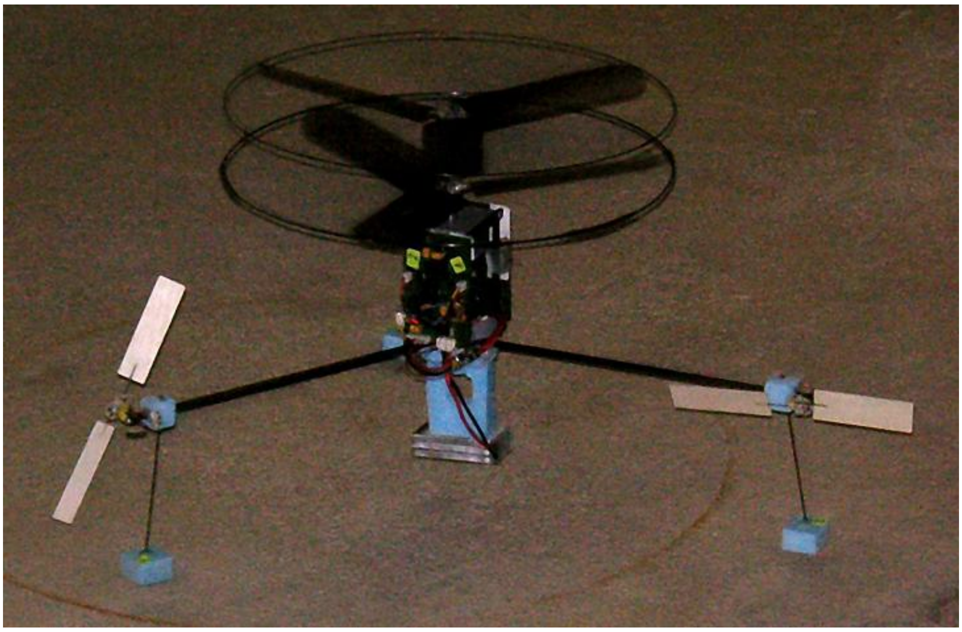
EIDGENÖSSISCHE TECHNISCHE HOCHSCHULE LAUSANNE
POLITECNICO FEDERALE LOSANNA
SWISS FEDERAL INSTITUTE OF TECHNOLOGY

INSTITUT D'INGENIERIE DES SYSTEMES, I2S
Autonomous Systems Lab, ASL

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Master Thesis

Coaxial Helicopter Design



Professor: Roland Siegwart
First supervisor: Samir Bouabdallah
Second supervisor: André Noth

Candidate: Yves Stauffer
Section: Microtechnology
Lausanne, February 2005

"The idea of a vehicle that could lift itself vertically from the ground and hover motionless in the air was probably born at the same time that man first dreamed of flying."

Igor Ivanovitch Sikorsky

CoaX

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

PROJET DE DIPLOME – HIVER 2004/2005

Titre:	**Contribution à la conception d'un micro hélicoptère à rotors coaxiaux**
Candidat:	Yves Stauffer — **Section:** MT
Professeur:	Roland Siegwart
Assistant 1:	Samir Bouabdallah — **Assistant 2:** André Noth

Donnée & travail demandé :

Le présent projet s'inscrit dans le cadre d'une thèse visant à concevoir et contrôler des micros hélicoptères. Il s'agit pour ce travail de concevoir la mécanique d'une nouvelle plateforme d'hélicoptère miniature à doubles rotors coaxiaux. Le but à long terme de ce projet est d'arriver à une plateforme autonome de moins de 50g. Ceci étant conséquent, le travail doit être divisé en plusieurs projets. Pour la première partie, le travail demandé est le suivant :

- Réflexion sur la conception mécanique.
- Etablissement d'un catalogue de solutions.
- Dimensionnement du robot.
- Réalisation de l'électronique.
- Synthèse d'un contrôleur simplifiée.
- Interface de contrôle simplifiée.
- Réalisation et tests du premier prototype (en collaboration avec un technicien).

Remarques :

Un plan de travail sera établi et présenté aux assistants avant le 1er novembre 2004.

Une présentation intermédiaire (environ 10 minutes de présentation et 10 minutes de discussion) de votre travail aura lieu dans le courant du mois de décembre 2004. Elle a pour objectifs de donner un rapide résumé du travail déjà effectué, de proposer un plan précis pour la suite du projet et d'en discuter les options principales.

Un rapport, comprenant en son début l'énoncé du travail (présent document), suivi d'un résumé d'une page (selon canevas), sera remis le vendredi 18 février 2005 en 4 exemplaires au secrétariat de votre section. L'accent sera mis sur les expériences et les résultats obtenus. Le public cible est de type ingénieur EPF sans connaissance pointue du domaine. Une version préliminaire du rapport sera remise à l'assistant le 11 février 2005. Tous les documents en version informatique, y compris le rapport (en version source et en version pdf), le document de la présentation orale et un résumé au format pdf, ainsi que les sources des différents programmes doivent être gravé sur un CD-ROM et remis à l'assistant au plus tard lors de la défense finale.

Une défense de 40 minutes (environ 20 minutes de présentation et démonstration, plus 20 minutes de réponses aux questions) aura lieu dans la période du 7 au 14 mars 2005.

Le professeur responsable:	L'assistant responsable:
Signature :	Signature :
Roland Siegwart	Samir Bouabdallah

Lausanne, le 18 octobre 2004

Autonomous Systems Laboratory

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Master Thesis Summary — Winter 2003-2004

Designt of a Micro Coaxial Helicopter

Stauffer Yves, Microtechnology

Professor : *Siegwart Roland*

Supervisors : *Bouabdallah Samir, Noth André*

Flying robots are an increasing field of research in the academic world. ASL (Autonomous Systems Lab) already gained valuable knowledge in this domain thanks to the OS4 and Flying Alice projects. As one knows both configurations depicted in figure 1 are naturally unstable, thus a fast and powerful control has to be performed. In this context it was decided to build a flying robot that would be auto-stable.

Figure 1: Flying Alice and OS4 and proxfly

The overall mechanical concept from proxflyer (www.proxflyer.com) was studied. The outcome of this is a novel coaxial helicopter that can be observed on figure 2.

Altitude is controlled by the two main propellers which are actuated by a brushless motor (Typhoon 05-3D). Three lateral propellers allow controlling yaw and translation. Furthermore this helicopter is equipped with an infra red distance sensor (Sharp) which allows performing altitude control and a gyroscope (ADXRS150 from Analog Devices). Finally communication between an on ground computer and the robot is done via Bluetooth (WML-C10 from Mitsumy). It is energetically autonomous thanks to Lithium Polymer batteries from Kokam.

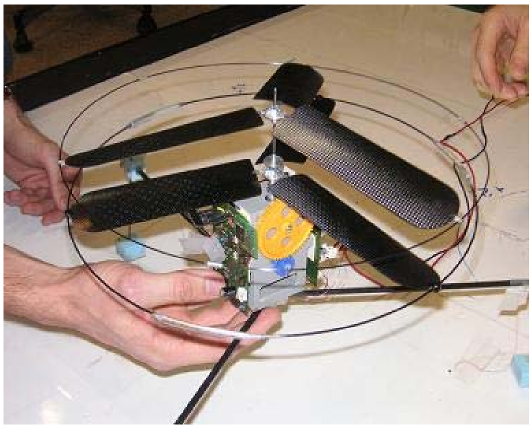


Figure 2: Coax

Tests were performed and pointed out that controlling yaw was feasible with this configuration. Translation however was not yet achieved. The main drawback of this design is its breakability. Indeed the two main propellers are subject to vibrations and tend to break quite often. A redesign of the latter would be a great step forward. Several other design hints are now available in the report for future projects. The work done for this project gives solid bases and chances for a fast evolution of the Coax family.

CoaX

1 Introduction

1.1 Feathers, helicopters and drones

The idea of vertical lift is over 2000 years old [7], indeed in 400 BC Chinese people were tying feathers to the top of a stick. When this device was spun rapidly vertical motion was achieved. At the beginning of the 18th century a French naturalist built a coaxial version of this toy, as depicted on Figure 1.

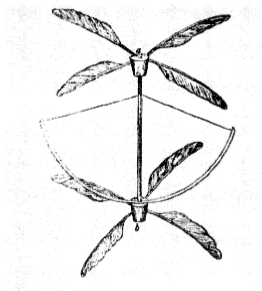


Figure 1: coaxial feather helicopter

In the meantime the avand-gardist thinker Leonardo da Vincy had already thought about an "aerial screw" as depicted on Figure 2, of course at the time he was living building such a device was impossible.

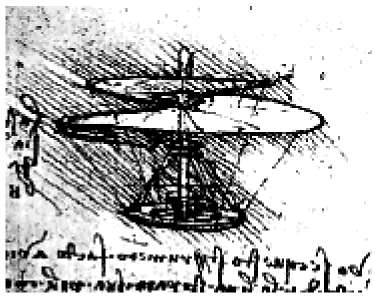


Figure 2: aerial screw from Leonardo da Vinci

One can see that imitating the hummingbird or the dragonfly, which are the two only animals to achieve the behaviour of helicopters[1], appeared quite a long time ago. However even at the beginning of the twentieth century major problems remained unsolved; these were:

Weight: aluminium was not easily available
Power: steam engines were too heavy
Control: helicopters are naturally unstable
Vibrations: insufficient understanding of rotating wings mechanics

One of the first successful helicopters was built by a Frenchman working for Peugeot in 1920. Its machine is depicted on Figure 3. As one can guess this device was underpowered, thus balloons were needed to provide additional lift; doing this also increased the stability of the system, making the control easier. This helicopter is reported to have flown a circuit of 1 km in 7 minutes and 40 seconds.

[1] The word helicopter comes from the Greek adjective "elikoeioas" meaning spiral and the noun "pteron" meaning feather or wing.

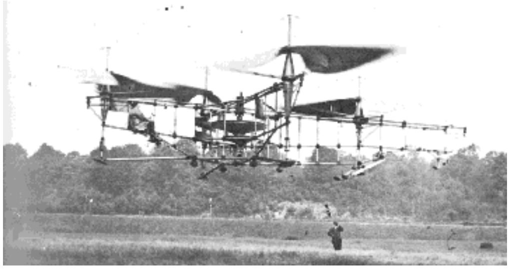


Figure 3: "first" helicopter

One can observe on Figure 3 that the first helicopter was not a conventional device with just one main rotor but a quad rotor. Several different rotor configurations exist, such as two rotors one in front of the other as can be found on the Chinook (Figure 4) or the same configuration but overlapping. The second successful helicopter, which was the first one to fly by itself, had a coaxial configuration and was built by Breguet-Dorand in 1935 (Figure 4).

Figure 4: two coaxial configurations, Chinook and first successful helicopter

All these early designs were slow, difficult to control and suffered from a lack of autonomy. Now these devices have evolved, mostly due to military constraints, to become one of the most amazing flying objects. State of the art helicopters are used for a variety of missions during all weather conditions. Some are even able to perform acrobatic tricks such as a looping. Figure 5 shows two of the latest military helicopters, which are used in most modern conflicts and are the ultimate evolution of the helicopter species.

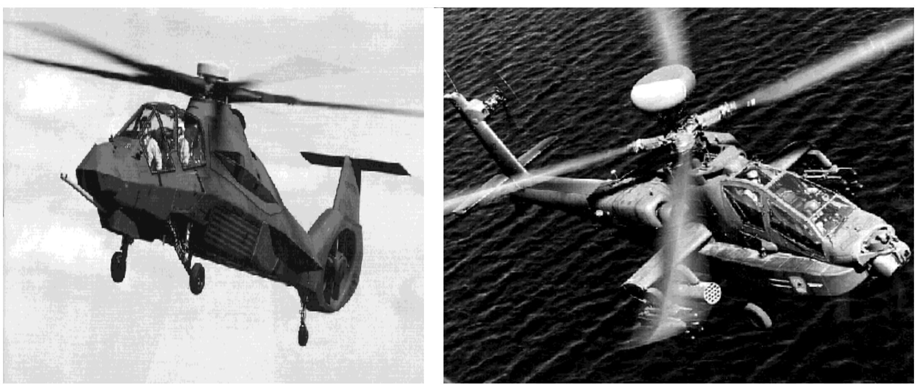


Figure 5: commanche and AH 64

Nowadays small scale helicopter, are well represented on the hobbyist scene. Unmanned helicopters on the other hand are still an emerging area of research. Some laboratories or passionate people have been successful in such designs; again state of the art projects and solutions have been financed and are currently used for military research. Drones of varying sizes are used or will be used in everyday life for tasks such as surveillance or search and rescue. For a small overview of different projects refer to "state of the art". Unsurprisingly when one designs autonomous helicopters the same problems as at the beginning of the last century are encountered; namely: **weight, motor unit, control and vibrations**.

1.2 Special considerations with flying objects

When one is designing flying objects, especially helicopters every component has to be optimized as a whole. This leads to two important issues. First, designing such a robot in a "parallel" way is not possible; indeed every part is linked to the others. This leads to a sequential design where the interaction of every part has to be taken into account. And a constant redesigning of the solution is necessary.

Second, every component has to be optimized and used to the best of it capabilities. This often means using it beyond the specifications given by the manufacturer. Thus every critical component has to be tested in order to make sure that the overload won't cause a too rapid damage.

2 Objectives

2.1 Goal of this project

The goal of this project is multifold. The Autonomous System Lab (ASL) has already gained valuable knowledge in quad rotor designs (OS4 [9]) as well as dual rotor designs (flying Alice [8]). Now the behavior of a purely coaxial configuration is to be studied as well as novel ways of controlling the motion of this new helicopter. For obvious reasons this robot will be called the COAX.

The focus is given to the mechanical aspects, auto stability is wanted and a robust way of control too. This is why all parts will be tested in order to find the best solution for this application. Nevertheless electronics are not to be neglected, this flying device will be fully autonomous yet the possibility of remote control via a computer will be possible. Thus a communication module as well as on board sensors will be available.

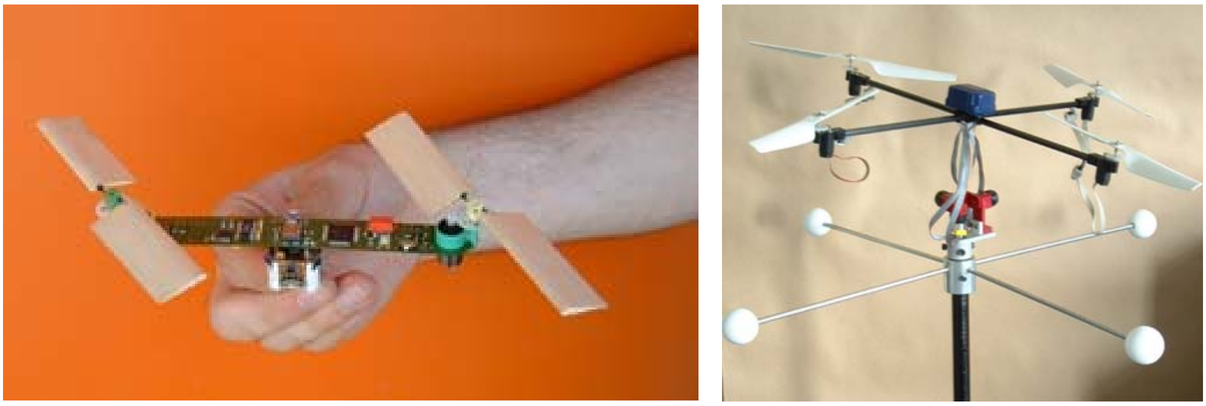


Figure 6: flying alice and OS4

2.2 Possible applications

Such small indoor helicopters offer several interesting capabilities. On an academic level a lot of research has still to be done and flying devices are getting more and more popular and offer challenging problems mostly in terms of control and localization. On an industrial level, search and rescue missions and building surveillance would be typical applications [2]. Of course military applications are always possible; however EPFL is not willing to go into this direction.

2.3 Overview of the tasks

Designing a such a flying device is an interesting, yet long task. Concealing all the work is not trivial. Thus a few words about the organization of this report are needed.

Chapter 1,2 and 3 are the standard introduction, objective and state of the art chapters.

Chapter 4 states the problems that have to be solved. Namely:

- How to control all the degrees of freedom
- What motors can be used
- What batteries are available
- What about the materials of the structure
- Which sensors are useful for such a device
- How to communicate with the robot
- How to process the information

Chapter 5 will give the theoretical background to the vital parts of chapter 4 and do some calculations to evaluate some possible solutions.

Chapter 6 crucial mechanical parts such as the motors, propellers and control systems will be tested and results are provided.

Chapter 7 the advantages and disadvantages of each solution will be stated and eventually the best design will be selected.

Chapter 8 is a summary of the dynamic modelisation of the Coax, this part was done by Fabien Gigon.

Chapter 9 is a summary of the tests that were done on the Coax, this includes tests done on a test bench as well as free flights.

Chapter 10 is the standard conclusion.

3 State of the art

Flying robots are an emerging field of research. Novel technologies such as high power to weight ratio batteries and motors are allowing the development of smaller devices with greater autonomy. The following section will deal with some of the emerging projects. These projects cover a vast range of sizes, propulsion principles as well as control possibilities.

Epson Micro-Flying Robot:

The Micro Flying Robot from Epson [2] is probably the most achieved example of coaxial flying robot. Its overall weigh is around 13g. Two ultrasonic motors are used to actuate the propellers. Translation is controlled by linear actuators, which shift the centre of mass of the robot. Sensing is provided by an altitude sensor, a gyroscope and a small CMOS based camera. The robot is also equipped with an onboard CPU as well as a communication device. The word's smallest autonomous helicopter can be seen on Figure 7

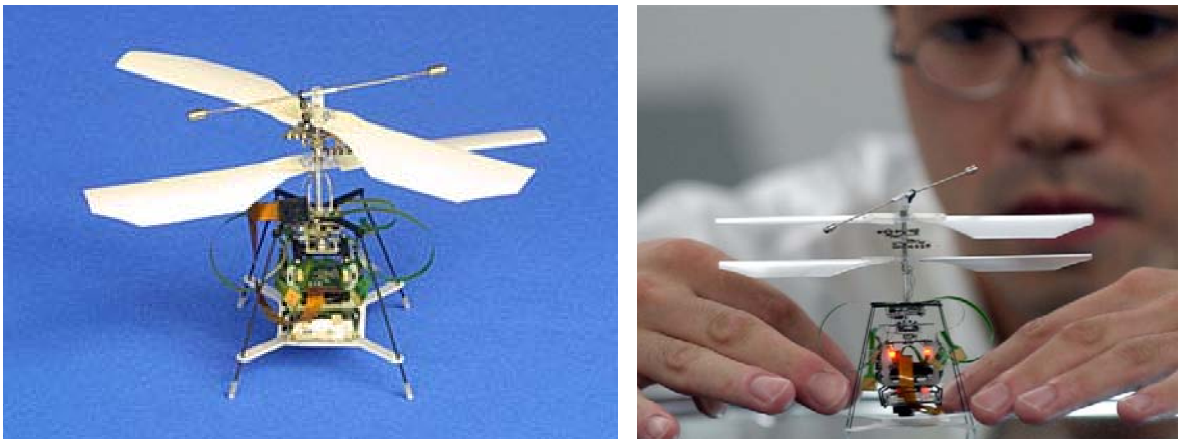


Figure 7: Epson's micro helicopter

Proxflyer:

The proxflyer concept is the achievement of several years of research led by Petter Murren [1]. The outcome of this study is a novel mechanical concept, which enables a full stability in pitch, roll and translation. The inventor of this concept built one of the smallest non autonomous helicopter: the Nanoflyer, that only weights 2.7g (Figure 8).

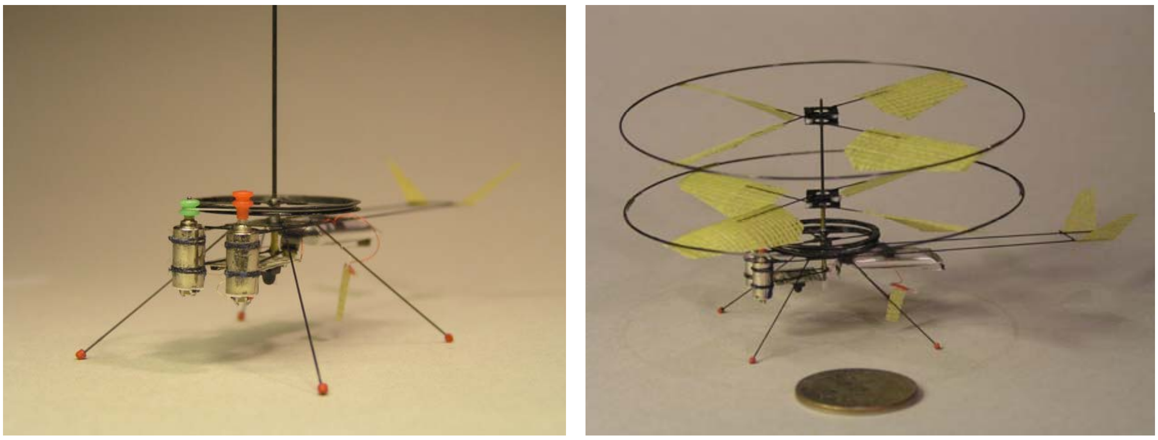


Figure 8: Nanoflyer from Proxflyer

This amazing technology is also used in a newly commercially available toy: the Bladerunner (Figure 9).

