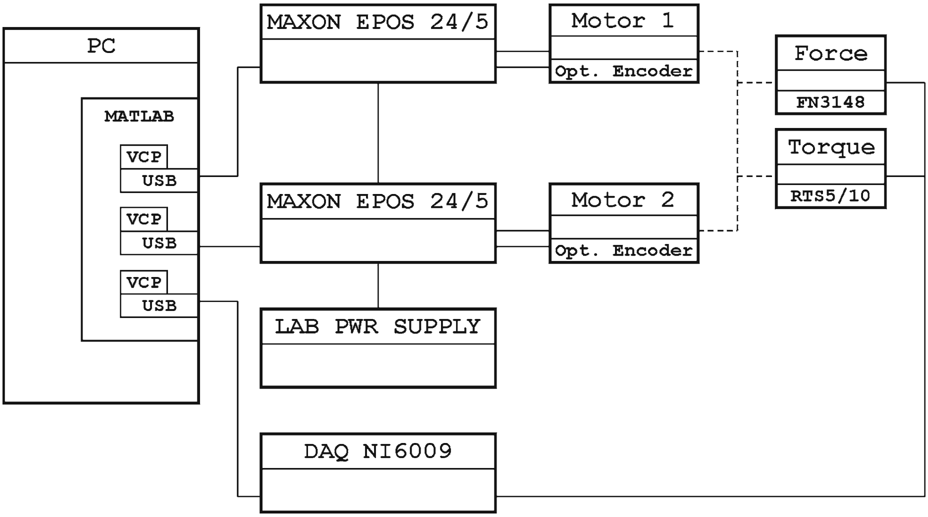


Fig. 3 Block diagram of the rotor test bench

is usually not a problem. Moreover, production on the rapid prototyping machine allows the testing of different aerodynamic enhancements like winglets or Gurney flaps. After designing the blades in CAD, the manufacturing takes only one hour of production time.

Some printed blades are displayed in Fig. 4.

Different parameters like radius, chord length, maximum camber, position of the maximum camber and twist are varied throughout testing. It is beyond the scope of this paper to discuss all the aerodynamic results, but for illustration Fig. 5 shows example results for different rotor radii. The data has been created using two *NACA0012* blades with a chord length of $c = 0.02$ m. The first two plots show the resulting thrust and torque at a pitch angle of $\Theta = 16°$ for different rotational speeds. As expected, a higher RPM leads to more thrust and also to higher torque,

Fig. 4 Different blades with different profiles, length and taper used on the test bench. The blades are manufactured using a rapid prototyping machine

