# Delft Aerospace Design Projects 2006 : aerospace and aerospace-related designs

# DELFT AEROSPACE
# DESIGN PROJECTS 2006

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Design in aeronautics, astronautics,
earth observation and related areas

Editor:
Joris Melkert

Coordinating committee:
Vincent Brügemann, Harald van Brummelen, Peter Joosten
Joris Melkert, Gillian Saunders-Smits,
Barry Zandbergen

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# PREFACE

The Design Synthesis Exercise forms the closing piece of the third year of the Bachelor degree course in aerospace engineering at TU Delft. Before the students progress to the first year of their Master degree course, in which they join one of the Faculty's disciplinary groups in preparation for their final year MSc thesis project, they learn to apply their acquired knowledge from all aerospace disciplines in the design synthesis exercise.

The objective of this exercise is to improve the students' design skills while working in teams with 9 or 10 of their fellow students for a continuous period of approximately 10 weeks with a course load of 400 hours. They apply knowledge acquired in the first years of the course; improve communication skills and work methodically according to a plan.

Despite the fact that the final designs result from a design process executed by small groups of students with limited experience, it may be concluded that the designs are of good quality. Not only the scientific staff of the Faculty of Aerospace Engineering, but also the external experts and industry, which have supported the design projects have expressed their appreciation for the results.

This book presents an overview of the results of the Design Synthesis Exercise 2006, based on summaries of each of the projects.
The Design Synthesis Exercise Coordination Committee, responsible for the organisation and execution of the exercise, has made this book with the aim to present an overview of the diverse nature of the various design topics, and of the aerospace engineering course itself. In addition, the book is intended as an incentive for further improvements to the exercise.

Finally the coordinating committee would like to thank the student-assistants, the student counsellors, Mr. Deken and Mrs. Kop and all who have contributed to the success of this year's exercise.

The Design Synthesis Exercise Coordination Committee 2006:
ir. V.P. Brügemann, dr.ir. E.H. van Brummelen, ir. P. Joosten,
ir. J.A. Melkert, ir. G.N. Saunders-Smits, ir. B.T.C. Zandbergen.

# 1. THE DESIGN SYNTHESIS EXERCISE

## 1.1 Introduction

The design synthesis exercise forms a major part of the curriculum at the Faculty of Aerospace Engineering, Delft University of Engineering. The main purpose of the exercise is the synthesis of the curriculum themes presented in the first two years of the educational program at the faculty.

The design exercise is scheduled in the last educational quarter of the third year at the faculty. The knowledge acquired in the first three years is applied to design topics related to aerospace technology.

Since this design exercise is organized approximately half-way through the complete five-year (3 year Bachelor of Science in Aerospace Engineering + 2 year Master of Science in Aerospace Engineering) program, the design results are not expected to be of a professional quality. Nevertheless the students and their tutors strive to create the best design they can. This is accomplished in an iterative way. Such an iterative process is a typical element of building up design experience.

The way in which a project is carried out and reviewed is only partly focussed on the design result. The design process itself is of greater importance. It is especially important for the students to work as a team, since this best reflects a design process in 'real life'. In this way, the students can take full advantage of their personal qualities.

## 1.2 Objective

The design synthesis exercise helps to meet the faculty's requirement to enlarge the design content of the aerospace engineering course. The goal of the exercise itself is to improve the design skills of the

students, in particular project management, communication, teamwork and the application of the knowledge gathered in the first three years of the course.

The student has the opportunity to increase his experience in designing. The whole process of designing is dealt with, from the list of requirements up to the presentation of the design. Typical aspects of such a process, such as decision making, optimization and conflicting requirements will be encountered. Acquiring experience often means going through iterative processes, so design decisions can be altered to make sure that the design requirements are met. The arguments supporting the decisions are reviewed, as well as the way the project is managed. Aspects of design methodology and design management are also taken into account.

Although the contents of the first years of the educational program is not applicable to design purposes in its entirety, much of the obtained knowledge can be applied in the design synthesis project. Skills like integrating and applying knowledge from different disciplines are one of the important elements of the design project.

During the project the student is expected to work in a team. This means that a student learns to cooperate, to schedule and meet targets, manage the workload, solve conflicts, et cetera. In this field, effective communication is of major importance. Apart from these capabilities the student is expected to be able to communicate ideas and concepts regarding the project subject with specialists and non-specialists. By means of integrated short courses in written reporting and oral presentation, the communicative skills of a student will be developed and assessed.