Figure 9: Bladerunner

The incredible possibilities unveiled by this new mechanical concept greatly inspired the COAX project. Indeed the original idea of the Proxflyer was transposed to a three blade propeller.

<u>MICOR:</u>
The MICOR [5] (Figure 10) is a coaxial robot that is roughly of the same size than the COAX. Two motors are used to control yaw and height. However there is no control for the translation. Furthermore the current project is net equipped with sensors. Finally it is not reported to have flown autonomously. Nevertheless this project was a great source of inspiration for the COAX.

Figure 10: MICOR

<u>Zero G-Eye :</u>
The Zero G-Eye [3] (Figure 11) as well as the lab notebook "Building a Micro Helicopter that actually flies" [4] by Stephan Marty were also of great interest. Even though the G-Eye didn't fly the concept of having lateral flaps to control yaw and translation could be reused on the COAX.
The lab notebook contained interesting thoughts about flying devices and possible reasons for the failure of the G-Eye. This report also provided the mechanism (Figure 12) that was used on the COAX to have two propellers that spin in two different directions.

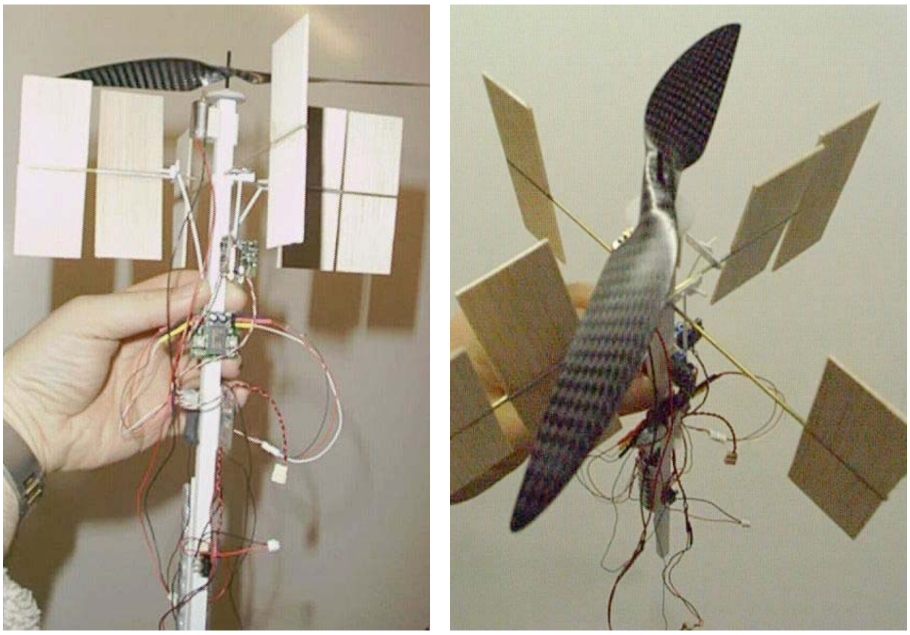


Figure 11: Zero G-Eye

Figure 12: inverter

<u>Kamov Ka-137:</u>
The Ka-137 [10] (Figure 13) is currently used in Russia for observation missions. This coaxial drone is able to cruise at speeds up to 175 km/h and carry a payload of over 50kg. Its take-off weight is 280 kg and the main rotor has a diameter of 5.3 m. A 65 hp gasoline engine is used. This device is able to fly in all directions and its onboard inertial satellite navigation system allows autonomous flights.

Figure 13: Kamov-137

4 Problems and possible solutions

Flying objects such as helicopters have usually 6 degrees of freedom (DOF), 3 translations and 3 rotations. The Coax will only have 4.

Altitude (translation along the **Z** axis)
Two Translations along the **X** and **Y** axis
Yaw

Pitch and **roll** are considered as being stable.

The whole purpose of a robot is to be perfectly controlled thus all the DOF that are not stable need to be controlled by one or more actuator. The following subsections will deal with these issues.

In the following sections possible solutions for every part of the Coax will be provided. Then chapter 5 will give a more theoretical insight. In chapter 6 practical tests will be performed and in chapter 7 the optimal solution will be chosen. Figure 14 shows how what pars of the Coax will be dealt with.

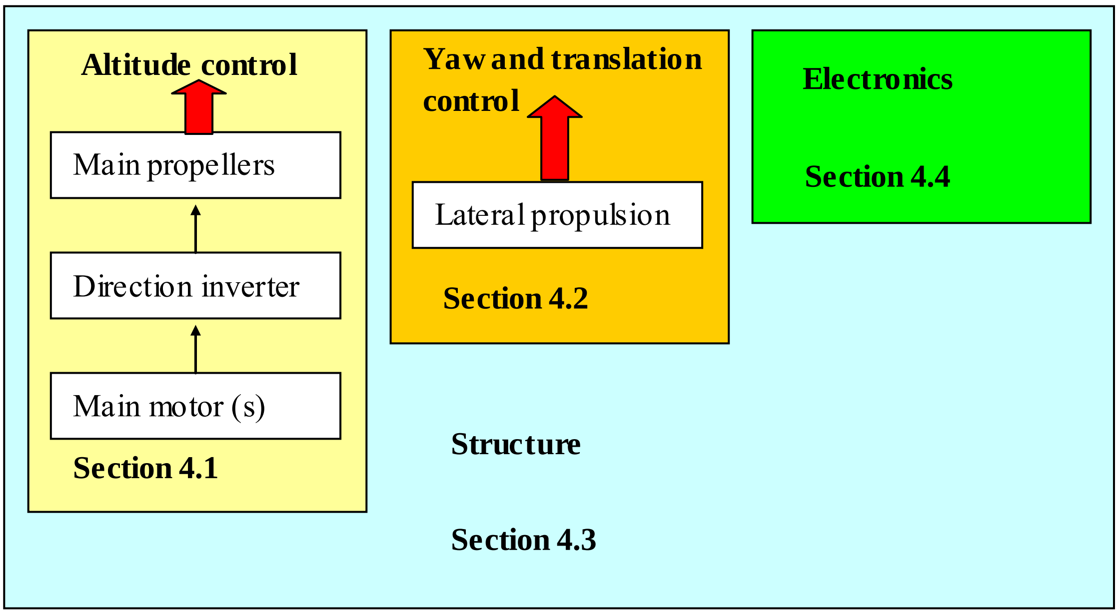


Figure 14: design issues of the Coax, what needs to be investigated

4.1 Altitude control

Altitude control is quite a challenging issue. Thus it has to be broken down in several sub parts. Each will have to be optimized.

4.1.1 Motor

Selecting the main motor is extremely important for the rest of the project. ASL has already some knowledge with flying devices, several projects showed that every electrical Watt that was injected in the motor would contribute to lift around 10 grams. Since the final device will weight around 200 grams the motor's power should be of 20 Watts or more.

Two kinds of motors were considered:

- DC: easy control (Pulse Width Modulation or PWM), low power/weight ratio
- BLDC: light, need a specific controller, high power/weight ratio

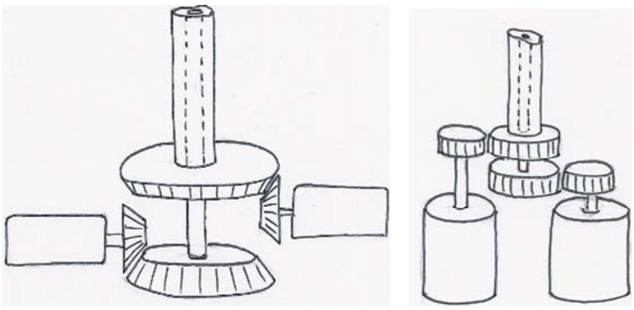


Figure 15: inverter using two motors[2]

Since two propellers will be employed using two motors would also be possible.

- **1 motor:** "cheaper", lighter, inverter needed, bigger motor
- **2 motors:** two motors have to be controlled, more expensive, possibility to control yaw by selecting the right differential speed between the two motors. Solutions using two motors are depicted on Figure 15.

It was decided that only one motor would be used. Furthermore no potential DC motor was found. This only left two brushless candidates:

- LRK 195.03 from Westechnik [14], weights 11g and delivers up to 35W
- Typhoon 05-3D from Eflight [15], weights 33g and delivers up to 80W (**2.4W/g[3]**)

Each motor has a dedicated brushless controller. The LRK uses a YGE4-BL (2g, up to 4A) available at Westechnik [14] and the Typhoon uses a Phoenix 10 (8g, up to 10A) available at Eflight [15].

[2] Drawing done by Fabien Gigon

[3] A power/weight ratio of 2.4W/g is good, indeed a DC motor such as the 1724 from Faulhaber has a power/weight ratio of only 0.1W/g

4.1.2 Direction inverter

Both main propellers have to spin in different directions an inverting mechanism is needed. Several possibilities exist to perform this operation.

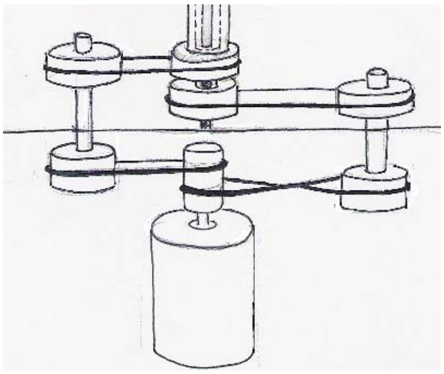


Figure 16: inverter using belts[4]

Using a system with belts as depicted on Figure 16 would be perfectly possible, since the symmetry of the helicopter is conserved. At these scales and powers belts have a low efficiency. Furthermore one belt has to be twisted in order to invert the direction of rotation, doing this reduces this system's performance even more. One can think of similar systems that would use flat gears, however the problems remain.

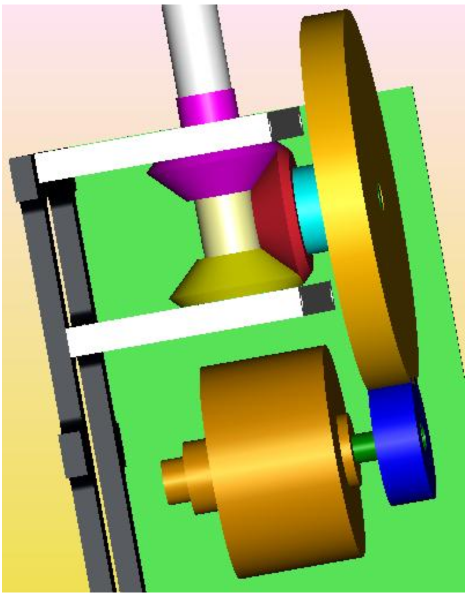


Figure 17: inverter, reduction and motor

Another possibility is to use a system as depicted in Figure 12, one of the lateral gears can even be omitted. Furthermore the motor can be placed under the inverter as shown in Figure 17. In this case the robot's symmetry is conserved and the efficiency of the system is higher than with belts.

[4] Drawing done by Fabien Gigon

4.1.3 Main propeller

Selecting the right propeller is critical. Indeed helicopters are usually unstable objects. However recent projects use “smart propellers” [1] . These propellers are depicted in Figure 18, without going into the detail of operation one simply has to know that they are not stiff as would be standard propellers (Figure 18).
Note however that a study pointed out [13] that having 3 blades was less effective than 2. Thus four blades must be even worse. Thus the original proxflyer idea will have to be remodelled to have an optimized propeller.

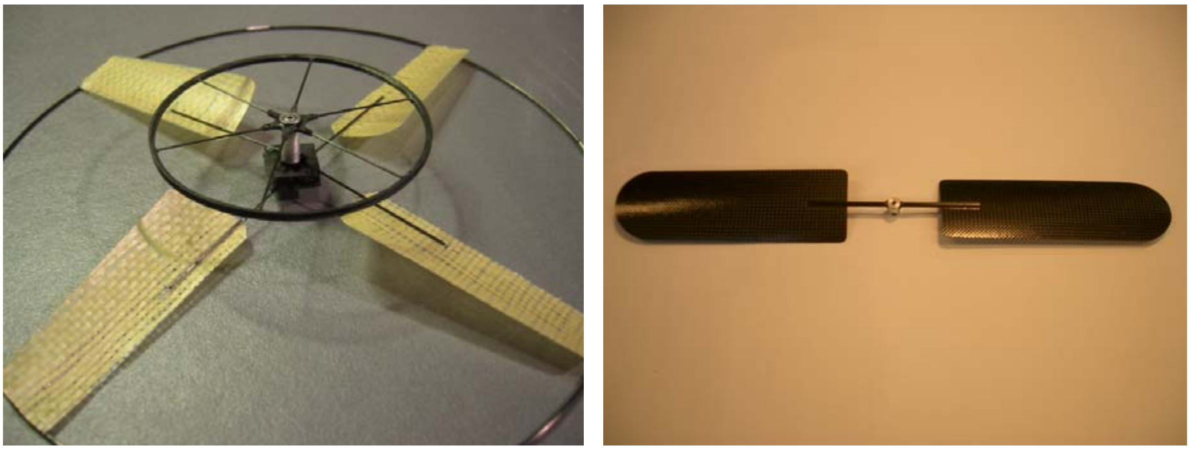


Figure 18: proxflyer propeller and conventional propeller

4.2 Yaw and translation control

As stated before one wants to control yaw, X and Y translation at the same time. In order to perform this operation at least three lateral actuators are needed. The following subsection will show different possibilities of actuators. Placing 3 actuators at 120° allows to translate in both directions and rotate at the same time. Figure 19 shows a simplified top view of the robot, $F_{1,2,3}$ are the forces generated by each actuator.
Special care was taken to select the right control system. The following sub sections will briefly explain what solutions were available. Then chapter 5 will give a clearer insight from a theoretical point of view. In this chapter one will also find calculations related to each propulsion system if it was to be used on the Coax. Eventually in chapter 7 all systems will be compared and one will be selected.

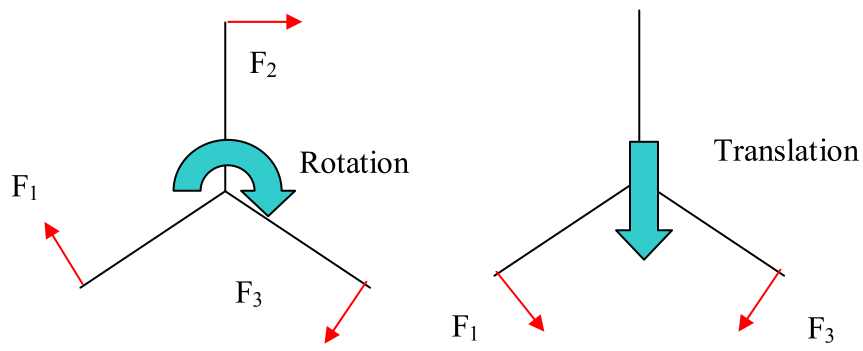


Figure 19: how to achieve rotation and translation

4.2.1 Flaps

<u>Small introduction to flaps:</u>
Flaps can be considered as a wind deflector. When placed in an airflow they generate two forces, one parallel to the airflow: the drag and one perpendicular to the airflow: lift. The idea is to take advantage of this in order to steer the robot. For a more theoretical approach to the flaps refer to the theory section.

<u>How flaps could be used:</u>
Three flaps could be mounted at 120° under the main propellers. They would make use of the airflow created by the main thrust to generate lateral forces. Moving these flaps can be done by small servo motors.

4.2.2 Small lateral propellers

<u>Small introduction to propellers:</u>
As everybody knows propellers are generating a lift force when they are rotating. This phenomenon could be used to steer the robot. For a more theoretical approeach to propellers refer to the theory section.

<u>How small lateral propellers could be used:</u>
Three small propellers could be mounted at 120° as shown on Figure 20. Placing them outside of the robot increases the overall size but allows to be independent of the main airflow. Didel [13] is selling interesting motors, reductions and propellers connectors (Figure 21). In this particular case the 4R25 reduction with a MK04S-10 motor is considered.

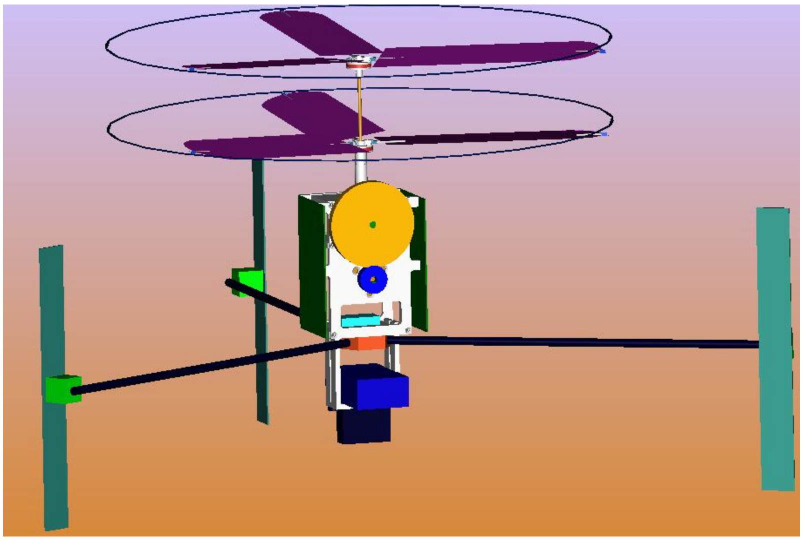


Figure 20: small lateral propellers

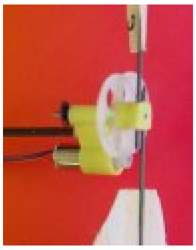


Figure 21: motor, reduction and propeller connector from Didel [13]

4.2.3 Magnus cylinders

<u>Small introduction to Magnus cylinders:</u>
If a rotating cylinder is placed in an airflow a lift force perpendicular to the flow will be generated. For a more complete theory refer to the theory section.

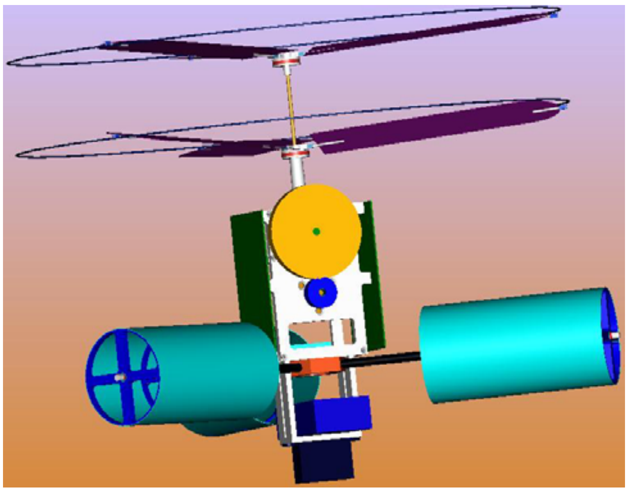


Figure 22: Magnus cylinders

<u>How Magnus cylinders could be used:</u>
Three Magnus cylinders could be mounted on the Coax as depicted on Figure 22.

4.3 Structure

The last mechanical piece is the structure. Its main function will be to hold together the robot. Of course it will have to be as light as possible and solid. Three kinds of materials are considered. Table 1 summarizes the advantages and disadvantages of each.

	Carbon fiber	Lightweight plastic	PCB material
Advantages	Light	Light (lighter)	Fancy forms possible
	Very solid	Very solid	Integrate electronics
		Easily available	
		Easy to realize	
Disadvantages	Has to be ordered	Thicker	Heavy
	Not all thicknesses		

Table 1: materials for the structure, pros and cons

4.4 Electronics

It is impossible to realize a robot without some minimal electronics. In this particular project the focus was given to the mechanical aspects. Nevertheless microprocessors have to be present to deal with the motor commands, sensors are needed to control the height and other parameters and communication with a ground platform is also needed in order to steer the helicopter

4.4.1 Sensors

Altitude:

The height of the helicopter can be monitored by several different kinds of sensors. Three available solutions are:

- Sharp infra red sensor [21]: cheap, mid weight (5g), easy to connect, non linear signal
- Pressure sensors: not enough resolution (usually), bigger
- Ultrasound sensors: SRF08 [22], mid weight, dispersion

Yaw:

The rotation can be measured by the following two sensors:

- Compass: small, cheap, sensitive to metallic objects
- Gyroscope: small, not too expensive, relatively good signal

Translation:

Monitoring the translation of the robot is more difficult, the following sensors might be of interest:

- Accelerometers: cheap, bad signal, gives only indication about acceleration
- Lateral sharp: same as for altitude, can make wall following/avoidance
- Laser scanner: expensive, heavy, would be of great interest however
- GPS: expensive, can be available in reasonable sizes/weights, “low” resolution

4.4.2 Motor control

A distinction has to be made between DC motors, which can simply be connected to a battery and brushless motors, which need a more sophisticated control, since each phase has to be driven correctly.

DC motors:
Controlling DC motors is usually done by sending a PWM (Pulse Width Modulation) signal from a microcontroller to a H-Bridge (device that amplifies this signal) and then directly to the motor.