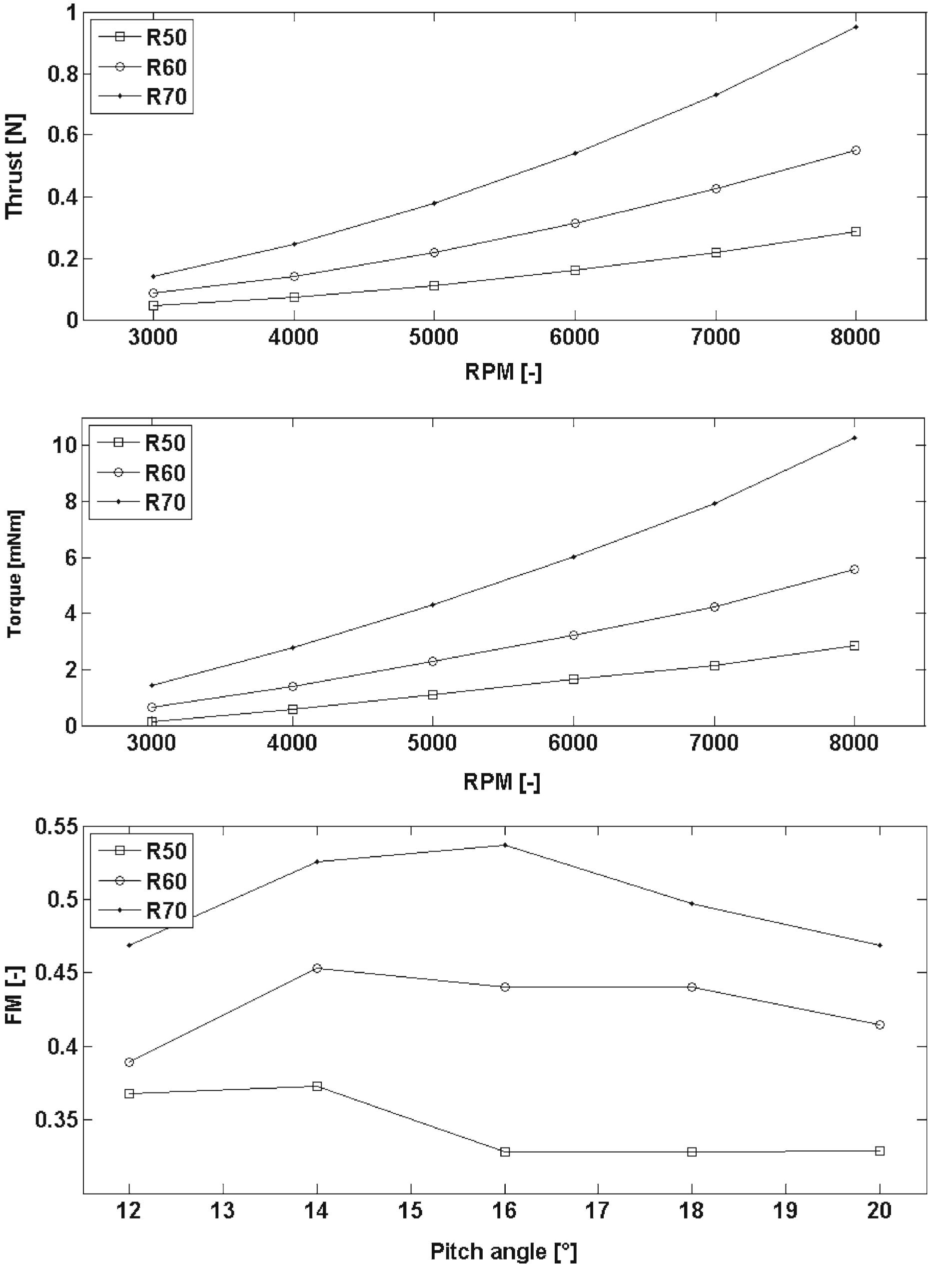


Fig. 5 Experimental results for rotors with different radii (*NACA0012*, $c = 0.02$ m)

since torque and thrust are related by the induced drag. Due to this dependency, the Figure of Merit FM [13] is used to evaluate the aerodynamic efficiency of the rotor. The third plot shows the FM of the different configurations, and it is obvious that a larger radius leads to a higher FM.