## 1.3 Characteristics of the exercise

The characteristics of the design synthesis exercise are:

- For all students, the design component of the study is reinforced by the design synthesis exercise.
- The design synthesis exercise consists of a design project integrated with workshops and courses on oral presentation, sustainable development, systems engineering and project management.

- The exercise has a fixed end date. This means that the third year ends with the design exercise.
- All discipline groups of the faculty provide the support needed during the exercise. This enhances the multi-disciplinary nature of the exercise in general and the design projects in particular.
- The design process is supplemented by lectures on design methodology and project management, as applied to the exercise.
- Aspects of sustainable development, such as noise emission, the use of raw materials, energy consumption and environmental impact are addressed explicitly during the exercise.
- Integrating short courses on oral presentations develops the communicative skills.

## 1.4 Organization and structure of the exercise

Students indicate their preferences after presentations by the staff introducing all project subjects. Students are divided into groups of approximately 10 persons as much as possible according to their preferences. The exercise takes place during a continuous period of eleven weeks, the last educational term of the third year. Technical aspects of the project take up 60 percent of the time; the remaining 40 percent is spent on general topics supporting the project work. General topics are spread over the nine weeks of the exercise. The general topics are sustainable development, design methodology and project management and oral presentations.

## 1.5 Facilities

To complete the exercise design within the given period of time, the groups of students can make use of several facilities. Each group has its own room, with various facilities (tables, chairs computers, flip-over charts et cetera). Commonly used software like AutoCAD, ProEngineer, CATIA, Matlab, MS Office, MS Project, C++, Fortran, MSC Nastran and more project specific software are available. A

special library is available, containing literature on typical project subjects. Finally each group has a budget for printing and copying.

## 1.6 Course load

The course load is measured in credit points according to the European Credit Transfer System, ECTS: 1 credit point equals 28 hours of work. The total course load is 14 ECTS credits. The division between the subparts of the exercise is as follows:

| Part | Credits |
|---|---|
| The design itself, reporting and presenting | 80% |
| Short course Systems Engineering & Project Management | 10% |
| Short course Oral Presentations | 10% |

Table 1.1: Distribution of credits for the third year design exercise

## 1.7 Support and assistance

An essential part of designing is making choices and design decisions. During a technical design process, the choices made in the first stages are often based on qualitative considerations. When details of a design take shape, quantitative analysis becomes increasingly important.
The considerations accompanying these design choices need mentoring and tutoring, since students lack experience in this field. The execution of the project demands a fair amount of independent work of the design team. This means that the team itself is capable of executing the design process. The task of the team of mentors is mainly to observe and give feedback on the progress. The team of mentors consists of a principal project tutor and two additional coaches. Each has a different area of expertise. The method of working, the organization, the communication of the team and the collaboration within the team itself are also judged. Where necessary, the mentors will correct the work and work methods of the team. Warnings of pitfalls and modeling suggestions for certain problems during design will be

given when needed, to ensure a satisfactory development of the design.

## 1.8 General topics

In this section the general topics of the design exercise are explained briefly. Oral presentations, project management, systems engineering and sustainable development are dealt with consecutively.

**Oral presentations**

As an integral part of the design exercise, the short course "oral presentation" is given. During this course students are taught how a presentation should be given. The subjects for training these skills originate as much as possible from the design project. In this way the courses and the design project are directly coupled which reduces the amount of redundant work.

**Project management**

'Working together as a team' means learning how to organize, how to plan and how to control the activities needed during the project so the desired final product is delivered within the given time span of 10 weeks. Using a project plan, the following subjects are dealt with: the project start, the project approach including a Work Breakdown Structure, and project phasing (including reviews), time and resource control using Gantt-charts, and finally the organization. Attention is paid to the software package supporting the design management processes. Apart from the lectures, care is also given to this subject during the project.

**Systems engineering**

The importance of systems engineering is that it provides a structured and explicit process approach to the design and development of a(n) (aerospace) system. In this course the various steps in the design of an aerospace system, whether an airplane, helicopter, sailplane, spacecraft or launcher, are dealt with as well as some techniques used in systems engineering. Techniques discussed include requirements discovery, functional analysis, generating design option trees, performing trade studies, technical performance measurement and

risk control. To increase the applicability of the methods and techniques, the lectures are presented in a workshop, where cases are treated in groups.