Brushless motors:
Brushless motors have three phases. In order to drive them correctly two solutions are possible. Use commercially available modules or build one.

4.4.3 Batteries

The best kind of batteries that can be considered for this kind of project are Lithium Polymers. Their power density is around 180Wh/kg (five to ten times less for NiCd). Then several parameters are free, the autonomy, which is usually related to the weight. The maximal discharge current. And how many batteries will be in series. Indeed these modules are available in single 3.7 volt cells, in 2 times 3.7 volts or 3 cells.
One has to keep in mind that the main motor can take voltages up to 15 volts, however most sensors and processors use standard 5 volt. If several LiPo cells are used a voltage conversion will have to be performed, this operation is quite effective, however heavy components are required.
Two LiPo modules were attractive for this project. Kok 910 H from Westechnik [14] that weights 70g and the ePowerSuperPack 450mAh from Eflight [15].
Using the 910 mAh pack would lead to a global weight of around 270g, in this case a powerful motor needs to be used.
Using the 450 mAh pack would lead to a global weight of around 235g, and even less since weight could be gained by using a lighter motor.

4.4.4 Communication

Two kind of communication protocols are considered. Bluetooth or a standard remote control. Table 2 summarizes the advantages and disadvantages of each solution.

	Bluetooth	**Standard remote control**
Advantages	User interface	Easy
	Light	Available
	Reading of sensors	Light
		Long range
Disadvantages	Expensive	Not instinctive
	"New" in lab	No information about sensors
	Hard to find	
	Short range	

Table 2: communication systems, pros and cons

4.4.5 Microprocessor

Processing data, sending and receiving information and driving motors requires microprocessors. ASL mostly uses PIC microcontroller, thus not much is to be chosen here. However it is believed that having one processor dedicated for each task would be a good thing. The three tasks are: Bluetooth communication, sensor reading, motor control. When several processors are used a standard communication protocol such as I2C allows to exchange information between the different microprocessors.

5 Theory

5.1 Propeller

Going into the details of how a propeller works is not the purpose of this report. For a small introduction refer to: “Short Fly Module for Alice Robot” [23] which is available on the ASL’s website.

5.1.1 Thrust and drag

A propeller can be viewed as a force: “lift” plus a moment: “drag.” Finite Element Modeling or complicated calculations are to be used to find these forces. However a simple model gives quite a good approximation when used around a given working point. Equation 5.1 and Equation 5.2 can be used to find the wanted forces.

$$Lift = b \cdot \omega^2 \tag{5.1}$$

$$Drag = d \cdot \omega^2 \tag{5.2}$$

Where:
Lift: lift force [N]
Drag: drag moment [Nm]
b: lift coefficient [Ns^2]
d: drag coefficient [Nms^2]
ω: angular velocity of the propeller [rad/s]

<u>Getting the coefficients:</u>
Computing b and d is done by using the test bench depicted on Figure 36. One simply has to measure the current, the rotational speed of the propeller and the generated lift. Then some simple math allows computing the wanted coefficients.

5.1.2 Wind speed

When working with elements such as flaps or Magnus cylinders knowing the wind speed is critical. Using Equation 5.3 [6] allows computing this magnitude with a certain precision.

$$V_{out} = 2 \cdot \sqrt{\frac{T}{2 \cdot \rho \cdot A}} \tag{5.3}$$

Where:
V_{out}: output velocity [m/s]
T: thrust [N]
ρ : air density [kg/m^3]
A: area created by rotating propeller [m^2]

5.1.3 Stability

Helicopters are naturally unstable. This is why special considerations were taken when designing the propellers. First three blades were used in order to have a symmetrical propeller inertia matrix. Second an angle of 5° of each blade allows gaining stability. Indeed the propeller acts as a pendulum. Observe its behavior in Figure 23. On the left side the propeller is in its natural state, the lift forces are arranged symmetrically. However if the helicopter tilts to the right then the vertical lift force increases on the right side which will bring the robot back to its natural state.

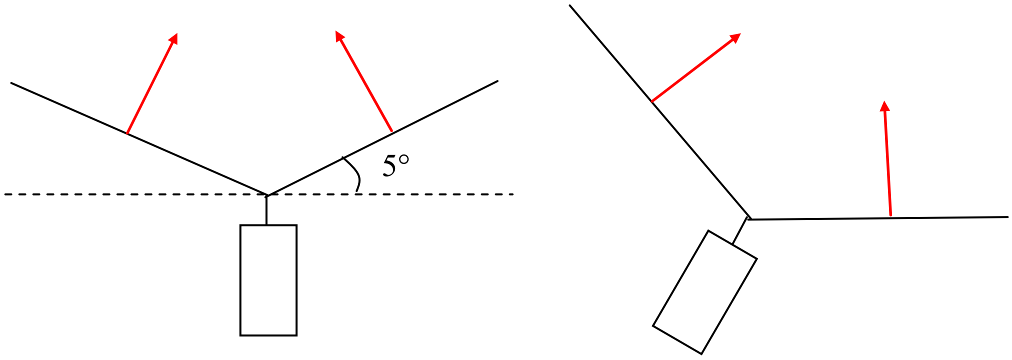


Figure 23: V shaped propeller => increased stability

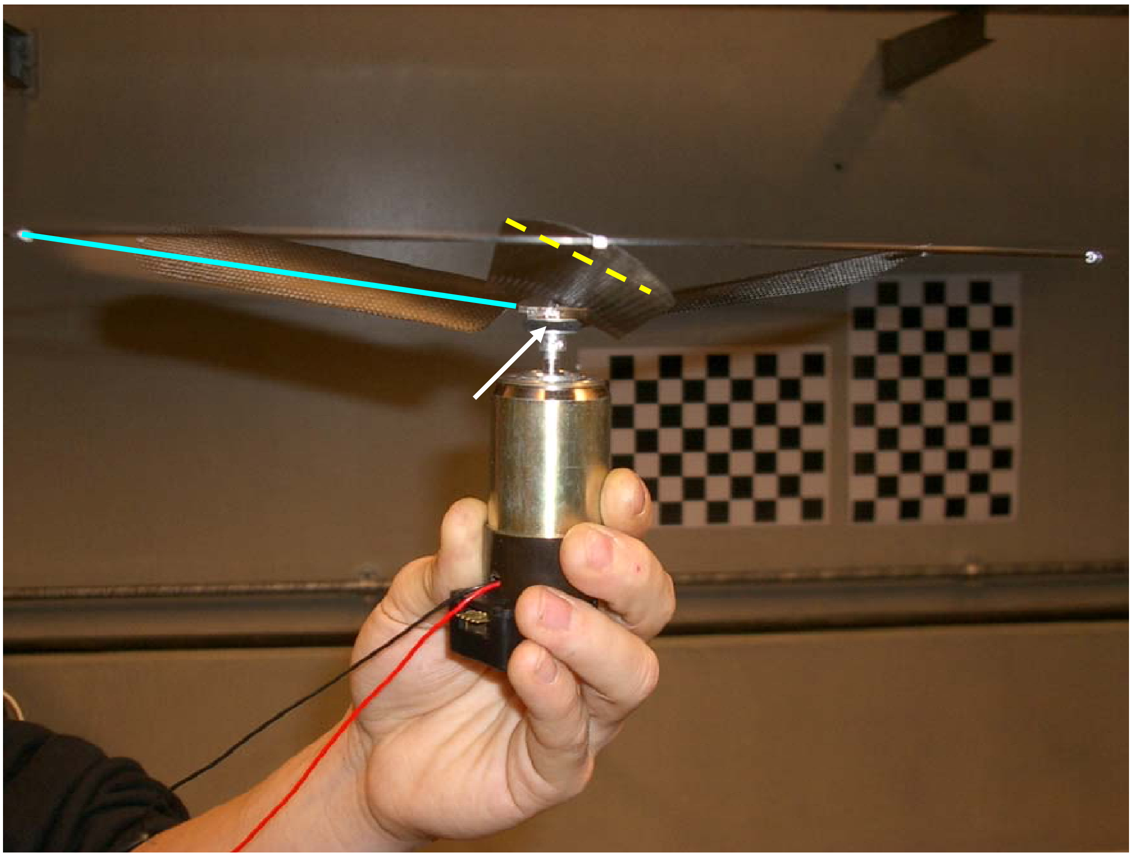


Figure 24: dashed line 15°, full line 5°, arrow: foam cushion

Third the overall design of proxyflyer [1] was studied and adapted to a three blade propeller. This leads to the following design: each blade has a given angle of attack (the provided blades were tuned for an angle of attack of 15°, Figure 24) that can freely move by 1 or 2 degrees. Each blade can move in a vertical plane by ± 10°. And the blades are connected to each other by a tiny ring. This ring has three main goals: maintain a connection between the blades, allow a synchronized up and down motion of the blades as well as a synchronized change of the angle of attack. Finally a cushion of foam (Figure 24) is used to filter out vibrations and gives more flexibility to the system. Figure 24 and Figure 25 depict this novel propeller.

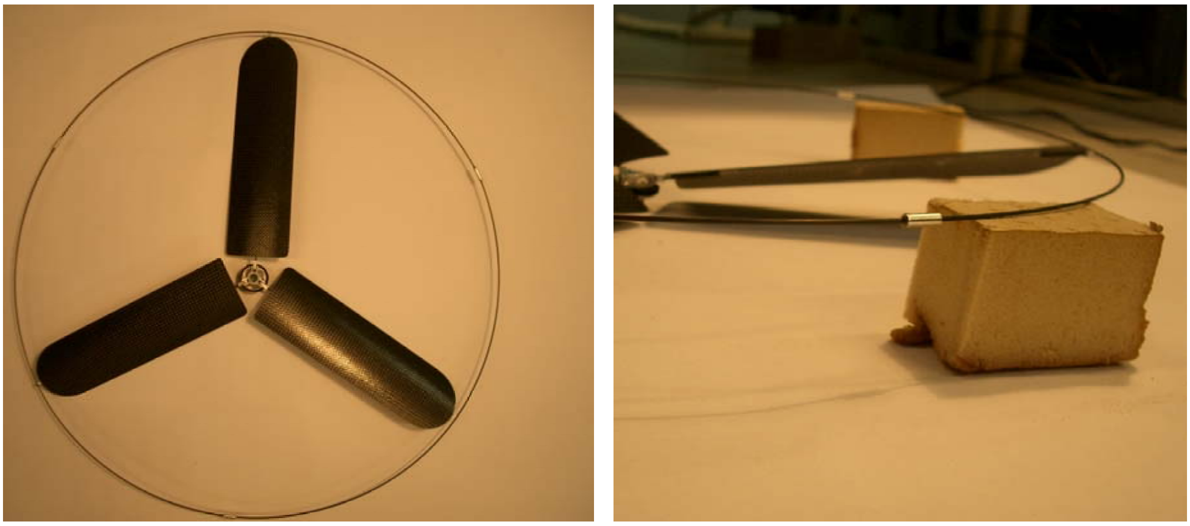


Figure 25: new propeller general and close up

5.2 Flap theory

The behavior of a flap is close to the one of a symmetrical wing. Again several models exist or Finite Element Modeling can be done. There is also free a software (foilsim [16]) available to illustrate this phenomenon. Again as for the propeller two important equations exist, one to give the lift (i.e. force perpendicular to the wind) and one to give the drag (force parallel to the wind).. Refer to Figure 26, Equation 5.4, Equation 5.5 and Equation 5.6

$$LiftCoef = 2 \cdot \pi \cdot \alpha \tag{5.4}$$ [5]

$$Lift = \frac{1}{2} \cdot LiftCoef \cdot \rho \cdot v^2 \cdot A \tag{5.5}$$

$$Drag = \frac{Lift}{5} \tag{5.6}$$

Where:
LiftCoef: lift coefficient of the considered flap at a certain angle
Lift: lift force [N]
Drag: drag force [N]
α: angle of attack [rad]
ρ: density of air [kg/m^3]
v: wind speed [m/s]
A: area of the flap [m^3]

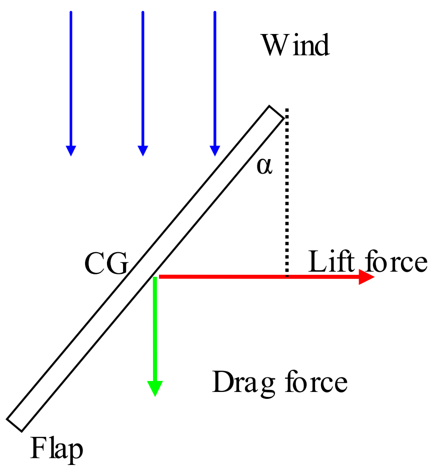


Figure 26: flap lift and drag force

Please note that computing the drag is more complicated thus a quite rough approximation has to be done.

[5] Please note that this equation is valid for small angles only.

5.3 Flaps calculations for the Coax case

In order to compare this system with the other possibilities (small propellers and Mangus cylinders) some rough calculations will be done. It will be assumed that in order to control the robot a yaw torque of 20 mNm has to be generated.

Using Equation 5.3 one can compute the wind speed for the given propellers and at 200 gram, its magnitude is of : 6.8 m/s.
Equation 5.5 shows that a flap of 10 by 10 cm tilted by 4.5° can generate a force of 66mN. Since 3 flaps are used and each flap is placed at about 10 cm of the helicopter's centre of gravity the resulting torque is 20mNm. If servo motors from Didel [13] or Falcon [19] were to be used these would work at 5V and consume in average 30mA each, or less. Thus the total consumption for the steering mechanism would be 150mW.

5.4 Magnus

In order to create lift one simply has to set a cylinder in rotation and place it into an airflow. As a result a depression is generated and eventually a force perpendicular to the wind will appear as illustrated on Figure 27.

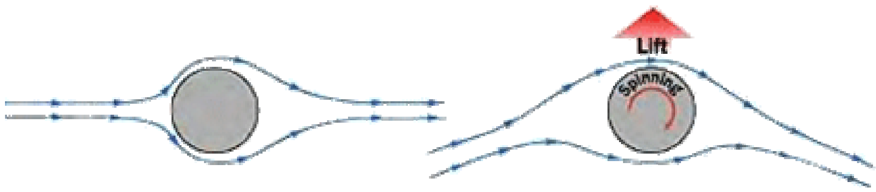


Figure 27: Magnus effect

To compute the magnitude there are two solutions, use the freely available software (foilsim [16]) or Equation 5.7.

$$Lift = 4 \cdot \pi^2 \cdot r^2 \cdot s \cdot v \cdot \rho \cdot l \qquad \textbf{(5.7)}$$

Where:
Lift: lift force [N]
r: radius of the cylinder [m]
s: rotational speed [rev/s]
v: wind speed [m/s]
ρ : density of air [kg/m^3]
l: length of the cylinder [m]

The Magnus effect is not wildly used in engineering. It was however employed at the beginning of the 20th on some ships, as can be seen on Figure 28.

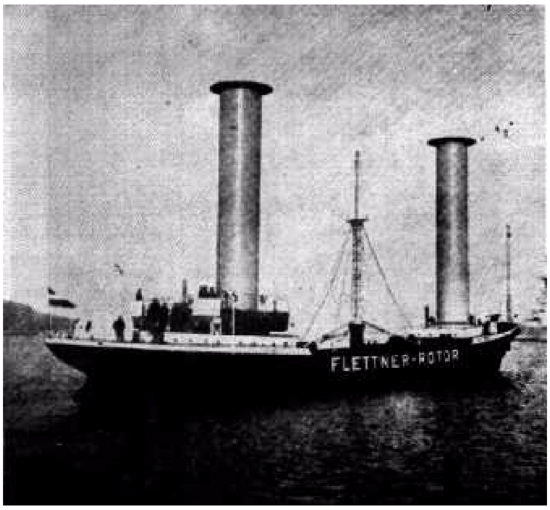


Figure 28: ship using Magnus cylinders instead of standard propellers

Or also to generate lift on some futuristic planes, refer to Figure 29.

Figure 29: airplane using Magnus cylinders instead of standard wings

This effect is wildly used in all sports involving balls. It allows the creation of curved trajectories by giving a rotational speed to the ball.

Interesting fact:

Figure 30: helicopter without tail rotor

Some helicopters without tail rotors (Figure 30) [17] use an effect that is very similar to Magnus. Instead of placing a cylinder in rotation they simply inject air with a certain velocity into the main airflow, which physically is the same as rotating a cylinder, please refer to Figure 31 for more clarity.
This effect is know as the Coanda effect [18], its principle is shown on Figure 32.

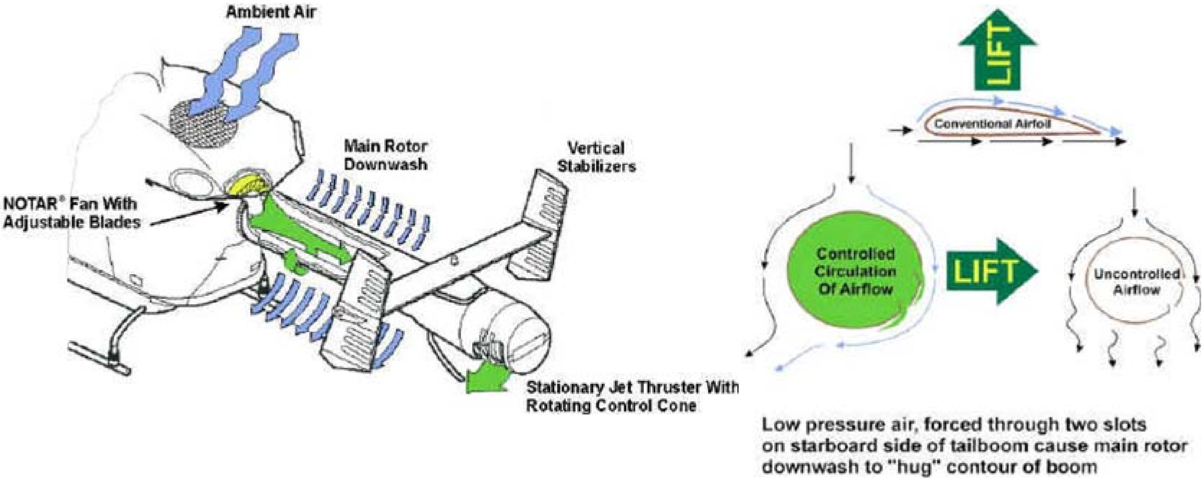


Figure 31: rotating cylinder replaced by pressurised air

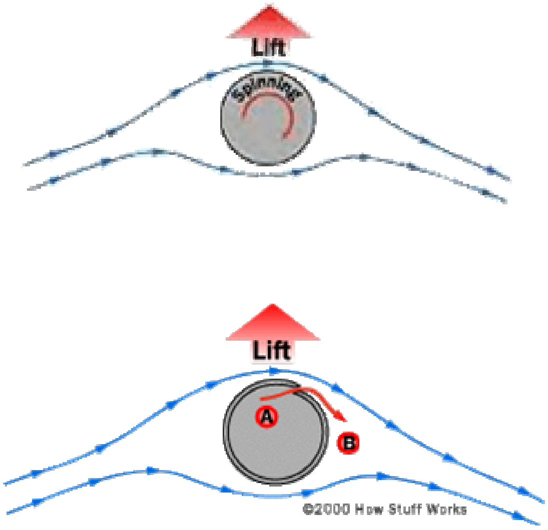


Figure 32: Coanda effect (bottom) vs Magnus effect (top)

5.5 Magnus calculations for the Coax case

In order to compare this system with the other possibilities (flaps and small lateral propellers) some rough calculations will be done. It will be assumed that in order to control the robot a yaw torque of 20 mNm has to be generated.

If a weight of 200g has to be lifted the needed airspeed is 6.8m/s (Equation 5.3).
Assuming that the cylinders have a radius of 2cm and a length of 10cm and that their centre of gravity is located at 10cm from the centre of the robot. Then each cylinder has to turn at 330rpm in order that the sum or their torques equals 20 mNm.

5.6 Small lateral propeller calculations for the Coax case

In order to compare this system with the other possibilities (flaps and Magnus cylinders) some rough calculations will be done. It will be assumed that in order to control the robot a yaw torque of 20 mNm has to be generated.

The mechanism sold by Didel is supposed to deliver 6 grams of thrust at 3.5 V 210 mA. Since these would be placed at about 25 cm of the robot's centre of gravity generating a torque of 20mNm would require a total power of 900mW.

6 Mechanical feasibility tests

As stated before the main goal of this project is to develop the mechanical part of a coaxial helicopter. For this reason most mechanical details will be tested in order to find the optimal solution. The second reason for this systematic testing is that calculations only give very approximative results for this kind of configurations (high Reynolds numbers, small parts, pulsed and turning airflows …).

6.1 Main motor and propellers

In this section two key elements will be determined. First what propellers have to be used second what motor. In order to answer these two questions there is almost no other choice but to test. Indeed the behavior of a coaxial configuration is hard to characterize. Thus first simple tests were done with two propellers, in order to find out what would happen. Second several different propellers were tested on different motors in order to find out what motor would have to be chosen.

6.1.1 1 vs 2 propellers

The purpose of the following test is to find out the behavior of a coaxial configuration. Will the lift force be twice the one if only one propeller was to be used or will it be smaller? Here one will also investigate if the distance between the two propellers is influencing the lift.