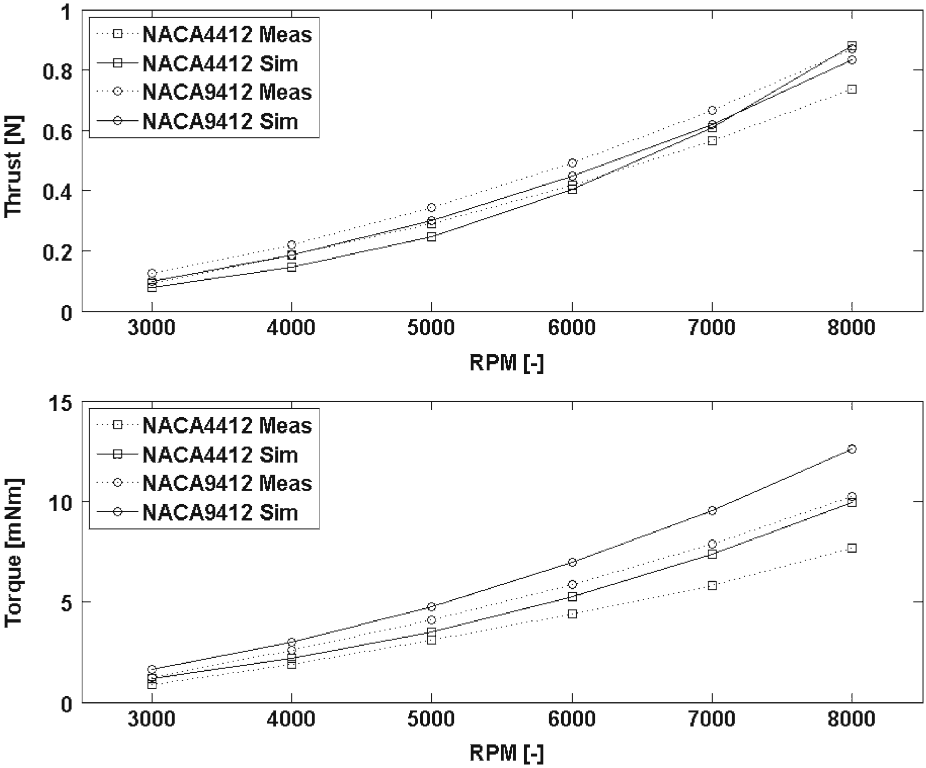


Fig. 6 Comparison between BEMT simulation and measurement ($R = 0.06$ m, $c = 0.02$ m)

On the simulation side, first results of the BEMT and CFD simulations show already good correlation, the in house development of a vortex approach code is still in development. In Fig. 6, some results for the BEMT simulation are shown. The results show the same behavior and order of magnitude as the measurement, but differ from the experimental data up to 20%. This is still in an acceptable range and is mainly a result of the inaccuracy of the BEMT model, unmodeled 3D effects (tip losses) and the aerodynamical coefficients obtained by X–Foil.

3 Understanding the Steering and the Passive Stability

Apart from the efficiency and the thrust of the rotors, there exists a strong interest in studying the behavior of the rotor during swash plate cyclic pitching. Since one goal of the project is to develop the whole propulsion system, it is necessary to quantify the forces and torques available for steering. In addition, the muFly helicopter uses a stabilizer bar for passive stabilization, thus it is important to know how to dimension this device. These two needs motivate the design of a swash plate test bench (STB) using a 6–axis sensor to measure the resulting torques and forces from swash plate inputs and helicopter motions, respectively (Fig. 7).

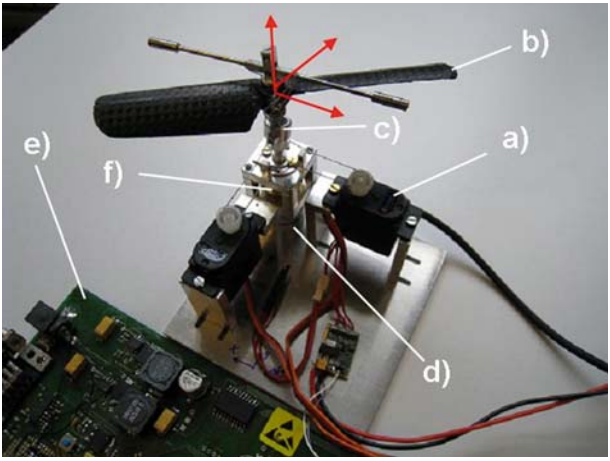


Fig. 7 Swash plate test bench. a) Servo motor, b) Rotor, c) Swash plate, d) 6–axis sensor, e) Control board, f) Electric motor

Two servo–motors actuate the swash plate, the resulting forces and torques are measured by the 6–axis sensor mounted beneath the motor. Since the side forces are very small (up to $\approx 0.15N$), and the sensor is very sensitive, obtaining meaningful results is not trivial. Nevertheless, after some changes in the mechanics and careful calibration, it is possible to measure the thrust vector direction and magnitude of a teetering rotor setup under cyclic pitch. This is still an ongoing work.

For the investigation of the passive stabilization, the STB is mounted on a pivoted platform driven by an electric motor (Fig. 8). The servo motors and swash plate are dismounted, and instead a rotor with stabilizer bar is mounted on the motor (see Fig. 7).