**Library instruction**

A library instruction aims to reinforce the student's capability to use a structured approach toward conducting a library search using advanced search tools. The purpose of this instruction is to allow students to perform a more efficient and effective search for information in the field they are researching. Specific attention is given to searching for articles, papers, periodicals, books using key words in the library catalogue, on-line databases as well as via the internet.

## 1.9 Design projects 2006

The Design Synthesis Exercise 2006 is divided into 21 different subjects. In table 1.2 an overview is given of these subjects. In the following chapters the results of the design teams are covered in detail. For each project, the important design characteristics are covered. These are: problem introduction, design specification or list of requirements, conceptual designs, the trade-off to find the "best" design, a detail design and finally conclusions and recommendations.

| Principal tutor | Subject | Chapter |
|---|---|---|
| Dr.ir. R.C. Alderliesten | Redesign of a large freighter fuselage section | 2 |
| Ir. V. Antonelli | Design of a floating solar chimney | 3 |
| Dr.ir. P. Ditmar | Unmanned airborne gravimetric surveying of the oceans | 4 |
| Dr.ir. B.G.H. Gorte | Sensor networks for traffic monitoring | 5 |
| Ir. R.J. Hamann | Micro-satellite for stereo imaging laser altimetry (MISILAT) | 6 |
| Ir. J.A. Melkert | Sailtug | 7 |
| Dr.ir. M.D. Bos-Pavel | Design of a human powered | 8 |

| | | |
|---|---|---|
| | helicopter | |
| Dr.ir. E.J.O. Schrama | Gravitational tractor for towing asteroids | 9 |
| Ir. W.A. Timmer | Space for wind | 10 |
| Ir. J. de Vries | Emergency escape pod | 11 |
| Ir. C. de Wagter | Autonomous micro UAV for atmospheric measurements | 12 |
| Dr.ir. B.W. van Oudheusden | The future of high-speed commercial air travel | 13 |
| Dr.ir. H. van der Marel | Space borne tsumani warning system | 14 |
| Ir. J. Sinke | Reusable shuttle for low orbit manned space flight | 15 |
| Ir. O. van der Jagt | Design of a floating solar chimney | 16 |
| Dr.ir. M.D. Bos-Pavel | Design of a human powered helicopter | 17 |
| Ir. J.A. Melkert | Design of a human powered helicopter | 18 |
| Prof.dr. A. Rothwell | Emergency escape pod | 19 |
| Ir. P.C. Roling | Autonomous micro UAV for atmospheric measurements | 20 |
| Prof.dr.ir. S. van der Zwaag | The future of high-speed commercial air travel | 21 |
| Ir. P.C. Roling | Fast interception unmanned aerial vehicle (international group) | 22 |

Table 1.2: Design subjects of the design exercise 2006

## 1.10 International design exercise

This year, one international team took part in the design exercise. The team consisted of six students from the School of aeronautical engineering of Queen's University Belfast and six students from Delft. The teams met each other three times during the exercise. The first

time during the kick-off session at the beginning of the semester. The second time for mid term review and finally in preparation for the symposium. The first meeting was held in Delft, the second one in Belfast and the last one in Delft.

In between meetings the students communicated by e-mail, telephone, video conferencing and the digital learning environment BlackBoard. The three face-to-face meetings proved to be essential for the results. All participants were convinced that this successful initiative should be continued.

## 1.11 The design exercise symposium

The one-day design exercise symposium forms the conclusion to the design project, during which all student teams present their designs. The presentations cover the design process as well as the design result. The symposium is primarily intended for participating students, mentors and tutors. Other staff and students and external experts are invited as well.
A group of experts from within the faculty as well as from industry form the jury and assess the presentations in style and technical content. Three criteria determine the score of the group:

1. technical content (40%).
2. presentation (20%).
3. design content (40%).