The test structure is depicted on Figure 33. Two commercially available propellers were used. The motor is a Faulhaber 1724 and the reduction ratio is 4:1. In order to avoid the ground effects the airflow was oriented upwards. The distance between the two rotors was also changed to find if there was an optimum. The results can be observed in Table 3 for one propeller, Table 4 and Graph 1 for two propellers.

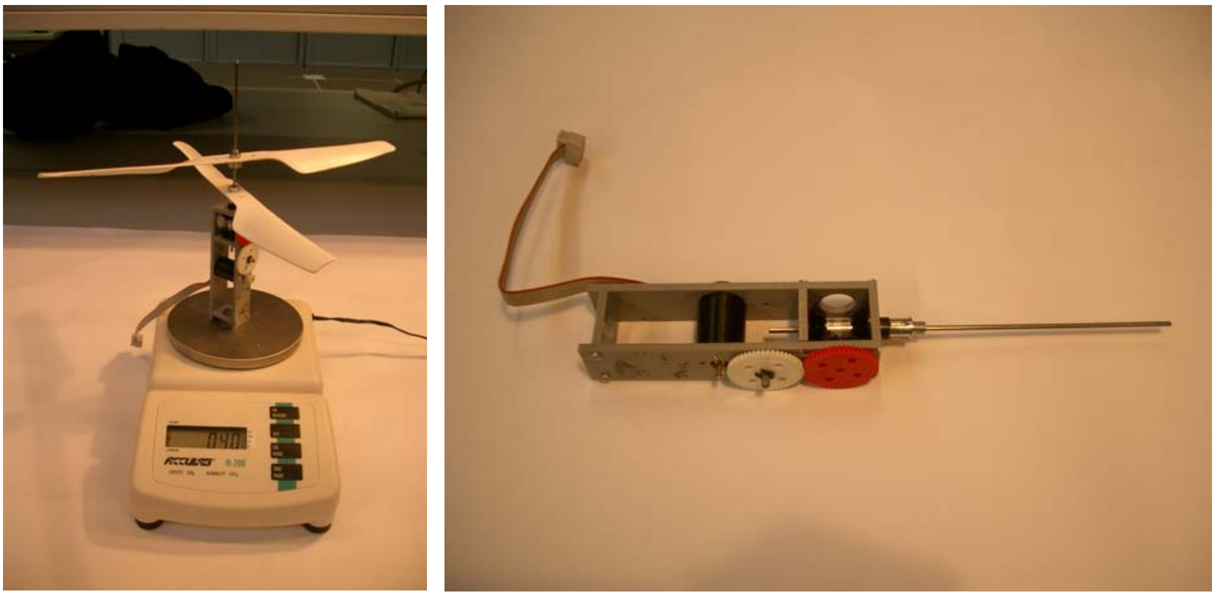


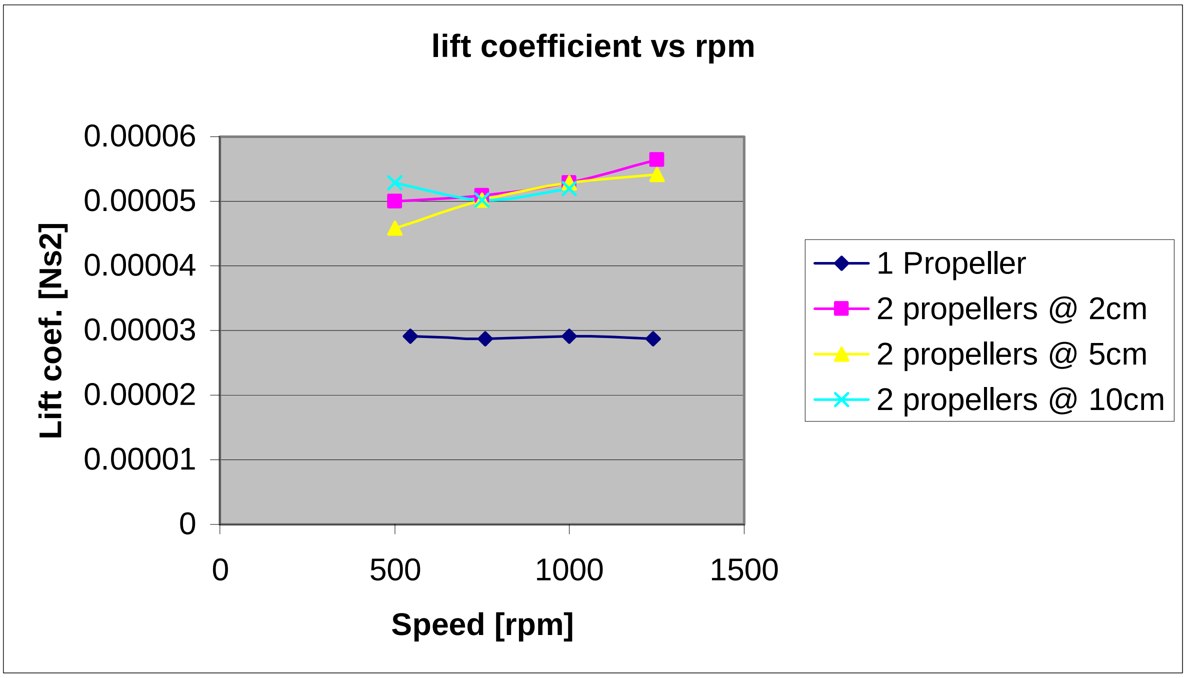
Figure 33: coax test structure general and close up

rpm	thrust	voltage	current	lift coef.	drag coef.	Elec power
	[g]	[V]	[A]	[Ns^2]	[Nms^2]	[W]
545	9.8	1.1	0.37	2.91E-05	1.29E-06	0.40
760	18.8	1.6	0.59	2.87E-05	1.06E-06	0.94
1000	33.0	2.3	0.91	2.91E-05	9.43E-07	2.09
1240	50.0	3.0	1.27	2.87E-05	8.56E-07	3.81

Table 3: 1 white propeller

rpm	thrust	voltage	current	distance	lift coef.	drag coef.	Elec power
	[g]	[V]	[A]	[cm]	[Ns^2]	[Nms^2]	[W]
500	14	1.2	0.55	2	4.94E-05	2.28E-06	0.66
750	32	2.0	1.02	2	5.09E-05	1.88E-06	2.04
1000	60	3.1	1.70	2	5.29E-05	1.76E-06	5.27
1250	100	5.0	2.68	2	5.64E-05	1.78E-06	13.41
500	13	1.2	0.52	5	4.58E-05	2.16E-06	0.62
750	32	2.1	1.05	5	5.02E-05	1.93E-06	2.20
1000	60	3.2	1.73	5	5.29E-05	1.79E-06	5.53
1250	96	4.7	2.68	5	5.42E-05	1.78E-06	12.59
500	15	1.2	0.56	10	5.29E-05	2.32E-06	0.67
750	32	2.0	1.02	10	5.02E-05	1.88E-06	2.04
1000	59	3.0	1.60	10	5.02E-05	1.66E-06	4.80

Table 4: 2 propellers



Graph 1: 1 vs 2 propellers, distance between propellers

One can observe in Graph 1 that the distance between the two propellers has only a small impact on the lift coefficient. One can also see that the lift provided by the second propeller corresponds to roughly 70% of the first propeller, in other words the lift coefficient of two propellers equals 1.7 times the lift coefficient of one propeller. This result is correlated by Felipe Bohorquez “Design, Analysis and Performance of a Rotary Wind MAV” [5]. Also due to heavy vibrations tests with 10cm between the two propellers had to be stopped at 1000rpm. Please note that lifting 100g with this DC motor is impossible. Indeed after only 15 seconds of operations the motor was already warm, and after 30 seconds it would stop working.

6.1.2 Custom propeller

Now one has a good insight about how two propellers behave. The next step is to find out how the homemade propeller works. Unfortunately at the time of the tests only one propeller was available. To test it a Faulhaber 3357 motor was used in direct drive as depicted in Figure 34.

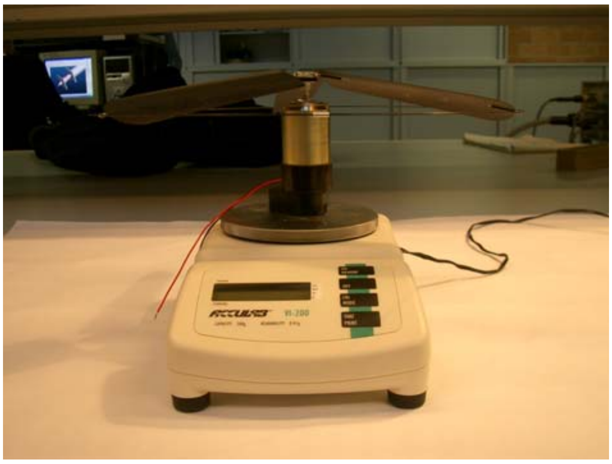
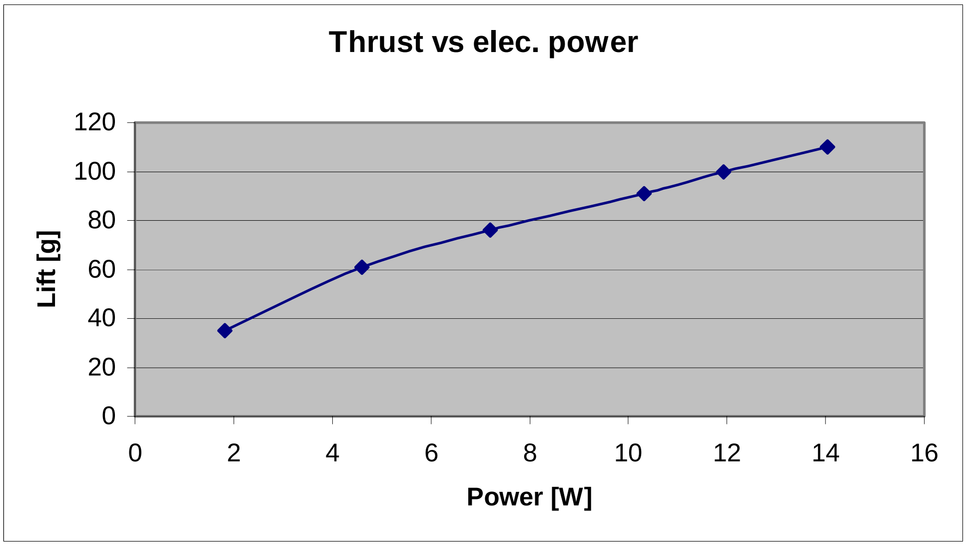


Figure 34: custom propeller with motor

Votage	Current	rpm	Thrust	Lift coef.	Drag coef.	Elec power
[V]	[A]	rpm	[g]	[Ns^2]	[Nms^2]	[W]
5.04	0.36	640	35	7.65E-05	3.27E-06	1.81
7.42	0.62	853	61	7.50E-05	3.17E-06	4.60
9.00	0.80	976	76	7.13E-05	3.12E-06	7.20
10.42	0.99	1083	91	6.94E-05	3.14E-06	10.31
11.15	1.07	1106	100	7.31E-05	3.25E-06	11.93
12.00	1.17	1166	110	7.24E-05	3.20E-06	14.04

Table 5: results for the custom propeller



Graph 2: lift vs electrical power for custom propeller

Additional tests were made with a simple optimized propeller that uses the same blades as the custom propeller (Figure 35). These tests pointed out that the lift coefficient of the custom propeller was 1.4 times higher than the lift coefficient of the standard propeller. And its drag coefficient was 1.8 times higher than the one of the standard propeller. This dissymmetrical evolution comes from the fact that 3 blades are less effective than two [13]. Furthermore as explained in section 5.1.3 this propeller was built to be auto-stable, thus a decrease of the lift/drag ratio is natural and acceptable.

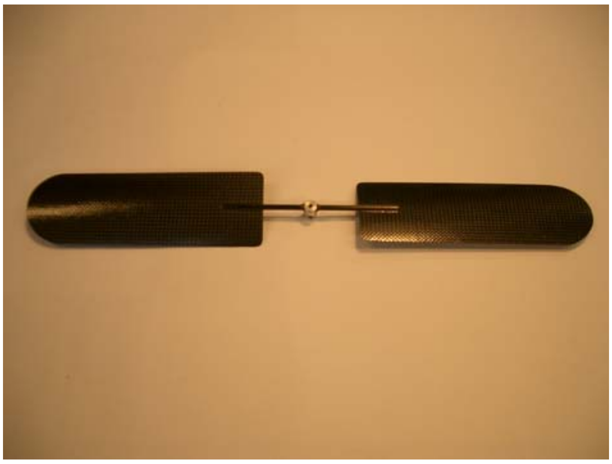


Figure 35: two blade propeller

6.1.3 Selecting motor

Choosing the right motor is vital four this application. As stated earlier DC motors were tested at the beginning but it was pointed out that in this case they were not interesting. Indeed Faulhaber 1724 motor was unable to lift 100g for more than 10 seconds. Two candidates are in competition for the final design, the Typhoon 05-3D (33g, up to 40W electrical power) and the LRK 195.03 (11g, up to 35W electrical power).
The two competitors were mounted on the test bench depicted on Figure 36, with a 4:1 reduction stage.

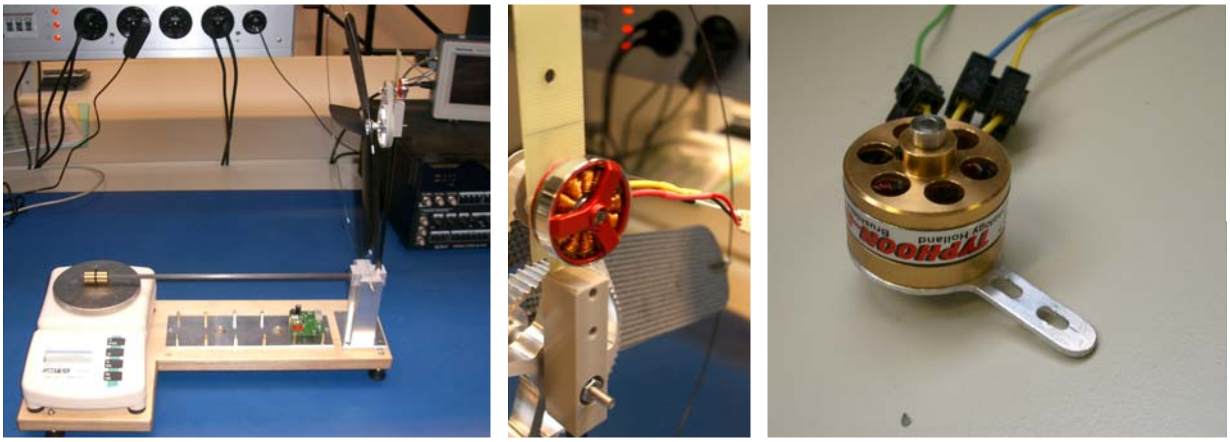


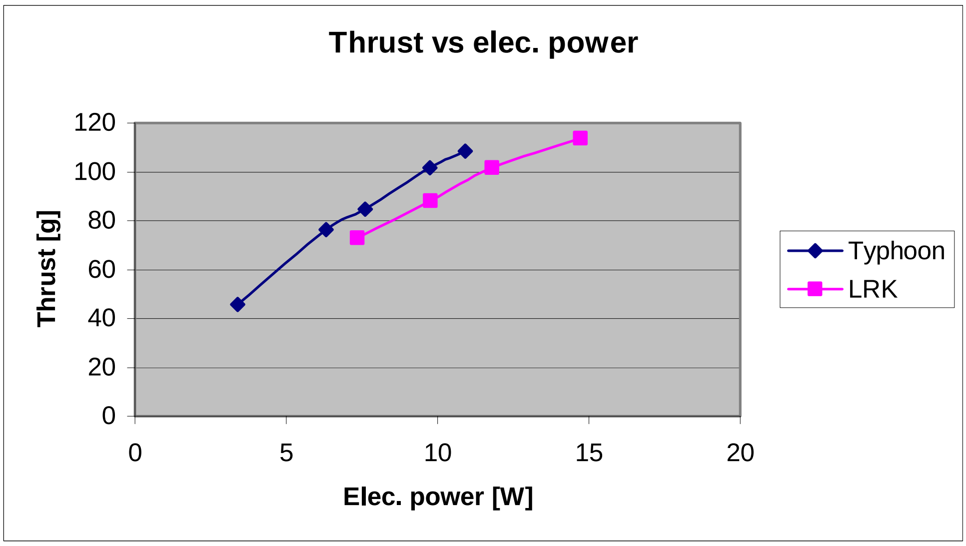
Figure 36: new test bench, LRK close up, typhoon close up

Voltage	Current	Thrust	Speed	Elec power
[V]	[A]	[g]	[rpm]	[W]
3.9	0.87	45.79	833.33	3.39
4.9	1.29	76.32	1066.67	6.32
5.2	1.45	84.80	1116.67	7.61
5.8	1.68	101.76	1216.67	9.74
6.1	1.79	108.54	1260.00	10.91

Table 6: custom propeller and Typhoon

Voltage	Current	Thrust	Speed	Elec power
[V]	[A]	[g]	[rpm]	[W]
4.3	1.70	72.93	1025.33	7.344
4.8	2.00	88.19	1133.33	9.76
5.3	2.20	101.76	1216.67	11.79
5.8	2.50	113.63	1266.67	14.72

Table 7: custom propeller and LRK



Graph 3: thrust vs electrical power for Typhoon and LRK

In order to decide which propulsion group to choose the following cost function is used.

$$Cost = \frac{Power}{Thrust - m_m} \tag{6.1}$$

Where:
Power: electrical power for a given thrust [W]
Thrust: thrust generated if the above power is used [g]
m_m: mass of the motor/reductor unit.

Table 8 summarizes the results for both motors.

	Power	Thrust	Mm	Cost
	[W]	[g]	[g]	[W/g]
LRK	11.7	101	32	**0.17**
Typhoon	9.7	101	52	**0.20**

Table 8: cost function applied to LRK and Typhoon

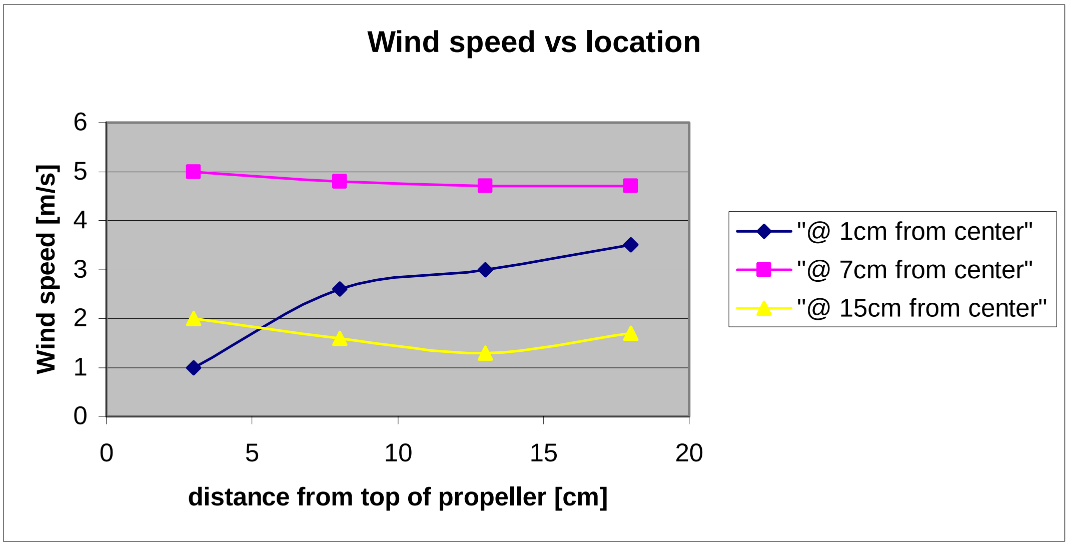
In the case of the LRK the cost to lift one gram is lower, thus this motor should be selected. However the maximal power of the LRK is limited, this has also to be taken into consideration when selecting the motor.

Later a more sophisticated cost function was developed as well as a quality function. Unfortunately the only custom propeller broke and the needed measurements could not be performed. Since only two motors were left in competition it was decided that the mechanical structure of the robot would be designed so that both motors are compatible.

6.1.4 Wind measurements

In order to have a better idea of what is going on under the propellers tests were done with an anemometer. The device as well as the setup can be observed in Figure 37. Results can be found on Graph 4. Please note that at the time the measurements were made only commercially available propellers, as depicted on Figure 37, were available, if possible new tests will be done with two custom propellers.