In the experiment, the STB is tilted with the platform, emulating a helicopter roll or pitch motion. As a result of the motion, the stabilizer bar exerts a cyclic

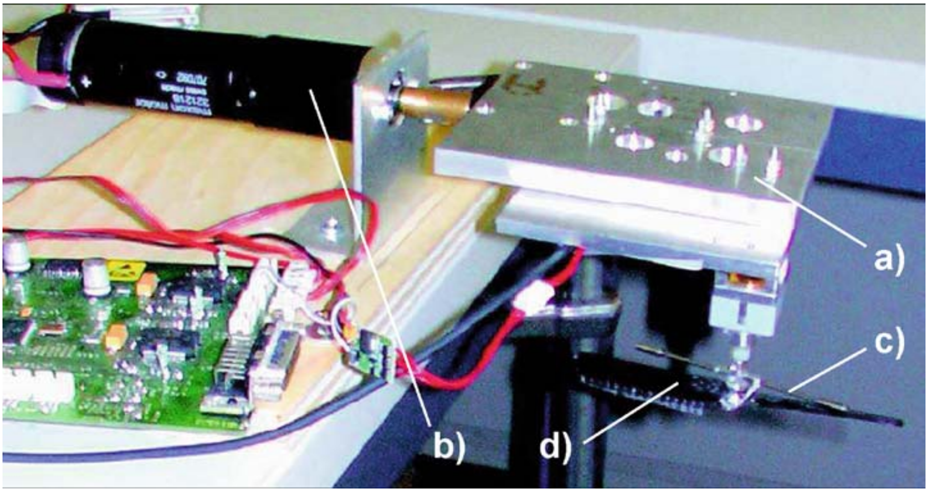


Fig. 8 STB with stabilizer bar mounted on pivoted platform: a) Platform, b) Electric motor for pivoting, c) Stabilizer bar, d) Rotor

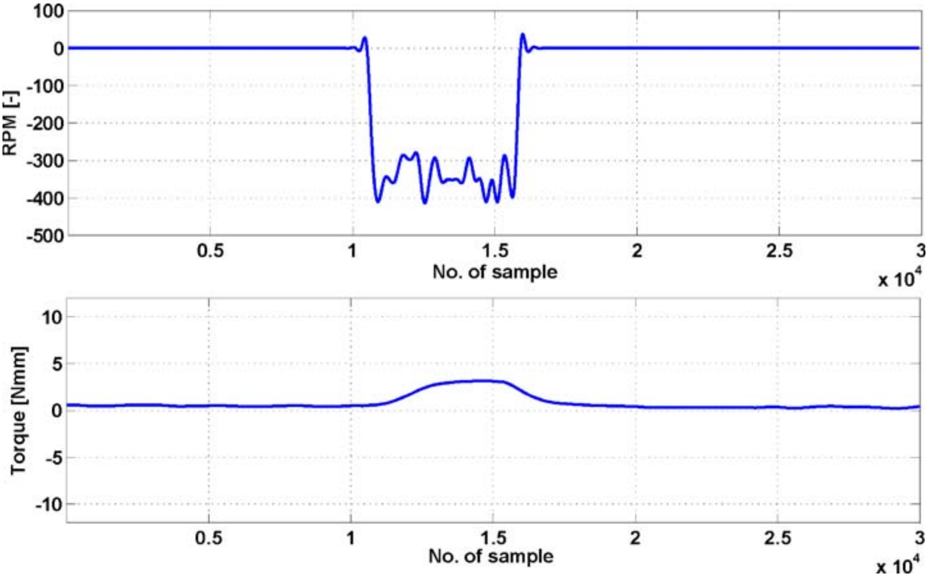


Fig. 9 Pivoted platform's angular velocity (top), and measured rotor moment along the pivoting axis (bottom)

input on the rotor, which in turn results in a change of the rotor's tip path plane orientation with respect to the body fixed coordinate system. The resulting forces and moments are measured by the 6–axis sensor. The investigation of different stabilizer bar inertias and constant phase angles with respect to the blade feathering axis is ongoing work. Figure 9 shows a first result of the experiments.

The two graphs show the pivoted platform's angular velocity and the measured moment along the pivoting axis, which corresponds to the stabilizer bar's response to a roll motion. With the start of the pivoting, the stabilizer bar reacts, however, it reaches mechanical saturation rather quickly. The result shows that the stabilizer bar response to an angular motion of the helicopter is measurable. Once the magnitude and direction of the response moment is known, this information can be used for the tuning of the stabilizer bar on the actual helicopter.