The jury of experts this year consisted of:

| | |
|---|---|
| Prof. B.A.C. Droste | TU Delft |
| Prof.dr.ir. J.L. van Ingen | TU Delft |
| Prof.dr. Lam Khin Yong | Nanyang Technological University |
| Prof.dr. Shaker Abdel Meguid | Nanyang Technological University |
| Prof.dr.ir. A. de Boer | Universiteit Twente |
| Dr.ir. G. Gadiot | NIVR |
| Ir. H. Minnee | Stork Fokker Aerospace |
| Ir. Y.W. Sit | SpaceTech |

| | |
|---|---|
| Ir. J. Verbeek | ADSE |
| Ir. H. Cruyssen | Dutch Space |
| Ir. M. Ellenbroek | Dutch Space |
| Ir. F. van den Bogaart | TNO |
| Ir. R. Voeten | Bradford Engineering |
| Ir. R. Kalmann | KLM |

# 2. REDESIGN OF A LARGE FREIGHTER FUSELAGE SECTION

*Students:* C.A. van der Bent, S. Cervera, M.A. Fiksinski, M.P. de Graaf, J. Hendrix, G.R. Ideler, J. Maarse, W.J.B. Mollers, T.M. Stouten, M.L.Verbist

*Project tutor:* Dr.ir. R.C. Alderliesten

*Coaches:* Dr. D.M. San Martin, Dr. M. Abdallah

## 2.1 Introduction

Fuselage section 18 of a large freighter aircraft, the A380F, is the section between the main wing and the tail section. This section is highly loaded. The current design of this section is a design full of compromises with respect to materials, structural aspects and manufacturing techniques. New materials and technologies were not always taken into account, but they can have some big advantages.
This is because a lot of politics is involved; some technical decisions might not be the most optimal. It is therefore interesting to see what result could be obtained if a team of future engineers would attempt to come up with a better design. Having this as a starting point, the following mission need statement for this project has been defined:

*To redesign a large freighter fuselage section optimized with respect to structural weight and cost.*

At the start of the project the requirements that have to be fulfilled by the design, have been determined. These requirements are divided

into technical requirements and constraints. Below, the top-level requirements of both types are mentioned.

- Technical requirements
  - Structural requirements
  - Mass requirements
  - Aerodynamic requirements
  - Maintainability requirements
  - Material requirements
- Constraints
  - Project schedule requirements
  - Sustainability requirements
  - Legal requirements
  - Cost requirements
  - Safety requirements
  - Market requirements

The design of a complex product in a relatively short period of time cannot be performed without making certain assumptions. For the redesign of section 18 of the A380F this is also the case. The following main assumptions have been made for the project:

- The skin thicknesses in the cross-sections are constant over the entire section
- The number of stiffeners is constant over the entire section.
- Section 18 is considered as a whole, and not as two parts like has been done by Airbus.
- More specific assumptions with respect to materials and manufacturing, structural analysis and cost analysis.

## 2.2 Concepts studied

**FML & Aluminum-Alloy Combination**

Concept 1 is very similar to the current section 18 design, because it is built up from the following materials:

- Glare skin for upper section
- Al-2091 skin for side and lower section
- Al-8090 stiffeners, floor beams and frames

Two versions of this concept have been proposed since the optimum number of stiffeners was not yet determined at this stage. One version is with 140 stiffeners, the other with 284 stiffeners.

The stiffener choice highly depends on the mass that can be saved by using a proper material. From this point of view the CFRP is the most obvious choice. However, a problem with this material in combination with aluminium is galvanic corrosion. To prevent this, a coating will be applied.

The main characteristics of this design options are:

- Estimated cost of $ 28 Million
- Approximated total mass of 4700 kg
- Upper skin of Glare (35 % of the total skin area)
- Side and lower skin of Al-2091 (65 % of the total skin area)
- 24 Frames of Al-8090
- 284 Stringers of Al-8090