Figure 37: anemometer and wind speed test bench



Graph 4: wind speed vs location

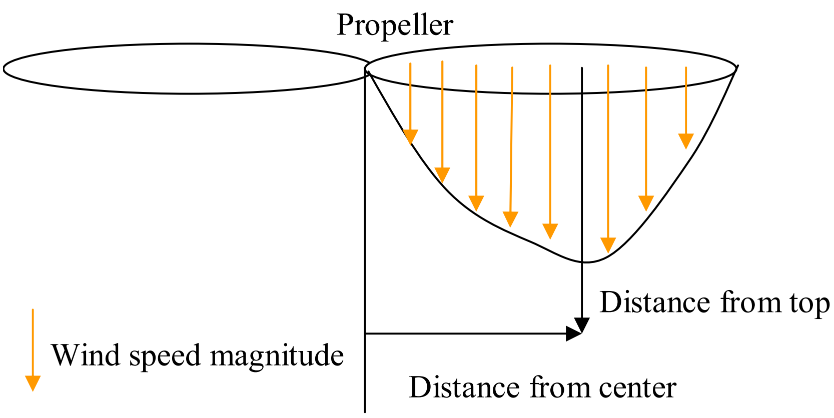


Figure 38: reference distances and wind speed magnitude distribution for white propellers

As expected the wind speed is maximal in the thrust area of the propeller. When located under the thrust area the wind speed is constant even for distances up to 20 from the propeller. Also the magnitude is consistent with the result given by Equation 5.3.
What this graph is not showing is that there is also a horizontal component of the wind, which makes the control even more difficult, its magnitude is about one fifth of the vertical velocity.
A recent report [5] deals with the complexity of the physics associated to the airflow created by propellers. Figure 39 depicts the airflow generated by a rotating propeller.

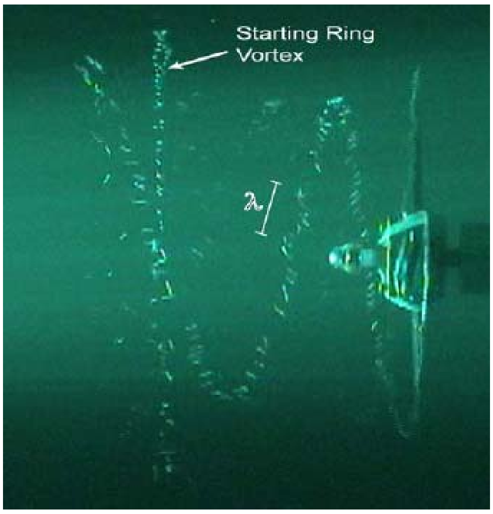


Figure 39: airflow generated by a rotating propeller

6.2 Lateral motor with propeller

Small lateral motors with propellers as shown on Figure 40 could be used to ensure yaw control and translation of the helicopter. In order to make sure that these devices work as told by the manufacturer they were mounted on the test bench as shown in Figure 40. Note that there is not much technical data available for this motor; the used reduction has a 25:1 ratio.

Table 9 and Graph 5 show the measured results for a symmetrical propeller (i.e. that can turn in both directions with the same efficiency). The manufacturer predicts a thrust of 6g at 3.5V 210mA (4R25-2 reductor from Didel [13] and MK04S-10 motor also from Didel). With the symmetrical propeller a thrust of 4g is achieved under the same power conditions. Further tests could be done with an optimized propeller.

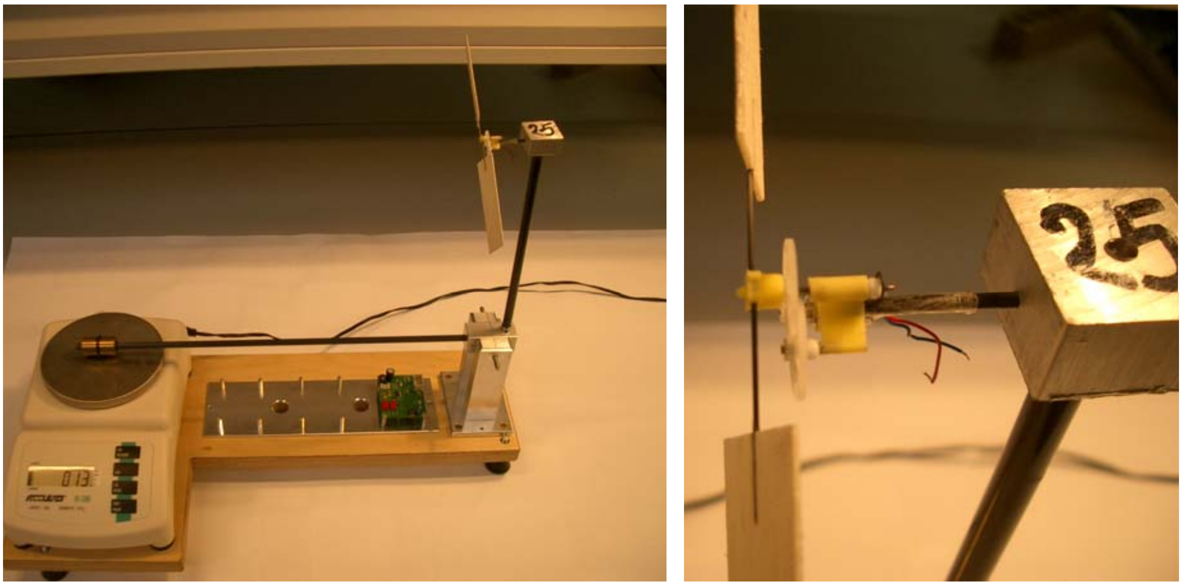
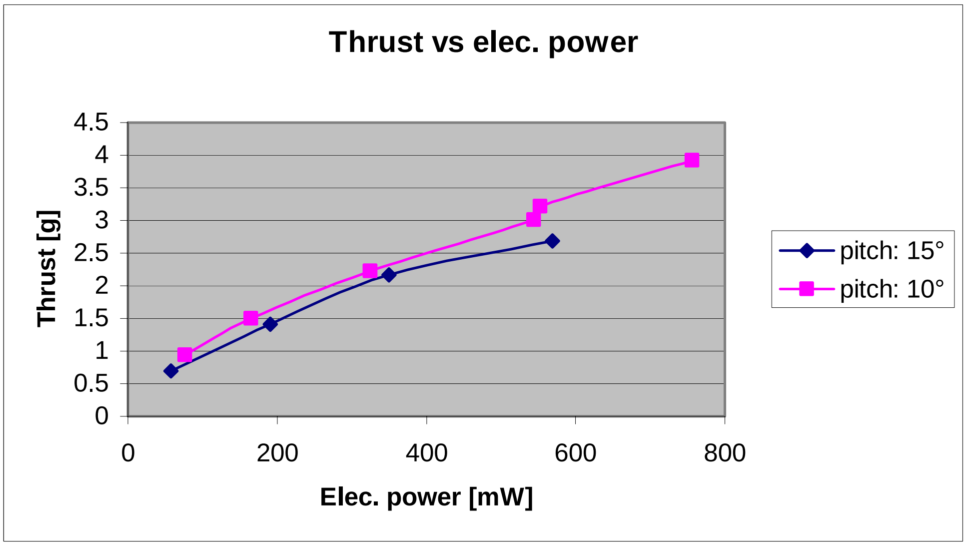


Figure 40: small propeller test bench and close up

Pitch	Votage	Current	rpm	Thrust	Lift coef.	Power
[°]	[V]	[A]	rpm	[g]	[Ns^2]	[mW]
15	1.0	0.05	440	0.70	3.5E-06	57.2
15	1.8	0.10	650	1.41	3.3E-06	191.1
15	2.5	0.14	770	2.17	3.6E-06	350.0
15	3.1	0.18	875	2.68	3.4E-06	568.8
10	1.2	0.06	650	0.93	2.2E-06	76.8
10	1.8	0.09	850	1.49	2.0E-06	164.7
10	2.5	0.13	1010	2.22	2.1E-06	325.0
10	3.2	0.17	1150	3.01	2.2E-06	544.0
10	3.2	0.17	1185	3.22	2.2E-06	552.5
10	3.6	0.21	1300	3.92	2.3E-06	756.0

Table 9: small motor and small propeller



Graph 5: thrust vs electrical power

6.3 Flap

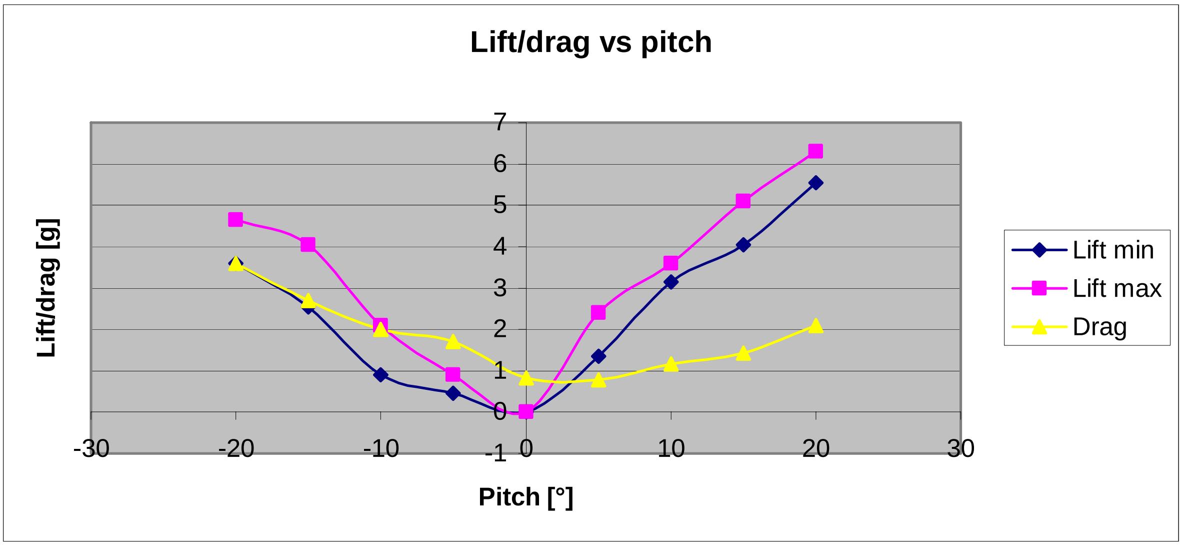
Testing the flaps was done on the same test bench as for the motors, please refer to Figure 41. Two white propellers were used and the thrust was set to about 100g. The flap was then placed as close as possible to the motor and in the effective area. The size of the flap was 10 by 10 cm. Furthermore two series of tests were performed, once the propeller was blowing from the top and once from the side, this allowed to measure once the lift force and once the drag force.

Figure 41: flap test bench, blow from top => lift (left side), blow from side => drag (right side)

The results can be found in Table 10 and Graph 6. Note that the measurements were really noisy, thus a maximal and minimal value was measured for the lift. Also due to the fact that there is also a certain amount of lateral wind the lift force is not symmetrical (i.e. +10° will give a different lift than -10°). When comparing theses measurements with the calculations a difference of roughly 8 to 10 times is observed. This must come from the fact that the airflow under the propellers is highly turbulent, pulsed and maybe also because the used equation are not valid at such small scales.

pitch [°]	-20	-15	-10	-5	0	5	10	15	20
air speed [m/s]	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
lift min [g]	3.6	2.5	0.9	0.4	0.0	1.3	3.1	4.0	5.5
lift max [g]	4.6	4.0	2.1	0.9	0.0	2.4	3.6	5.1	6.3
drag [g]	3.6	2.7	1.9	1.7	0.8	0.7	1.1	1.4	2.1

Table 10: lift/drag vs pitch



Graph 6: lift/drag vs pitch

6.4 Magnus

Due to time constraints and a severe influenza; proper tests could not be performed in time for this report. If possible these tests will be done for the project presentation. There is no evidence that anybody ever steered a micro helicopter with Magnus cylinders, pushing the investigations into this directions would be very interesting.

7 Choices

In chapter 4 different solutions for each problem were presented. Then chapter 5 gave a theoretical approach. Followed by chapter 6 where practical tests were done. In chapter 7 it will be decided what solution is the best for the Coax.

7.1 Main motor and altitude control system

7.1.1 Main motor

First DC motors were eliminated, for a given power they are much heavier that brushless motors. It was decided that only one motor would be used, because brushless motors as well as their controllers are expensive. Furthermore it is more interesting from an energetic point of view to have one big motor rather than two small. However this solution doesn't allow to compensate completely for parasitic yaw rotation.

Since the overall weight of the robot was set to about 250 grams using the LRK 195.03 was not possible. Table 4 gives the general behavior if two propellers are used. Then using the fact that 2 propellers only generate the lift of 1.7 times one propeller (if rotating at the same speed) and using the values from Table 5 (custom propeller). One finds that more than 4 A would be needed to lift the helicopter causing the destruction of the LRK motor. Thus the Typhoon 05-3D has to be used, even though the cost function (section 6.1.3) would have recommended to use the LRK.

7.1.2 Inverter

Since only one motor is used an inverter is needed. Using belts was the first solution to vanish because of its complexity and low efficiency. Using several flat gears instead of the belts was then excluded for the same reasons.
This only left the best alternative: the differential like inverter. That can be observed on Figure 42.

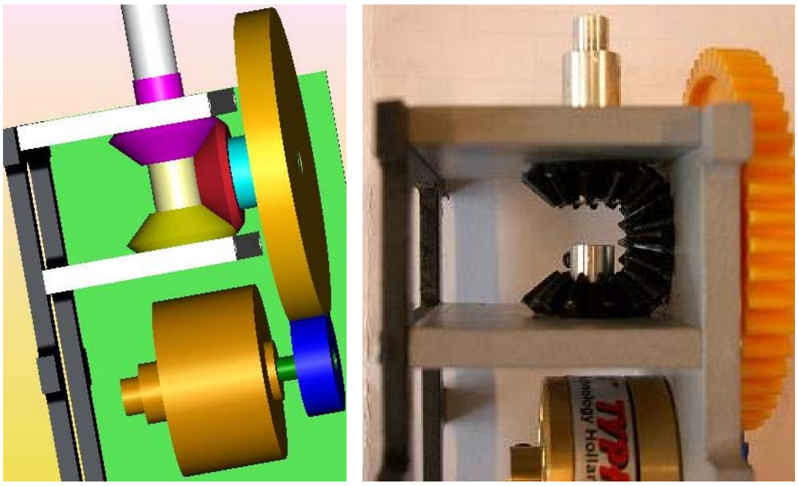


Figure 42: inverter, ProE model and real

7.1.3 Main propeller

There was not much to choose for the main propeller. Since auto stability was wanted the proxflyer [1] design was adapted to a 3 blade propeller.

7.2 Yaw and translation control system

Table summarizing the flaps

Advantages	Disadvantages
Lightweight	Non linear behaviour
Low Consumption	Complex
Quiet	Vibrations
Compact	Drag dissymetry
Increase drag on yaw axis	

Table 11: flaps pros and cons

Table summarizing the small lateral propellers

Advantages	Disadvantages
Lightweight	Not compact
Increase drag on yaw axis	Average/high consumption
Easy control	
Linear	
No vibrations	

Table 12: lateral propellers pros and cons

Table summarizing the Magnus cylinders

Advantages	Disadvantages
Simple control	Not trivial to build
High lift	Average consumption
Linear	High consumption
Less drag	Vibrations
Innovative	

Table 13: Magnus cylinders pros and cons

Tests showed that using only flaps was feasible but would create a great amount of vibrations. Furthermore small servo motors are hard to find and expensive. Indeed the ones from Didel [13] are no longer available. Finally controlling servo motors is not done by the same signals as for DC motors. Table 11 summarizes the results for the flaps.
This left the small lateral propellers (Table 12) and the Magnus cylinders (Table 13). After a heavy brainstorming it was decided that both solutions would be implemented. This is easily feasible from a mechanical point of view, one simply has to “unplug” one system and replace it by the other. And from an electrical and electronic point of view there is no major problem since both alternatives use DC motors with have roughly the same characteristics.

<u>How to cope with the yaw offset:</u>
Using two main propellers that rotate at the same speed will result in a non zero yaw torque. This is due to the fact that the airflow of the upper propeller is influencing the behavior of the lower propeller. In other words the helicopter will rotate. There are several ways to cope with this. One could try to tune the pitch of the blades. Doing this is extremely hard, indeed assembling the propellers is quite difficult and a slight dissymmetry results in high vibrations. One possibility would be to add fixed angle flaps that would take care of the non zero yaw torque in hover condition. This solution is depicted on Figure 63.

7.2.1 Lateral propellers

Three 4R25-02 gear reductions with MK04S-10 motors from Didel [13] are used as shown in Figure 43.

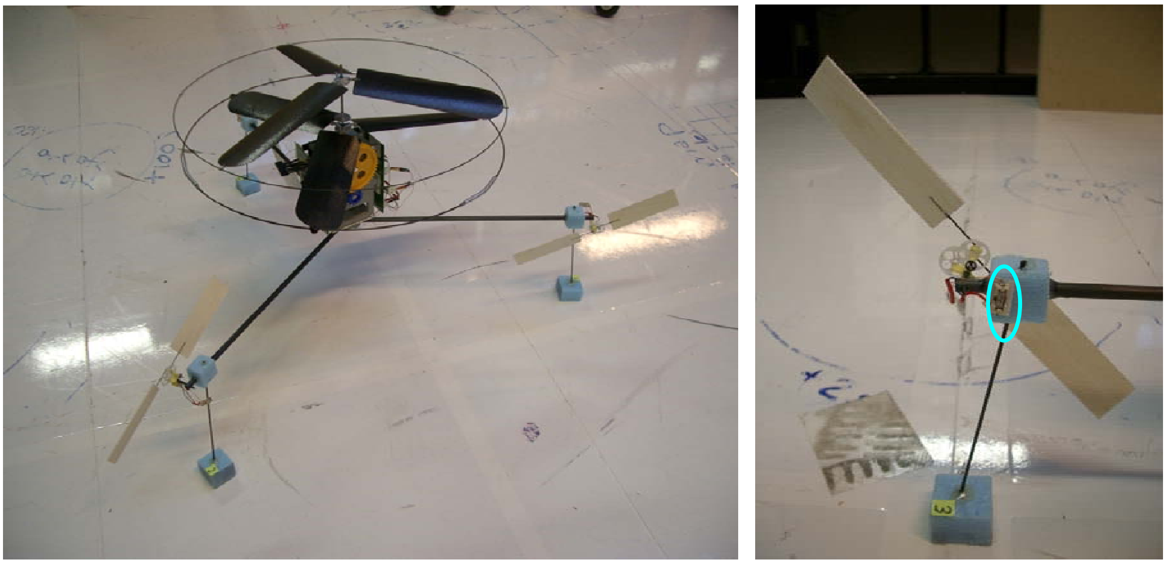


Figure 43: three lateral motors, and one lateral motor with fuse (circle)

Tests showed that these motors can deliver easily up to 4 grams of thrust. According to the manufacturer the use of an optimal propeller could increase this thrust by 2 grams.
If each motor delivers 4 grams of thrust and is placed at 25 cm then the yaw torque is of 15 mNm, which is enough to steer the robot.
Note that changing from lateral propellers to Magnus cylinders can be done by unplugging this system and replacing in by the Magnus cylinders, refer to Figure 44.

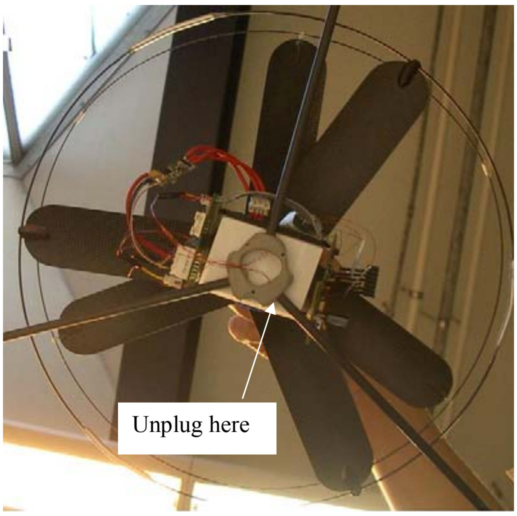


Figure 44: piece used to hold the three lateral tubes

7.2.2 Magnus

As stated in 6.4 there was not enough time to design a system using Magnus cylinders. However meetings with Mr. Guignard were done to discuss the feasibility. This propulsion system should be available in the month to come.

7.3 Mechanical structure

The main choice for the structure was the material (Table 1). It was decided that lightweight plastic would be used. Because it is easily available, can be shaped easily and screws can be used.

The purpose of the structure is to hold together the robot. There is a place for the main motor. A place for the PCB as well as for the sensors. Note that the distance sensor has to be placed at at least 15cm of the ground, the reason for this will be explained later. Of course lightweight legs are also present. Refer to Figure 45 and Figure 46 for more details.