4 Designing the First Prototype

Among the different decisions related to MAV design, sensor selection is of high importance. It strongly influences the overall configuration and the performance of such vehicles. This is especially true because the designer is often constrained to few sensor variants to choose from. Table 2 shows possible combinations of different sensors for the five basic functionalities of muFly, namely: attitude and altitude control, take–off and landing, 3D navigation and obstacle avoidance. The evaluation of the different possibilities suggests the use of an omnidirectional camera with a laser for obstacle avoidance and navigation, an ultrasonic sensor for altitude control and an Inertial Measurement Unit (IMU) for attitude control.

Table 2 The concept selected for the first muFly prototype

	Attitude control	Altitude control	Take-off and landing	Navigation	Obstacle avoidance	Complexity
IMU	+					low
Laser Omnicam		+		+	+	high
Down looking camera		+	+	+		high
Down looking sonar		+	+			low
Side looking sonar				+	+	average
Forward looking ste. cam.		+		+	+	high
Down looking ste. cam.		+	+	+		high

The IMU and the omnidirectional camera are specifically designed for the purpose of the project. In fact, the IMU is an extremely lightweight piece of electronics combining state of the art 2D gyroscope and 3D accelerometer, for a total mass of 2 g. The novelty with the omnidirectional camera is the polar radial arrangement of pixels, which, in combination with a conic mirror and a 360° laser plane, provides an extremely lightweight (3.5 g) range finder based on triangulation.

On the structural side, a lightweight, robust and reliable frame is required for the muFly helicopter.

A first concept that incorporates all of these aspects is shown in Fig. 10.

The rotor system is surrounded by a cage–like carbon structure which offers several advantages: it ensures not only protection of and from the rotor system, but also provides the possibility to place the motors face to face on top and bottom of the cage. Thus, despite the coaxial rotor system no gear box is needed. Subsequently, losses due to gear box efficiency are reduced and the mechanical reliability is increased. Furthermore, with the cage the helicopter possesses a non–rotating surface on top, where the laser plane generator can be placed. This allows for

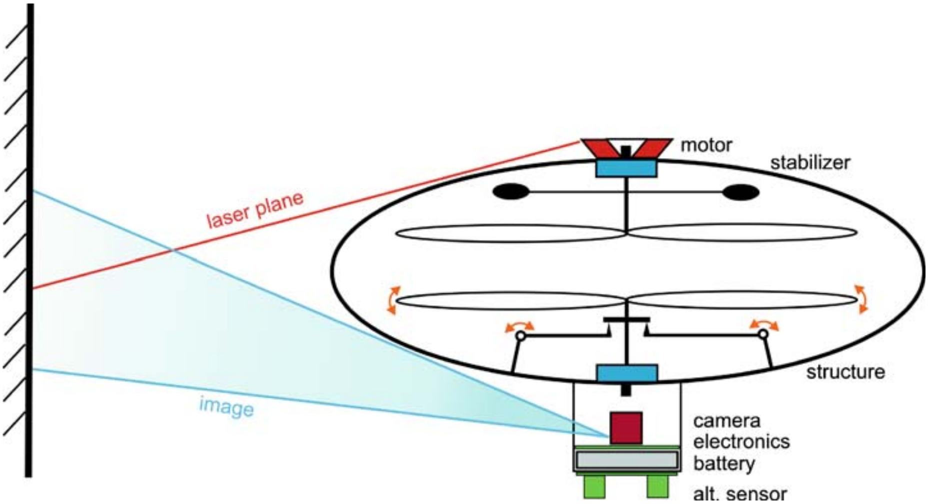


Fig. 10 The concept of the first prototype of the muFly helicopter

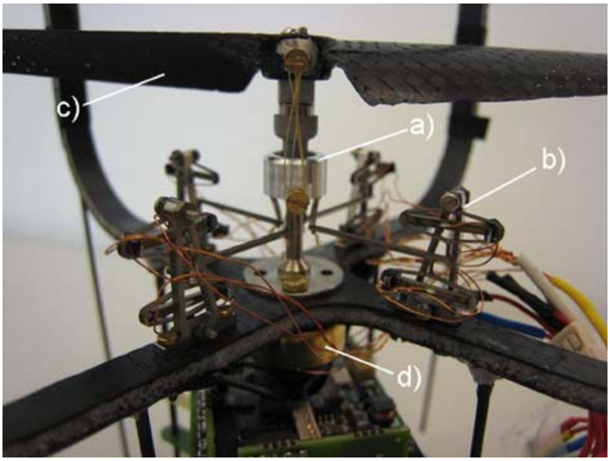


Fig. 11 Bimorph piezoelectric actuators: a) Swash plate, b) Piezo actuator, c) Rotor blade, d) BLDC motor

a sufficiently high distance between camera and laser plane to increase the resolution of the triangulation.