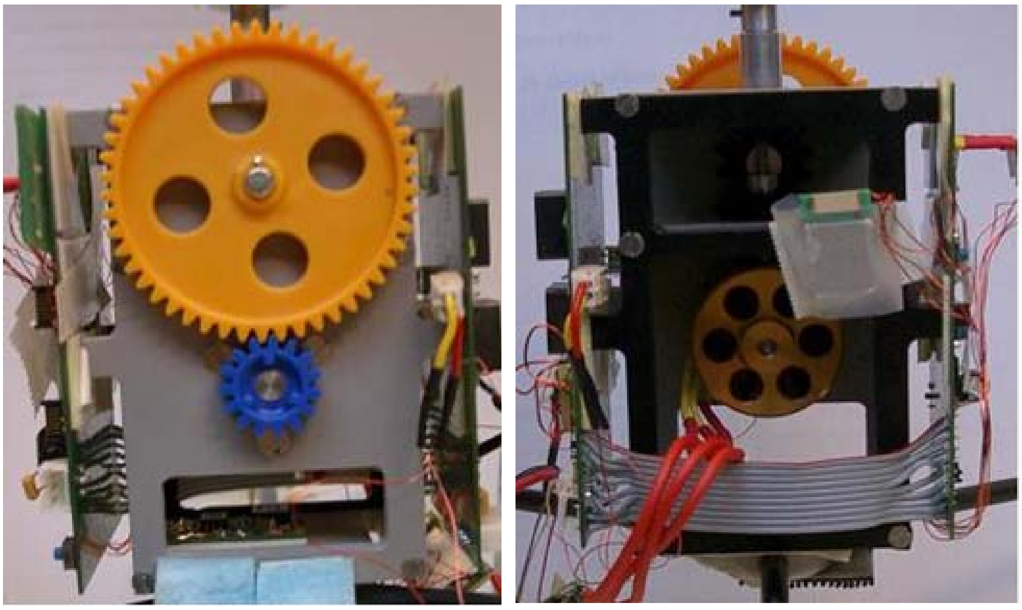


Figure 45: front and rear view

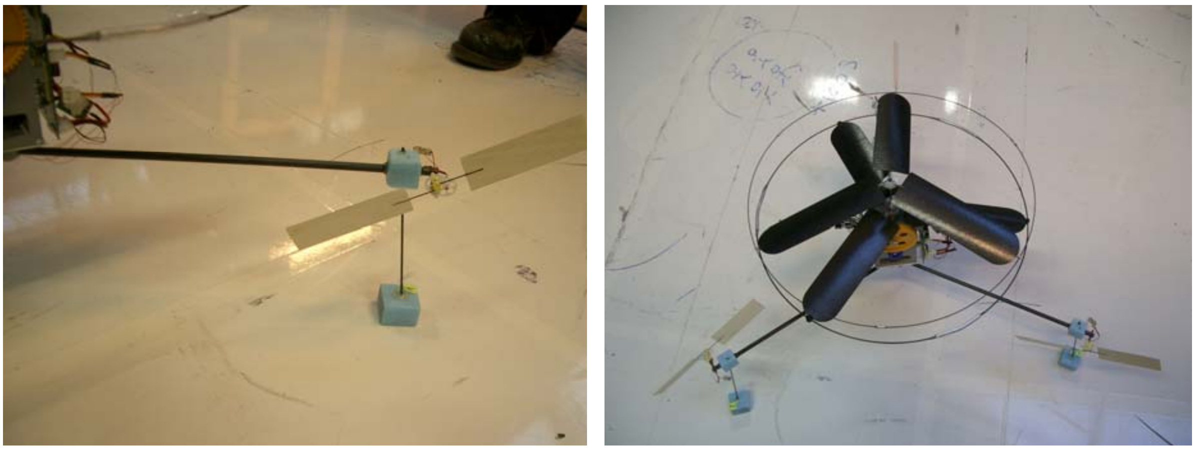


Figure 46: close up on one leg and general view of the Coax

7.4 Electronics

7.4.1 PIC network

As stated before a total of three PIC microprocessors will be used in this design. Figure 47 shows what kind of processor is used as well as the communication protocols.

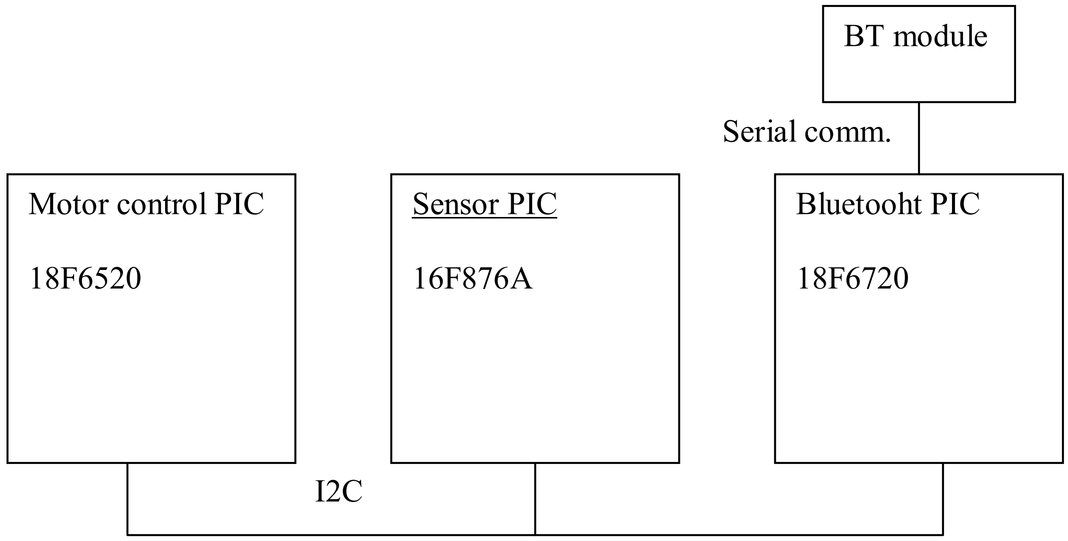


Figure 47: PIC network

7.4.2 Remote control

It was decided that even if Bluetooth communication was harder to implement, it was more intuitive and the possibility of reading back information from the robot was also very attractive. Figure 48 depicts the bloc diagram.

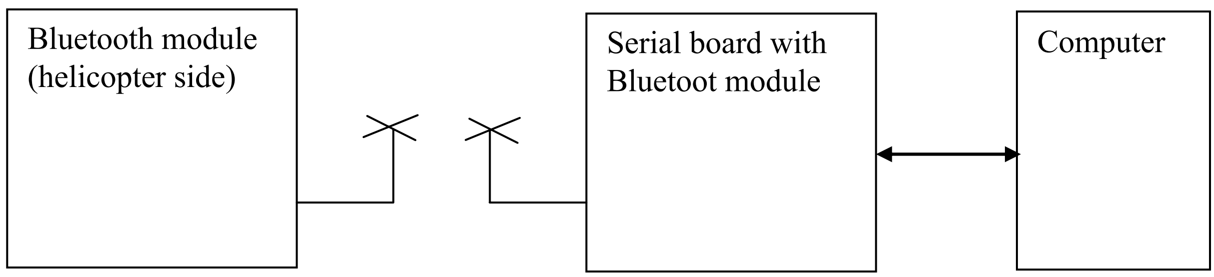


Figure 48: communication

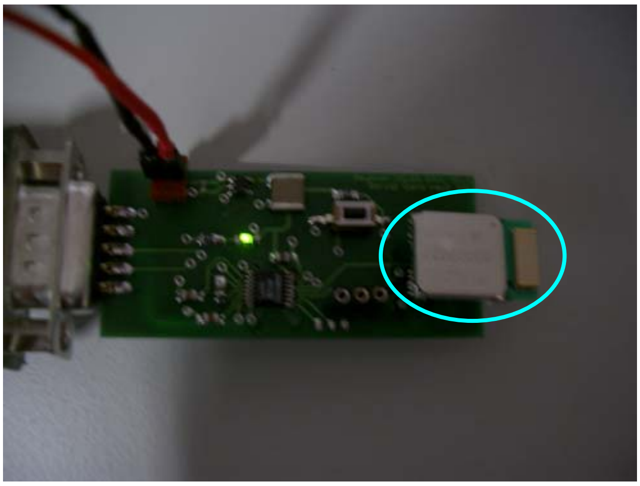


Figure 49: Bluetooth serial board and helicopter module

The Bluetooth module is a WML-C10-AH from Mitsumi. Note that two modules are needed, one on the robot and one on the PC serial card.

7.4.3 Sensors

Global overview of the sensors:
Please refer to Figure 50 for more information about the sensors.

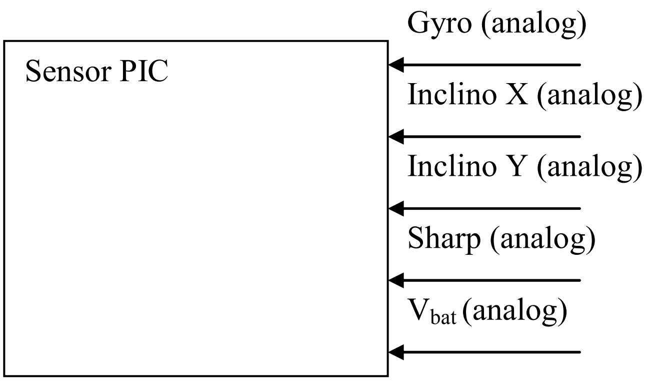


Figure 50: sensors

V_{bat} is simply the battery voltage; in order not to damage the PIC a voltage divider is required to lower the voltage from 11V to 5V. The other sensors are explained in detail in the following sections.

Yaw:
An ADXRS150 gyroscope from Analog Devices is used. First this device is small, consumes a minimal amount of current and was available in the lab. The following lines deal with electronic output characteristics. Figure 51 shows how this sensor's output behaves.

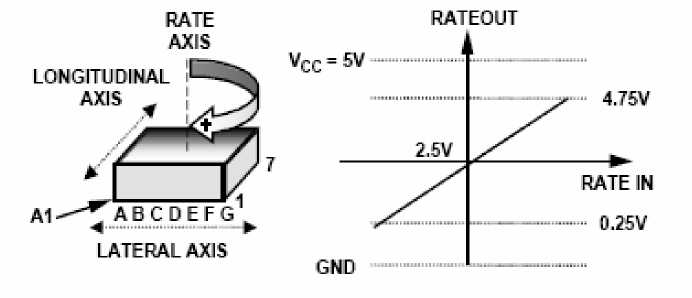


Figure 51: theoretical output of the gyroscope

The sensors sensitivity is 12.5mV/°/S, and the ADCs is 8bits on 5V. Thus every increment of the ADC represents a velocity of 1.52°/S. Furthermore at 0°/s the output is 2.5V or 127[6] dec. Thus to convert from a value read by the PIC to [°/s] Equation 7.1 can be used.

$$Velocity = (ADC\_value - 127) \cdot 1.52 \quad \textbf{(7.1)}$$

Where:
Velocity: angular velocity of the robot [°/s]
ADC_value: value returned by the ADC conversion

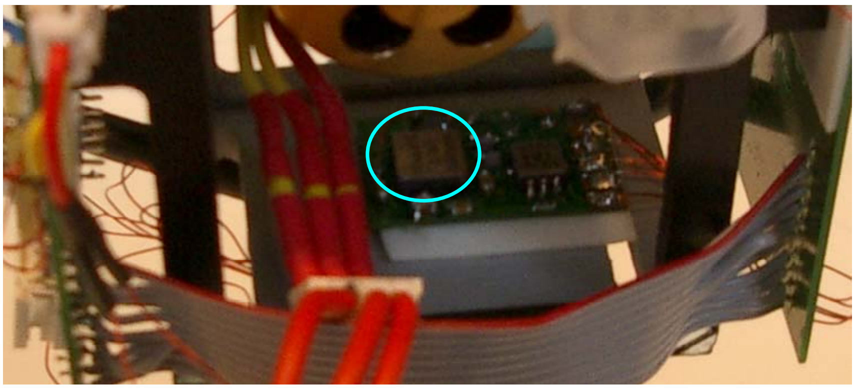


Figure 52: gyroscope (blue circle) and accelerometer located inside the Coax

The gyroscope is located at the center of the structure, as depicted on Figure 52, in order to have the best reading possible of the yaw.

Translation, inclination:

An ADXL311 dual axis inclinometer from Analog Devices was used. The robot is supposed to be stable in pitch and roll, furthermore the lateral accelerations should be small. The ADXL311 was available in the lab; this is why it was used. Otherwise no inclinometer would be present on the robot.

Its response is 167mV if a 90° rotation is performed. Using a 8 bit ADC (out of 5V) this means that a resolution of roughly 10° is achievable. This is of course not enough for this application. In order to be useable the signal should be amplified before being converted. However having an information on the robot's pitch or roll is almost useless since it is not used for the dynamic modelisation. It could however give indications on how well the stabilization works, or simply give the magnitude of the vibrations, which are extremely high on the Coax.

[6] This value has to be measured for each sensor, it can vary from 125 to 130.

Altitude:
An infrared distance sensor from Sharp was used. This device is light, easily connectable to a PIC and its signal is good enough for this application.
Figure 53 shows the analog output of the sensor for different distances.

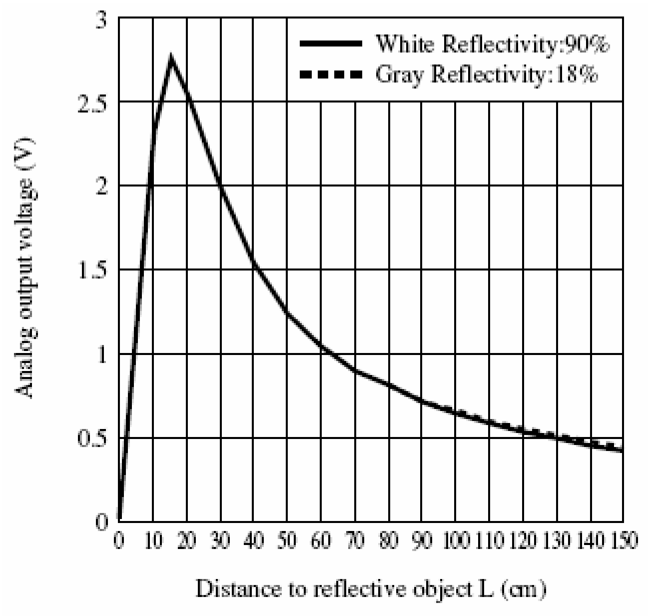


Figure 53: theoretical output of the Sharp distance sensor

One can see that the response is not linear, thus a look up table has been implemented on the PIC. Furthermore the analog output is the same for 10cm and 30cm. The best way to cope with this is to place the sensor so that it will NEVER be at less than 15cm of the ground. One can see on Figure 54 how the sensor is placed on the robot.

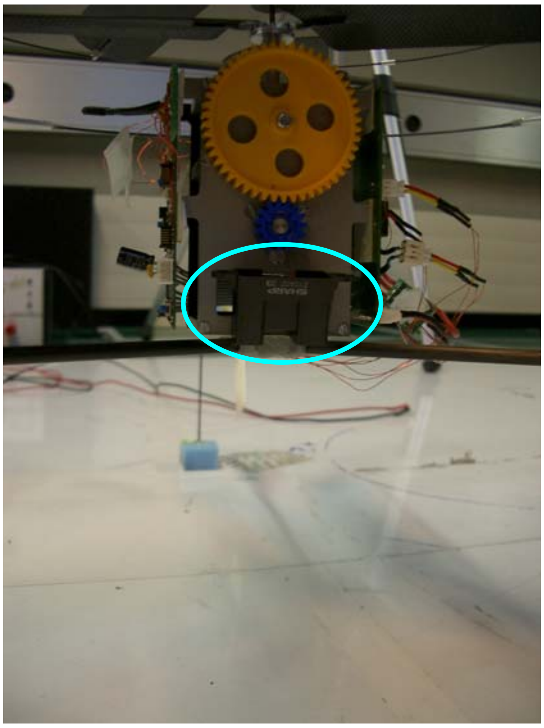


Figure 54: emplacement of the Sharp distance sensor

CoaX

7.4.4 Motor control

DC motors:

Controlling the three lateral DC motors is naturally done by commercially available H-bridges from Vishay (SI9986). The only disadvantage of these devices is that two PWM are needed to drive one motor, one PWM for each direction.

Brushless motors:

Controlling the main motor is done by using a commercially available controller. It is available at Westechnik [14] under the name YGE4-BL. Communication between the PIC and the Controller is done by using a standard PPM signal At the time this choice was made ASL was not yet able to build brushless controllers. At the end of this project a major breakthrough was done in this domain, further project will be able to take advantage of this.

Please refer to Figure 55 for more details.

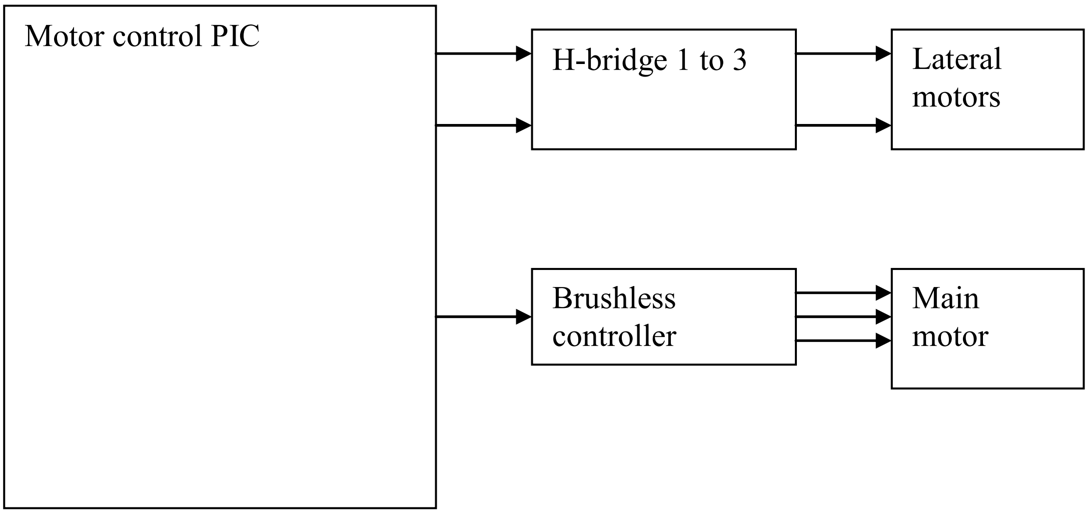


Figure 55: motor controller PIC

7.4.5 Batteries and power sources

Power sources:

Figure 56 shows how the power is managed on the robot. The main motor is directly alimented by the LiPo batteries. The electronics (PIC, sensors, …) have a dedicated 5V converter, the same is true for the lateral motors.

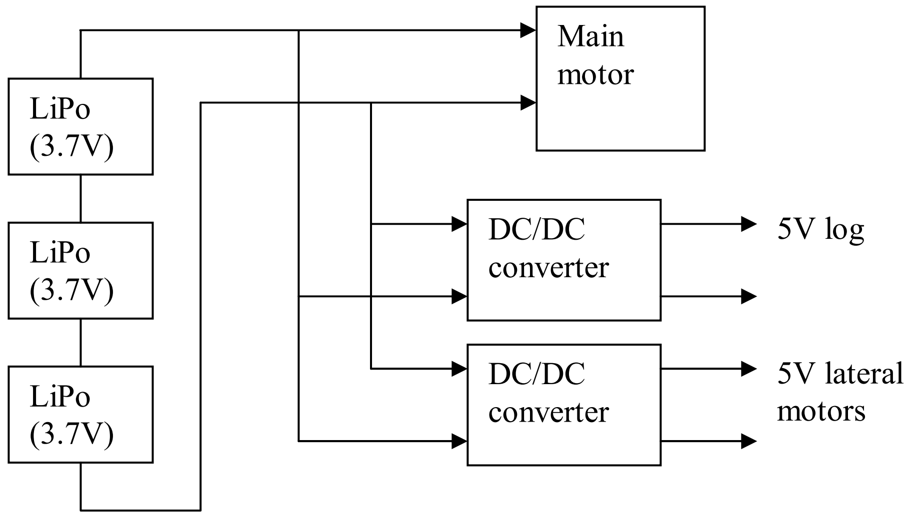


Figure 56: power management

Selecting the battery:

As stated earlier the only possible choice was to use LiPo packs.
Since the motor needs a voltage that goes up to 11V choosing a pack of 3 cells is logical.
The only parameter that is still free is the capacity.
If the Kok 910 from Westechnik [14] is used a global weight of about 270 has to be lifted. Measurements have shown that under these conditions the current drawn by the main motor is around 4.7A, the lateral motor plus electronics will draw around 400mA, thus the total amperage would be 5.1 A. With a 910 mAh pack the theoretical autonomy would be of about: 10 minutes.
If the 450mAh pack from Eflight [15] is used, the robot's weight can be lowered to about 200g. Under these conditions the main motor would need 3.4 A. The lateral motors plus electronics still 400mA thus a total current of 3.8 A. This would lead to an autonomy of 7.2 minutes.
Logically the Kok 910 was selected, unfortunately once everything was assembled it was found that at a thrust of 220 grams heavy vibrations started to appear. Making some changes on the propellers allowed to resolve the problem, however for safety reasons it would be better to use the 450mAh battery.

Type	Battery weight	Robot total weight	Current needed	Autonomy
	[g]	[g]	[A]	[min]
Kok 910	70	270	5.1	10.0
Kok 450	35	235 (less if LRK 195.03 is used)	3.8	7.2

Table 14: 910mAh vs 450mAh battery

7.4.6 PCB subtility

At the time the first PCB was made the final mechanical design was not fully known. Yet the very short time constraints did not allow waiting any longer. It was thus decided to split all the electronics on three different PCB.