Concerning the actuators for propulsion, brushless DC (BLDC) outrunner motors are presently the best solution available in terms of power to mass ratio and thermal behavior. Adversely, the selection of appropriate steering actuators, where high bandwidth, stroke and force are needed, is much more difficult. Several actuation mechanisms have been looked at, and the decision to use piezoelectric elements has been made mainly because of their high bandwidth and precision. The four piezoelectric actuators used are operating at 150 V and their initial stroke is amplified by a lever arm. Placed in cross configuration, each opposite pair of actuators operates

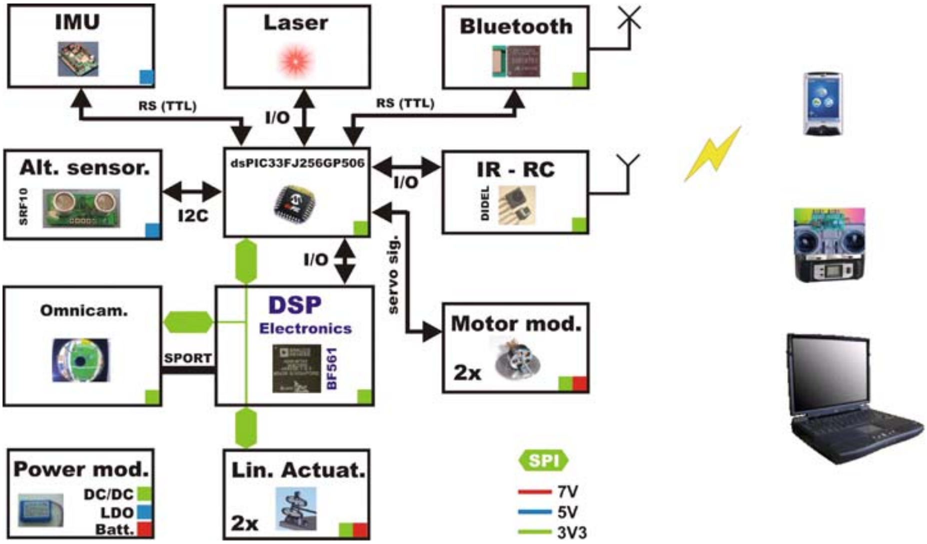


Fig. 12 muFly electronics block diagram

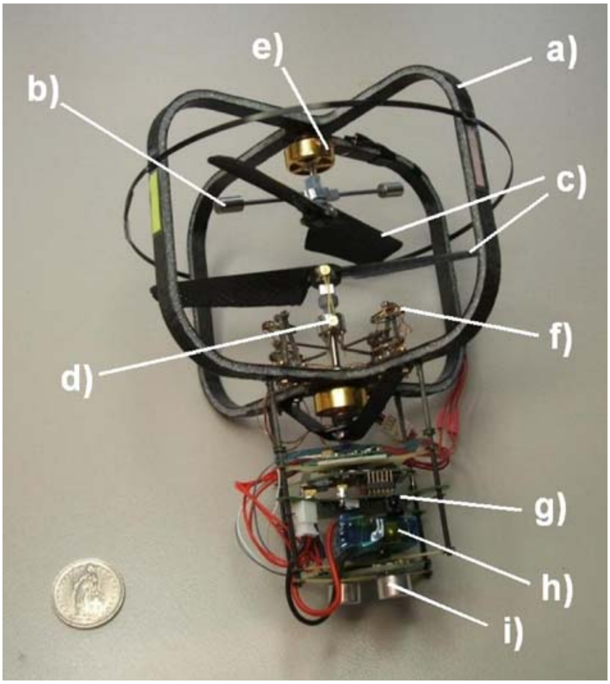


Fig. 13 The muFly helicopter with a) carbon fiber sandwich cage, b) stabilizer bar, c) carbon fiber rotor blades (in–house made), d) swash plate, e) BLDC motors, f) linear actuators, g) PCB main board with double core DSP, h) lithium–polymer battery, i) ultra–sound sensor. Not shown are the omnidirectional camera, the inertial measurement unit and the laser plane generators (not mounted)

one of the swash plates tilting axes. While one actuator pulls, the other one pushes (push–pull mode) which results in a higher actuation force (Fig. 11).

On the electronic side, muFly uses a double core DSP and a micro controller for the sensor/actuator interface, an infrared receiver for manual control and a bluetooth module for communication with the ground station. The block diagram is shown in Fig. 12.

All the electronics are accommodated in a pod structure attached under the cage structure. This design meets the objectives in terms of compactness, mass and processing power, achieving the five capabilities listed before. Altogether, the first prototype of muFly is a coaxial helicopter with an overall mass of 78 g, 12 cm span and 15 cm height (Fig. 13).

5 Analyzing the Dynamics

The instability inherent to helicopters in general makes it very difficult to analyze the system behavior in flight, and thus to validate the dynamic simulation model. A training platform that eliminates the risk of a crash is a solution to this problem. However, it has to provide sufficient space for the helicopter to operate in, and, more importantly, it should only exert minimal external forces and moments on the helicopter in normal flight mode.

The vehicle test bench (VTB) created during the project is an original 6 DoF cable–based system on which one can mount a muFly helicopter on the central structure as shown in Fig. 14.

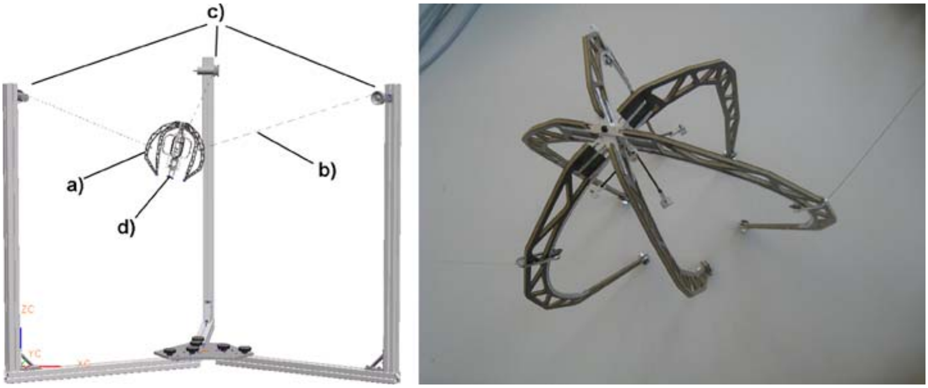
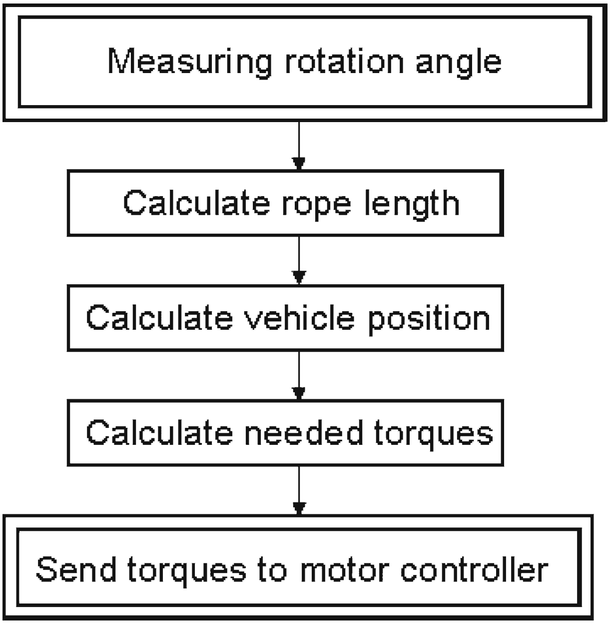


Fig. 14 CAD design (left) and manufactured carbon structure (right) of the vehicle test bench: a) Carbon structure, b) Wires, c) Electric motors with pulleys, d) muFly helicopter

This structure is supported by three wires, and actively controlled by three electric motors, which permits permanent gravity compensation. The control is done feed–forward by using the geometric properties of the test bench and the motor controllers (Fig. 15). Thus, for the three translations, muFly endures only the motors' and the pulleys' inertia when translating in an arbitrary direction.