Power PCB: DC/DC converters, H-bridges
Control PCB: motor control, acquisition and communication PIC
Sensor PCB: gyroscope and inclinometer

Doing this had several advantages. First there was a clear separation between the power circuitry and the logic, which reduced the risk of interferences. Second, the symmetry of the helicopter was conserved, indeed Power and Control PCB are of equal size, thus one can be placed on each side of the robot. Third, if needed only one PCB can be changed or updated. Fourth, the routing of the PCB is simplified, since less components have to be placed on the same substrate. Also the position of the sensor PCB is not yet known, however it is thought that the best location is on the center of the robot and with this three PCB configuration doing this is extremely simple.

7.4.7 Quick changes on PCB

Some changes had to be done on the PCB.
First, when the PCBs were ordered the robot was supposed to have only two lateral motors. However after a meeting it was decided that controlling all DOF at the same time would be a good thing thus a third motor had to be added. This explains why a H-bridge had to be mounted on the “power PCB”.
Second, at the beginning of the project reusing an old Bluetooth code was intended. However in the meantime a new code was developed at ASL2, unfortunately this code didn’t fit on a 16F876A PIC, thus a 18F6720 had to be mounted on the “logic PCB”.

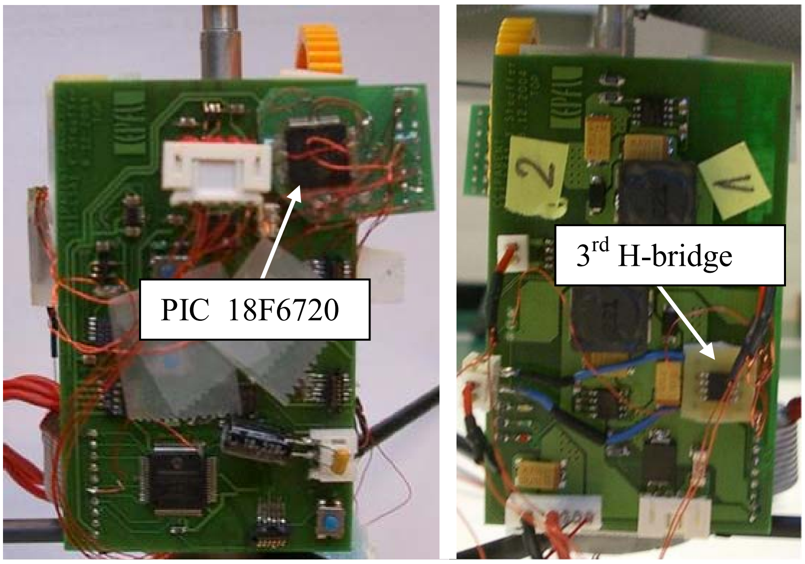


Figure 57: logic and power PCBs with changes

First it was thought that making a new version of the PCBs was important. However since a new semester project will redesign the Coax, making new PCBs would be a waste of time and money.

7.4.8 GUI

There was not much to chose for the GUI. Figure 58 depicts what was implemented.

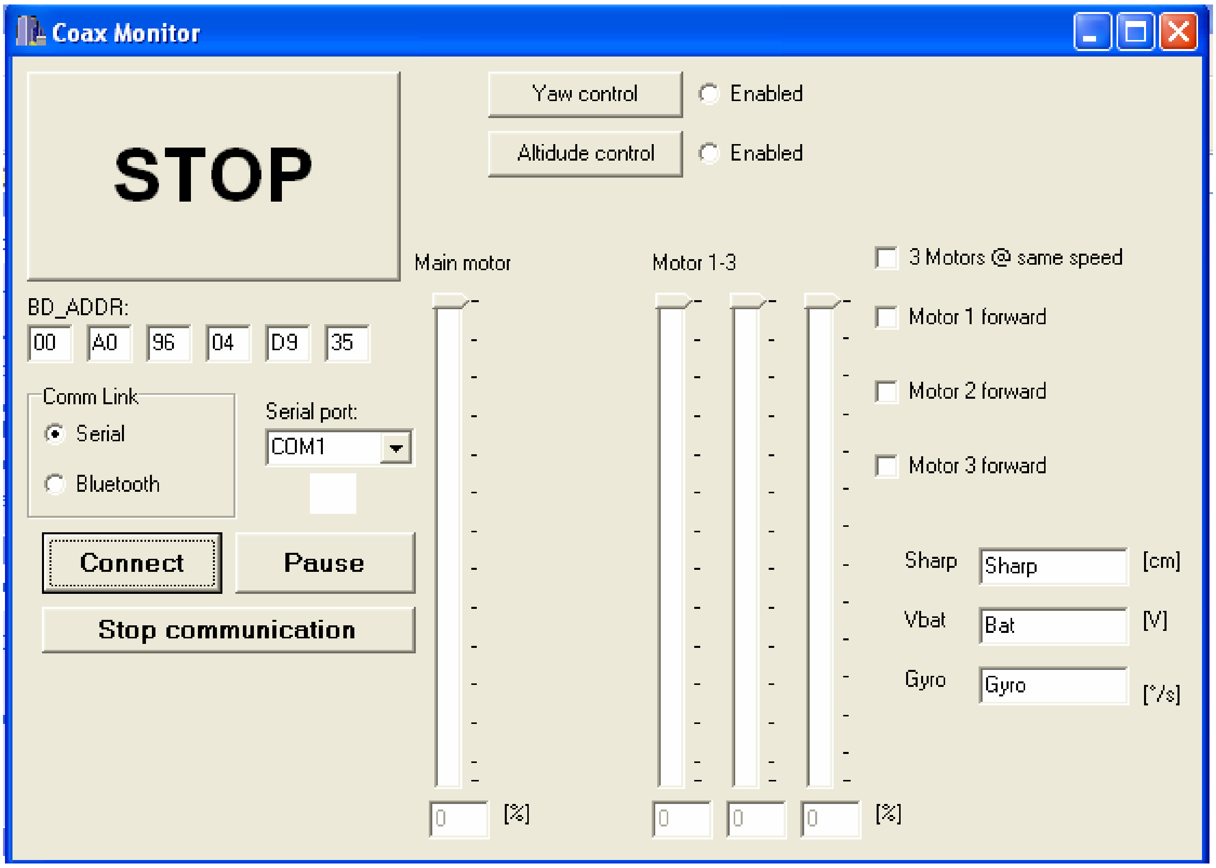


Figure 58: GUI for the Coax

This interface has the basic functionalities. Namely:

- Connecting to the robot
- Setting the main motor's speed
- Setting the lateral motors' speeds, individually or all at the same time
- Setting the direction of rotation of the lateral motors
- Reading back the values from the sensors as well as the battery voltage
- Yaw and altitude control are still to be implemented

8 Dynamic modelisation

A complete Newton-Euler modelisation was done by Fabien Gigon. For the complete development and hypoteses please refer to “Contribution à la conception d’un micro hélicoptère à rotors coaxiaux” [20]. The following equations and schematics are borrowed from this report.

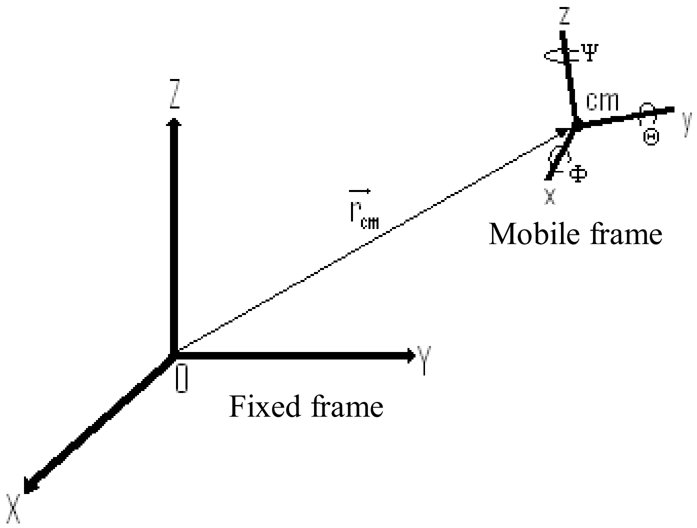


Figure 59: fixed and mobile frame, used fore the dynamic modelisation of the Coax

As depicted in Figure 59 the Coax has 6 DOF. Three translations and three rotations.

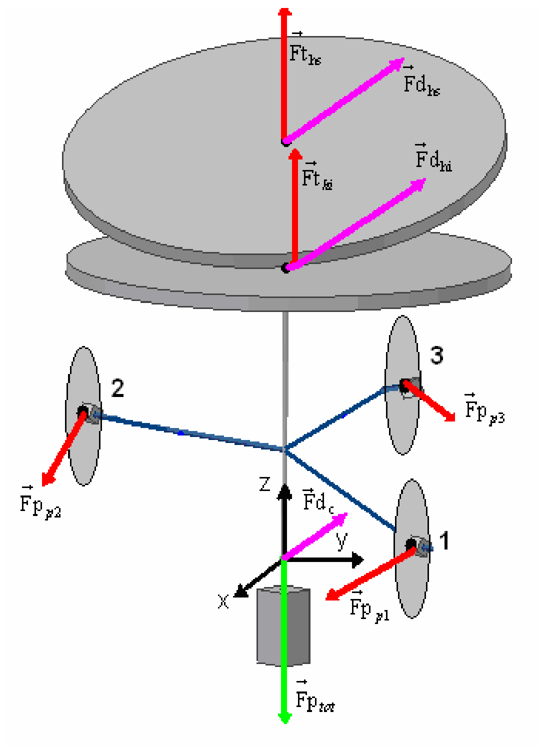


Figure 60: forces acting on the Coax

Figure 60 shows the forces that act on the Coax. These are:

Weight forces

Fp_{hs}	:	Weight of upper propeller
Fp_{hi}	:	Weight of lower propeller
Fp_{a}	:	Weight of axes
Fp_{t}	:	Weight of lateral tubes
Fp_{p1}	:	Weight of lateral propulsion set 1
Fp_{p2}	:	Weight of lateral propulsion set 2
Fp_{p3}	:	Weight of lateral propulsion set 3
Fp_{m}	:	Weight of motor bloc, batteries and electronics
Fp_{tot}	:	Total weight acting on the centre of mass

Forces generated by the system

Ft_{hs}	:	Lift force of upper propeller
Ft_{hi}	:	Lift force of lower propeller
F_{p1}	:	Lateral propulsion force 1
F_{p2}	:	Lateral propulsion force 2
F_{p3}	:	Lateral propulsion force 3

Drag forces acting on the robot during translation

Fd_{hs}	:	Drag force acting on upper propeller during translation
Fd_{hi}	:	Drag force acting on lower propeller during translation
Fd_{c}	:	Drag force acting on helicopter body during translation

Now one can express the different forces in the mobile frame:

X direction:

Weight: $$\mathrm{Fp}_x = R\ \vec{F}p_{tot}\begin{pmatrix}1\\0\\0\end{pmatrix}$$

Traction: $$\mathrm{Ft}_x = R\ \left(\vec{F}t_{hs} + \vec{F}t_{hi}\right)\begin{pmatrix}1\\0\\0\end{pmatrix}$$

Propulsion: $$\mathrm{F}_{px} = \mathrm{F}_{p1_x} + \mathrm{F}_{p2_x}$$

Drag: $$\mathrm{Fd}_x = \left(\mathrm{Fd}_{hs_x} + \mathrm{Fd}_{hi_x} + \mathrm{Fd}_{c_x}\right)$$

Y direction :

Weight: $$\mathrm{Fp}_y = R\ \vec{F}p_{tot}\begin{pmatrix}0\\1\\0\end{pmatrix}$$

Traction: $$\mathrm{Ft}_y = R\ \left(\vec{F}t_{hs} + \vec{F}t_{hi}\right)\begin{pmatrix}0\\1\\0\end{pmatrix}$$

Propulsion: $$\mathrm{F}_{py} = \mathrm{F}_{p1_y} + \mathrm{F}_{p2_y} + \mathrm{F}_{p3_y}$$

Drag: $$\mathrm{Fd}_{\mathrm{y}} = \left(\mathrm{Fd}_{\mathrm{hs_y}} + \mathrm{Fd}_{\mathrm{hi_y}} + \mathrm{Fd}_{\mathrm{c_y}}\right)$$

Z direction :

Weight: $$\mathrm{Fp}_z = R\ \vec{F}p_{tot}\begin{pmatrix}0\\0\\1\end{pmatrix}$$

Traction: $$\mathrm{Ft}_z = R\ \left(\vec{F}t_{hs} + \vec{F}t_{hi}\right)\begin{pmatrix}0\\0\\1\end{pmatrix}$$

Finally in vectorial form :

$$\boxed{\vec{\mathrm{F}}_{\mathrm{tot}} = \begin{pmatrix}F_{\mathrm{x}}\\F_y\\F_z\end{pmatrix} = R\ \left(\vec{F}p_{tot} + \vec{F}t_{hs} + \vec{F}t_{hi}\right) + \begin{pmatrix}\mathrm{F}_{p1_x} + \mathrm{F}_{p2_x}\\ \mathrm{F}_{p1_y} + \mathrm{F}_{p2_y} + \mathrm{F}_{p3_y}\\ 0\end{pmatrix} + \begin{pmatrix}C_s + C_i + C_{cx}\\ C_s + C_i + C_{cy}\\ 0\end{pmatrix}\begin{pmatrix}\dot{x}^2\\ \dot{y}^2\\ \dot{z}^2\end{pmatrix}}$$

With:

- Total mass acting on the center of mass, always directed in the Z direction of the fixed frame:

$$\vec{\mathrm{F}}\mathrm{p}_{\mathrm{tot}} = R\vec{g}\sum m_i\begin{pmatrix}0\\0\\1\end{pmatrix} \quad \text{avec} \quad \vec{g} = -9.81\begin{pmatrix}0\\0\\1\end{pmatrix}$$

• Lift of the upper, lower and lateral propellers:

$$\vec{\mathrm{F}}\mathrm{t}_{\mathrm{hs}} = R\begin{pmatrix}0\\0\\1\end{pmatrix}D_s\Omega_h{}^2 \quad , \quad \vec{\mathrm{F}}\mathrm{t}_{\mathrm{hi}} = \begin{pmatrix}0\\0\\1\end{pmatrix}D_i\Omega_h{}^2 \quad , \quad \vec{\mathrm{F}}_{\mathrm{p1}} = \begin{pmatrix}\cos(120°)\\-\sin(120°)\\0\end{pmatrix}D_p\Omega^2{}_{p_1}$$

$$\vec{\mathrm{F}}_{\mathrm{p2}} = \begin{pmatrix}\cos(120°)\\\sin(120°)\\0\end{pmatrix}D_p\Omega^2{}_{p_2} \quad , \quad \vec{\mathrm{F}}_{\mathrm{p3}} = \begin{pmatrix}0\\1\\0\end{pmatrix}D_p\Omega^2{}_{p_3}$$

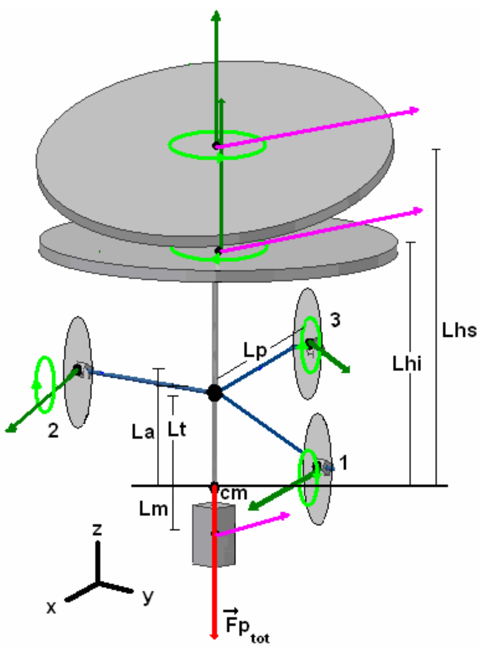
D_s , D_i and D_p are constants that are associated with the propellers $\Omega_{h,p_{1,2,3}}$ is their angular velocity.

• Drag due to the translation in the x, y space:

$$\vec{\mathrm{F}}\mathrm{d}_{\mathrm{hs}} = \begin{pmatrix}\mathrm{Fd}_{\mathrm{hs}_x}\\\mathrm{Fd}_{\mathrm{hs}_y}\\0\end{pmatrix} = C_s\begin{pmatrix}\dot{x}^2\\\dot{y}^2\\0\end{pmatrix}, \ \vec{\mathrm{F}}\mathrm{d}_{\mathrm{hi}} = C_i\begin{pmatrix}\dot{x}^2\\\dot{y}^2\\0\end{pmatrix} \ \text{et} \ \vec{\mathrm{F}}\mathrm{d}_{\mathrm{c}} = \begin{pmatrix}C_{cx}\dot{x}^2\\C_{cy}\dot{y}^2\\0\end{pmatrix}$$

C_s , C_i , C_{cx} and C_{cy} are constants associated with the shape of the propellers and the form of the helicopter's body.

Moments acting on the centre of mass



Usefull equations:

Cinetical moment:

$$\boxed{\vec{L} = \vec{r} \times m\vec{v}}$$

Rotation around a main axis:

$$\boxed{\vec{L} = I\vec{\omega}}$$

Resulting momentum:

$$\boxed{\vec{M} = \dot{\vec{L}}}$$

Momentum of a force ::

$$\boxed{\vec{M} = \vec{r} \times \vec{F}}$$

Around the x axis:

$$M_x = Q_{p1_x} + Q_{p2_x} + \mathrm{Fd}_{\mathrm{hs_y}} L_{hs} + \mathrm{Fd}_{\mathrm{hi_y}} L_{hi} + \mathrm{Fd}_{\mathrm{c_y}} L_m + \mathrm{Ft}_y \frac{\left(L_{hs} + L_{hi}\right)}{2}$$

With Q_{p1_x} *et* Q_{p2_x} the components in x of the counter momentum due to the wind friction on the propellers.

Around the y axis:

$$M_y = Q_{p1_y} + Q_{p2_y} + Q_{p3_y} + \mathrm{Fd}_{\mathrm{hs_x}} L_{hs} + \mathrm{Fd}_{\mathrm{hi_x}} L_{hi} + \mathrm{Fd}_{\mathrm{c_x}} L_m + \mathrm{Ft}_x \frac{\left(L_{hs} + L_{hi}\right)}{2}$$

With Q_{p1_y} *et* Q_{p2_y} the component in y of the counter momentum due to the wind friction on the propellers.

Around the z axis:

$$M_z = L_p \left(F_{p1_z} + F_{p2_z} + F_{p3_z}\right) + Q_z$$

With Q The resulting counter momentum due to the friction of the air on the main propellers.

Eventually the vectorial expression:

$$\boxed{\vec{M}_{tot} = \begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} = \vec{Q}_{p1} + \vec{Q}_{p2} + \vec{Q}_{p3} + \vec{Q} + \begin{pmatrix} \mathrm{Fd}_{\mathrm{hs_y}} L_{hs} + \mathrm{Fd}_{\mathrm{hi_y}} L_{hi} + \mathrm{Fd}_{\mathrm{c_y}} L_m + \mathrm{Ft}_y \dfrac{\left(L_{hs} + L_{hi}\right)}{2} \\ \mathrm{Fd}_{\mathrm{hs_x}} L_{hs} + \mathrm{Fd}_{\mathrm{hi_x}} L_{hi} + \mathrm{Fd}_{\mathrm{c_x}} L_m + \mathrm{Ft}_x \dfrac{\left(L_{hs} + L_{hi}\right)}{2} \\ L_p \left(F_{p1_z} + F_{p2_z} + F_{p3_z}\right) \end{pmatrix}}$$

With:

- Counter momentum due to the friction of the air on the lateral propellers :

$$\vec{Q}_{p1} = \begin{pmatrix} \cos(120°) B \Omega_{p1}{}^2 \\ -\sin(120°) B \Omega_{p1}{}^2 \\ 0 \end{pmatrix}, \ \vec{Q}_{p2} = \begin{pmatrix} \cos(120°) B \Omega_{p2}{}^2 \\ \sin(120°) B \Omega_{p2}{}^2 \\ 0 \end{pmatrix} \text{ et } \vec{Q}_{p3} = \begin{pmatrix} 0 \\ B \Omega_{p3}{}^2 \\ 0 \end{pmatrix}$$

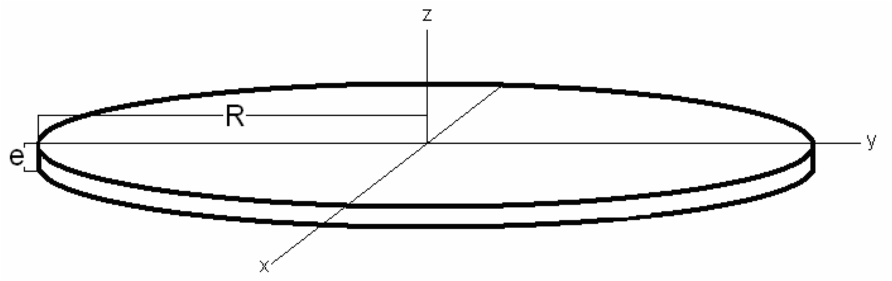
Where B depends on the propellers.