Concerning the three rotations, the central carbon–made structure (see Fig. 14 right) is equipped with three rolls allowing rotational motions thanks to its three sets of arms. The three sets are mounted on a common axis and can rotate independently of each other. Each set is composed of two arms, one for the gravity compensation

Fig. 15 Vehicle Test Bench control block diagram



with a counter weight, and one for the wire connection to the motor pulleys. Thus, for the three rotations muFly endures only the low friction torques on the rolls. At the end, the VTB is mechanically almost transparent to the helicopter. This feature allows to fly the helicopter freely in the working space of the VTB, almost like in normal flight. At a later stage of the project, the VTB will be used for parameter identification experiments with the muFly helicopter.

6 Conclusion and Outlook

This paper presents the European project muFly and the approach advocated for the design of the micro coaxial helicopter, which consists first in the development of several test benches before developing the flying system itself.

The challenges of designing an efficient rotor in this scale is investigated by measuring the thrust and torque for different rotor configurations on a coaxial test bench. The test bench is explained in detail and first results are shown as an illustration. Furthermore the experimental research is supported by simulation and a first comparison is given. After looking at the efficiency of the rotor the forces and moments on the rotor during cyclic pitch are measured on a swash plate test bench (STB). In addition, the STB is used to investigate the effect of the stabilizer bar used on the helicopter.

The development of the first prototype is explained, especially the choice of the sensors, the actuators and the structural design. Finally, a vehicle test bench (VTB) system has been designed and built in order to test the passive stability of muFly and also to fly it safely in a confined work space. The VTB compensates all the gravity effects and emulates an almost free flight of the helicopter in safe conditions. Several investigations are still ongoing. On the aerodynamical side, more rotor configuration will be tested and compared with the further developed simulations with the goal of proposing an efficient propulsion system for a micro coaxial helicopter in the size of mufly. Additionally, the rotor system will be optimized to achieve high steering and control performance by extensive testing on the swash plate test bench. An intermediate design of the helicopter is already started for testing and optimization of the whole system.

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References

1. Noth, A., et al.: Autonomous Solar UAV for Sustainable Flights. Springer, ch. 12, pp. 377–405 (2007)
2. Taylor, C.N.: Techniques for overcoming inaccurate pose estimates in mavs. In: Proc. (IEEE) International Conference on Intelligent Robots (IROS'07), San Diego, USA (2007)
3. Grasmeyer, J., Keennon, M.: Development of the black widow micro air vehicle. In: Proc. 39th AIAA Aerospace Sciences Meeting and Exhibit, Reno, USA (2000)

4. Kemp, C.: Visual control of a miniature quad-rotor helicopter. Ph.D. dissertation, University of Cambridge (2006)
5. Wang, W., et al.: Autonomous control for micro-flying robot and small wireless helicopter x.r.b. In: Proc. (IEEE) International Conference on Intelligent Robots (IROS'06), Beijing, China (2006)
6. Bouabdallah, S., et al.: Design and control of an indoor coaxial helicopter. In: Proc. (IEEE) International Conference on Intelligent Robots (IROS'06), Beijing, China (2006)
7. Bohorquez, F.: Design, Analysis and Performance of a Rotary Wing Mav. Alfred Gessow Rotorcraft Center, USA (2001)
8. Pines, D., Bohorquez, F.: Challenges facing future micro air vehicle development. AIAA J. Aircraft, **43**(2), 290–305, (2006)
9. Bohorquez, F., et al.: Hover performance of rotor blades at low reynolds numbers for rotary wing micro air vehicles. An experimental and cfd study. AIAA Paper 2003-3930 (2003)
10. Coleman, C.P.: A Survey of Theoretical and Experimental Coaxial Rotor Aerodynamic Research. NASA Technical Paper 3675 (1997)
11. Drela, M.: X-foil subsonic airfoil development system. http://raphael.mit.edu/xfoil (2004)
12. Griffiths, D., Leishman, J.: A study of dual-rotor interference and ground effect using a free-vortex wake model. In: Proc. of the 58th Annual Forum of the American Helicopter Society, Montréal, Canada (2002)
13. Bramwell, G.D.A.R.S., Balmford, D.: Helicopter Dynamics. Butterworth-Heinemann (2001)