• Resulting counter momentum due to the main propellers:

$$\vec{Q} = \begin{pmatrix} 0 \\ 0 \\ Q_{hs} - Q_{hi} \end{pmatrix}$$

Computation of the inertia momentums:

Inertia momentum of a propellers:



Thin disk:

$$I_x = m\left(\frac{R^2}{4} + \frac{e^2}{12}\right)$$

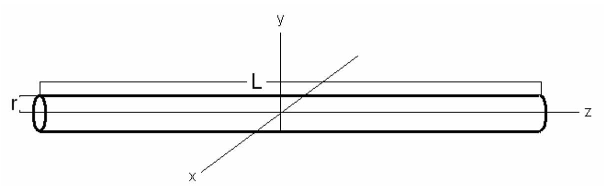
$$I_y = m\left(\frac{R^2}{4} + \frac{e^2}{12}\right)$$

$$I_z = \frac{1}{2} m R^2$$

Using the Steiner rule one gets:

$$I_{hs} = m_h \begin{bmatrix} \left(\frac{R_h^2}{4} + \frac{e^2}{12}\right) + L_{hs}^2 & 0 & 0 \\ 0 & \left(\frac{R_h^2}{4} + \frac{e^2}{12}\right) + L_{hs}^2 & 0 \\ 0 & 0 & \frac{1}{2} R_h^2 \end{bmatrix} \qquad I_{hi} = m_h \begin{bmatrix} \left(\frac{R_h^2}{4} + \frac{e^2}{12}\right) + L_{hi}^2 & 0 & 0 \\ 0 & \left(\frac{R_h^2}{4} + \frac{e^2}{12}\right) + L_{hi}^2 & 0 \\ 0 & 0 & \frac{1}{2} R_h^2 \end{bmatrix}$$

The same is done for the axis:



Thin axis:

$$I_x = m\left(\frac{r^2}{4} + \frac{L^2}{12}\right)$$

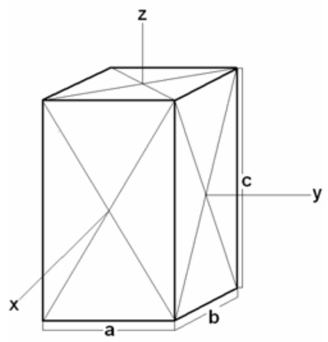
$$I_y = m\left(\frac{r^2}{4} + \frac{L^2}{12}\right)$$

$$I_z = \frac{1}{2} m r^2$$

With the Steiner rule:

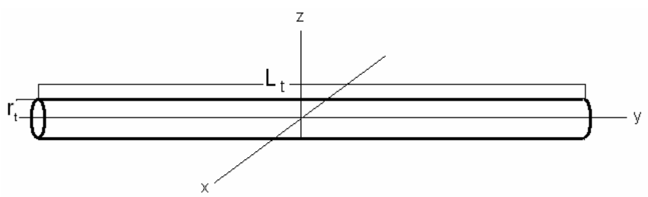
$$I_a = m_a \begin{bmatrix} \left(\frac{r^2}{4}+\frac{L^2}{12}\right)+L_a^{\,2} & 0 & 0 \\ 0 & \left(\frac{r^2}{4}+\frac{L^2}{12}\right)+L_a^{\,2} & 0 \\ 0 & 0 & \frac{1}{2}r^2 \end{bmatrix}$$

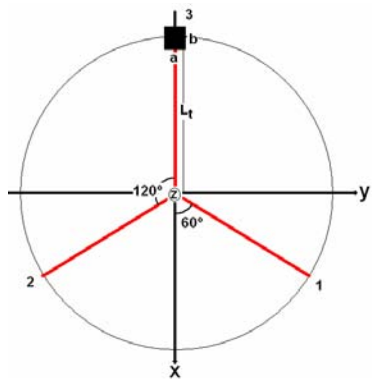
The same is done for the motor, batteries and electronics:



$$I_m = \frac{1}{12} m_m \begin{bmatrix} \left(a^2+c^2\right)+12\ l_m^{\,2} & 0 & 0 \\ 0 & \left(b^2+c^2\right)+12\ l_m^{\,2} & 0 \\ 0 & 0 & \left(a^2+b^2\right) \end{bmatrix}$$

And the three rodes that hold the lateral propulsors:





$$I_{t3} = m_t \begin{bmatrix} \frac{1}{2}r_t^2 + L_p^{\,2} & 0 & 0 \\ 0 & \left(\frac{r_t^2}{4}+\frac{L_p^{\,2}}{12}\right)+\left(L_p^{\,2}+\frac{L_t^{\,2}}{4}\right) & 0 \\ 0 & 0 & \left(\frac{r_t^2}{4}+\frac{L_p^{\,2}}{12}\right)+\left(\frac{L_t}{2}\right)^2 \end{bmatrix}$$

$$I_{p3} = \frac{1}{12} m_p \begin{bmatrix} \left(a_p^2 + c_p^2\right) + 12L_p^2 & 0 & 0 \\ 0 & \left(b_p^2 + c_p^2\right) + 12\left(L_p^2 + L_t^2\right) & 0 \\ 0 & 0 & \left(a_p^2 + b_p^2\right) + 12L_t^2 \end{bmatrix}$$

The rodes and propulsors 1,2 and 3 are placed at 120° around the z axis. Thus using the following rotation matrices is required.

$$I_{t1} = \begin{bmatrix} \cos 120° & -\sin 120° & 0 \\ \sin 120° & \cos 120° & 0 \\ 0 & 0 & 1 \end{bmatrix} I_{t3} \qquad I_{t2} = \begin{bmatrix} \cos 240° & -\sin 240° & 0 \\ \sin 240° & \cos 240° & 0 \\ 0 & 0 & 1 \end{bmatrix} I_{t3}$$

$$I_{p1} = \begin{bmatrix} \cos 120° & -\sin 120° & 0 \\ \sin 120° & \cos 120° & 0 \\ 0 & 0 & 1 \end{bmatrix} I_{p3} \qquad I_{p2} = \begin{bmatrix} \cos 240° & -\sin 240° & 0 \\ \sin 240° & \cos 240° & 0 \\ 0 & 0 & 1 \end{bmatrix} I_{p3}$$

Adding up all the momentum of inertia:

$$\boxed{I_{tot} = I_{hs} + I_{hi} + I_a + I_t + I_p}$$

Equations of motion

Now all the elements are available to compute the equations of motion.

Using the classical Newton-Euler equation:

$$\boxed{\begin{array}{l} \vec{F}_{tot} = m_{tot} \ddot{\vec{X}} \\ \vec{M}_{tot} = I_{tot} \ddot{\vec{\xi}} \end{array}} \qquad \text{where } \vec{X} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \text{ and } \xi = \begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix}$$

And the rotation matrix:

$$R(\phi,\theta,\psi) = \begin{bmatrix} \cos\psi\cos\theta & \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \sin\psi\sin\theta\cos\phi - \sin\phi\cos\psi \\ -\sin\theta & \cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix}$$

Allows finding the equation of motion of the helicopter.

$$\ddot{\vec{X}} = \frac{1}{m_{tot}} \left[R \ \left(\vec{F}p_{tot} + \vec{F}t_{hs} + \vec{F}t_{hi} \right) + \begin{pmatrix} \mathrm{F}_{p1_x} + \mathrm{F}_{p2_x} \\ \mathrm{F}_{p1_y} + \mathrm{F}_{p2_y} + \mathrm{F}_{p3} \\ 0 \end{pmatrix} + \begin{pmatrix} C_s + C_i + C_{cx} \\ C_s + C_i + C_{cy} \\ 0 \end{pmatrix} \dot{\vec{X}}^2 \right]$$

$$\ddot{\vec{\xi}} = \frac{1}{I_{tot}} \begin{pmatrix} Q_{p1_x} + Q_{p2_x} + \mathrm{Fd}_{\mathrm{hs_y}} L_{hs} + \mathrm{Fd}_{\mathrm{hi_y}} L_{hi} + \mathrm{Fd}_{\mathrm{c_y}} L_m + \mathrm{Ft}_y \dfrac{\left(L_{hs} + L_{hi}\right)}{2} \\ Q_{p1_y} + Q_{p2_y} + Q_{p3} + \mathrm{Fd}_{\mathrm{hs_x}} L_{hs} + \mathrm{Fd}_{\mathrm{hi_x}} L_{hi} + \mathrm{Fd}_{\mathrm{c_x}} L_m + \mathrm{Ft}_x \dfrac{\left(L_{hs} + L_{hi}\right)}{2} \\ L_p \left(F_{p1} + F_{p2} + F_{p3} \right) + Q \end{pmatrix}$$

9 Testing the Coax

Now that the Coax is assembled every part has to be tested. First non autonomous tests will be done on a test bench; power will be supplied by a standard laboratory alimentation. Once these tests will have been successfully completed autonomous free flights will be done.

9.1 Main motor and propellers

In order to test the main motor and the two custom propellers the coax was fixed to a weight scale as shown in Figure 61. The weight of the Coax is 190g without batteries and 260 if Kokam 910mAh batteries are used.

Figure 61: Coax ready for lift test (left), Coax ready for yaw test (right)

Tests were performed and quite rapidly the foam cushion (Figure 24) broke. Furthermore heavy vibrations started to appear when 170g or more were lifted. It was decided that this foam would be removed.
Doing this allowed lifting 220g, but again heavy vibrations appeared ant the propellers broke, again. By looking carefully at the videos of the “crash” one could observe that the problem came from the lower main propeller, the carbon rind was not rigid enough. It was replaced from a 1mm rode to a 1.5mm rode.
Tests were performed again and it was shown that 260g could be lifted without causing too many vibrations. For security reasons it was decided not to push the tests beyond this limit, however a 20% power margin was available.
Until now the Typhoon 05-3D [15] motor was used. Since a LRK 195.03 [14] motor was available it was decided that it would be tested too. However as expected by the calculations this motor was not able to lift the 270g of the Coax.

9.2 Lateral motors and propellers

In order to see if the lateral propellers are powerful enough the Coax was fixed on a rotating chair as shown in Figure 61. The motor was set to lift 260 grams. Doing this allowed observing a counter clockwise rotation; this is the direction of rotation of the upper propeller. Then the lateral motors were turned on, the force generated was sufficient to counter the rotation of the Coax and even reverse it. However to do this they have to be set to full power all the time. Furthermore the two stage reductor (Figure 40) has to be handled very carefully.
The fastest and most effective way to increase the power of the lateral propellers was to reuse the propulsion system of flying Alice [8]. Figure 62 shows the reductor (10R5 from Didel [13]) and the propeller. This system weights almost 5g, which 3g more that the system previously used. However it is 3 times more powerful, indeed delivering 12g of lift is perfectly feasible.

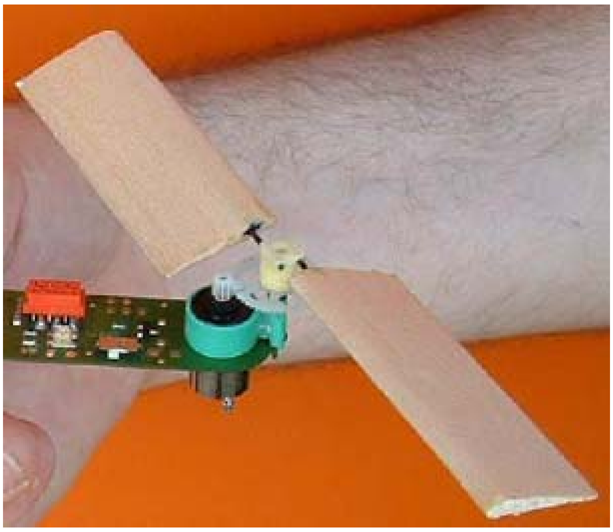


Figure 62: motor, reductor and propeller of the flying Alice

9.3 Lateral fixed angle flaps

In order to counter the permanent yaw rotation tests were performed with fixed angle flaps as can be observed on Figure 63. The outcome is that the depicted flaps (10 by 10cm) were able to bring the residual yaw rotation to zero.

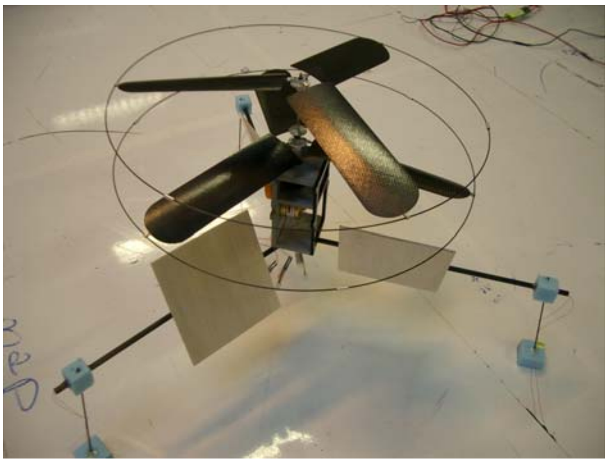


Figure 63: Coax with fixed angle flaps

9.4 Sensors

Gyroscope:

The values returned by the gyroscope are sent to the GUI in order to give the user an idea of the robot's rotational speed. Tests have been performed and pointed out that this device worked properly. The main issue are vibrations which are extremely high in the Coax and an important filtering has to be performed.

Sharp:

A look-up table was implemented for the Sharp distance sensor. As expected the output is now linear and the distance can easily be computed. This sensor works as expected.

Accelerometer:

As explained in the sensor section before, the chosen accelerometers were not adapted for this application. Since not much time was left and that having this information was not vital for the Coax no further investigations were done in this domain.

9.5 Free Flights

For the first free flight a Kokam 910 was used, this lead to an overall weight of 265g. As expected the robot took of at about 70% of the maximal available power. Yaw was properly controlled by the lateral propellers, which at this time were still using the two stage reductor from Didel.

However these two stage reductors were too fragile for the Coax, furthermore they had to be set to full speed in order to compensate the yaw rotation, indeed they were designed for a lighter robot. Thus as explained before they were changed from a 4R25-02 (Figure 40) to a 10R5 (Figure 62). Doing this allowed to notice an amazing change in controllability. Indeed now there was enough power in the lateral motors to allow the robot to spin in one direction and reverse this rotation in short amount of time. Furthermore the propellers from Flying Alice were optimized which is of course beneficial for this application.

Nevertheless the lightweight mechanics of the propellers still caused some problems. Indeed lifting 265g is quite demanding for such a system, mostly for the propellers. It was thus decided to try with a Kokam 450 battery. Using this lighter model allowed to lower the total weight of 30grams, which is quite significant for such a system.

A final flight was performed in the Polydome[7], again autostability was achieved but one of the lateral propeller broke, which caused the crash of the Coax.

[7] Place at EFPL that can be reserved for special occasions.

9.6 Observations and improvements

When observing the behaviour of the Coax one can see that autostability is achieved as well as altitude and yaw control. However the system never flew more than 10 seconds. This is due mostly to vibrations and a too fragile design of the main propellers. The following changes should be done in order to improve the Coax:

- Lower the overall weight by integrating the electronics on the structure. It is possible to have some parts of the structure done with PCBs.

- Make use of bigger propellers that wouldn't have to rotate too fast. This solution would result in a bigger helicopter, which might not be wanted.

- Change the dimensions of the axis of the upper propeller from 2mm to at least 3 or 4. Indeed this axis is too weak and tends to oscillate. Furthermore it is destroyed at each crash. Changing the material from steel to carbon fibre could also be an improvement

- Make all the pieces that are associated with the head of the rotor at least 2 to 3 times bigger. Indeed the first pieces that broke were the ones associated with the propellers. Centrifugal forces become really important at these angular velocities and the glue is not able to hold the pieces together.

- Have the propellers assembled by professionals. Even a slight unbalancing causes high vibrations.

- Don't allow the two main propellers to collide. Indeed in this design the propellers can move up and down. The down motion of the upper propeller is problematic if the lower propeller is going up (Figure 64)

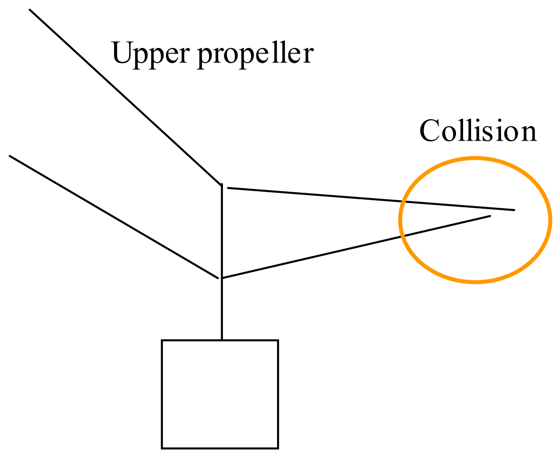


Figure 64: collision of the two main propellers

- 2 main motors could be used. This would allow controlling the yaw by operating a differential control on their velocities. Doing this would mean that the lateral control system is ONLY used for steering. Whereas now it is used to compensate for the permanent yaw too.

- The structure could be molded. This would reduce the mass and allow a fancier design.

- Helicoidal gears could be used for the main transmission mechanism. Reduction of the noise and higher efficiency would be the main benefits.

- Make use of the gyroscope and altitude sensor to stabilize the robot. Indeed hand controlling the device needs a good pilot. Implementing a basic controller would be of great interest.

- If one is not sure about the system's stability, don't try to fly in a small room, rent the Polydome.

10 Conclusion

10.1 Acknowledgements

I would like to thank:
Samir Bouabdallah and André Noth for their support and patience
André Guignard for his advices and for amazing work on the Coax mechanical parts
Prof. Daniel Nicoud for all the material from Didel
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David Stalder for building a copy of the proxflyer propellers and for the nice small propellers
Thierry Frank and Xavier Raemy for their hints and support
The ASL team for their support
Prof. Roland Siegwart for accepting this challenging project

10.2 General conclusion

Working on the coax project was a great experience. Indeed flying devices are an emerging field of research and lot still has to be discovered. Such a project involves many fields of the waste world of engineering:

- Mechanics: structure and propellers
- Electronics: sensors, motors, batteries and microprocessors
- Programming: microprocessors
- Physics: behavior of propellers and modelisation of the device

Furthermore due to very short time constraints a perfect cooperation with Mr.Guignard, who is responsible for the fabrication of the mechanical parts and the ACORT, department that responsible for building the PCBs was vital. Even more important was the cooperation with my colleague Fabien Gigon. Only by achieving a perfect coordination between all these people was it possible to build a working prototype of the Coax in time.

To goal of this project was to investigate the behavior of a coaxial helicopter that would use a novel auto-stability principle. In other words everything had to be realized, from the mechanical structure to the electronics.

Tests showed that the prototype behaved as expected, it was auto-stable. Altitude as well as yaw could be controlled via Bluetooth. Translation however could not yet be achieved. This project allowed discovering the behavior of such devices and several conclusions can be drawn from our design. This report gives the necessary improvements that will have to be done on future projects as well as small design hints. All the necessary tools are provided for a rapid evolution of the Coax family.

Working on this project was interesting because of its multidisciplinarity. Furthermore developing a fully functional robot and see it fly at the end of the semester is extremely satisfying. I have also learnt the way flying objects had to be designed and discovered the world of PIC programming.

Yves Stauffer

February 18th 2005

11 Bibliography

[1] Proxflyer, http://www.proxflyer.com, 2004-2005
[2] Epson, "The Micro-Flying Robot", Epson 2004
[3] Stephane Marty, http://web.media.mit.edu/~stefanm/FFMP/, 2001
[4] Stephane Marty, "Building a Micro Helicopter that actually flies", 2000
[5] Felipe Bohorquez, "Design, Analysis and Performance of a Rotary Wing MAV", 2001
[6] Stephen Waslander, "STARMAC Vehicle Dynamics", 2004
[7] Gordeon Leishman, "History of Helicopter Flight", 2000
[8] Fabien Tâche, “Flying Alice 2”, 2003
[9] André Noth, “Synthèse et Implémentation d'un contrôleur pour micro-hélicoptère à 4 rotors“, 2004
[10] Kamov, http://www.sergib.agava.ru/russia/kamov/137/ka137_e.htm, 2000
[11] Ron Fearing, http://robotics.eecs.berkeley.edu/~ronf/MFI/index.html, 2004
[12] James Stack, “Experimental Investigation of Rotor Vortex Wake in Descent”, 2004
[13] Didel, http://www.didel.com, 2005
[14] Westechnik, http://www.wes-technik.de, 2005
[15] Eflight, http://www.eflight.ch, 2005
[16] Foilsim, http://www.grc.nasa.gov/WWW/K-12/airplane/foil2.html, 2004
[17] MdHelicopters, http://www.mdhelicopters.com, 2005
[18] HowStuffWorks, http://travel.howstuffworks.com/airplane16.htm, 2005
[19] Falcon, http://www.falconmodels.uk.com/, 2005
[20] Gigon Fabien, «Contribution à la conception d’un micro hélicoptère à rotors coaxiaux», 2005
[21] Sharp distance sensor, http://zuff.info/SharpGP2D12_E.html, 2005
[22] SRF08 distance sensor, http://www.robot-electronics.co.uk/htm/srf08tech.shtml, 2005
[23] Günter and Tosetti, “Short Fly Module for Alice Robot”, 2003