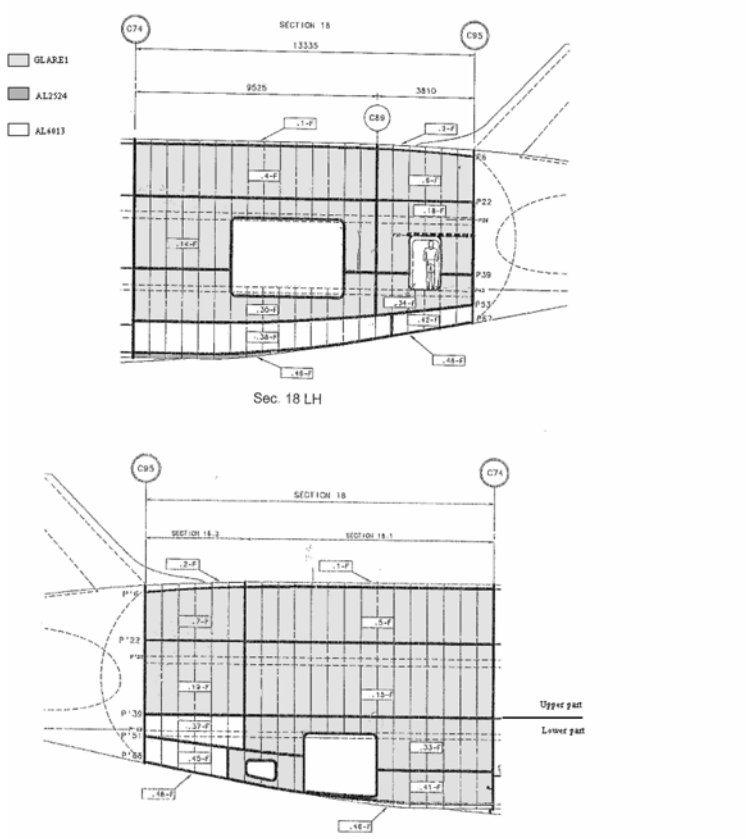



Figure 2 .1: Division of the Skin Material within Concept 1

The number of floor beams is estimated upon an average value of 2.3 for each frame. This number is derived from the fact that the first fourteen frames have three floor beams. The remaining part of the section has just 2 floor beams per frame.
The division of the skin material is visualized in figure 2.1.

**CFRP Skin**
Concept 2 is a rather daring concept, since it completely exists of CFRP (HT Carbon T300 with Epoxy 3501-6).
The airworthiness regulations force applications of CFRP to be designed according to the "safe life" philosophy. This means that higher safety factors have to be used. To stiffen the skin, longitudinal stiffeners have to be used. This implies the need to use non-metal stiffeners. The large potential difference – that exists between the two materials – results in galvanic corrosion. For these reasons, this concept is bound to the use of CFRP stiffeners. Once again the material properties are excellent, but the main concern is focused on the high factor of safety and the inevitable investment costs with respect to the manufacturing procedure.

The main characteristics of this design options are:
- Estimated cost of $ 36 Million
- Approximated total mass of 3800 kg
- Complete CFRP skin
- 17 CFRP Frames
- 200 CFRP Stringers

An impression of a fuselage made according to concept 2 is shown in figure 2.2.

Figure 2.2: Impression of a CFRP Fuselage

**Sandwich Fuselage**

Concept 3 is a sandwich fuselage, without stiffeners and frames. Here also, higher factors of safety have to be applied due to airworthiness regulations. The main characteristics are:

- Estimated cost of $ 34 million
- Estimated total weight of 4100 kg
- Facings completely made of CFRP
- Honeycomb core consists of Aluminium 5056 CR-PAA

In the sandwich fuselage there is no need for stiffeners and, if the fuselage is winded, there is also no need for frames. The result is that a sandwich fuselage is in principle far less complex then a stiffened fuselage since fewer parts are needed. For the sandwich fuselage it is assumed that the entire section is made out of one part. The major advantage is fewer parts since no frames or stiffeners are needed.
Like with concept 2 the problem of galvanic corrosion can be expected in this concept as well, in the interface between carbon and aluminium. Therefore the Aluminium honeycomb has been treated with a corrosion resistant coating in order to prevent this galvanic corrosion.

## 2.3 Trade-off

To be able to perform the trade-off in an efficient and objective way use has been made of the 'attractiveness' formula.

$$U_i = \sum_{j=1}^{N} A_{ij} W_j$$

This formula is a tool that enables evaluation of the attractiveness of an option in an objective way. This is done by multiplying the score of a specific option on each attribute with the weight of that attribute. The higher the value of the total attractiveness, the better the design option. The selected attributes and weights are presented in table 2.1.

| Attribute | Weight |
|---|---|
| Mass | 1 |
| Cost | 1 |
| Risk Assessment | 1 |
| Maintainability | 2/3 |
| Manufacturability | 2/3 |
| Sustainability | 1/3 |
| Safety | 1/3 |

Table 2.1: The Trade-off Attributes and their Weight

The trade-off, which was done for the design options, resulted into a score for each attribute. These scores are presented in table 2.2. To determine the attractiveness of each design option, including the current design as it is modelled, the scores of each attribute have to be multiplied with the weight of the attribute. The attribute scores have been assigned according to a scale from one to five. The first three attributes are quantifiable; the rest is merely scaled qualitatively.

| | Attribute | | | | | | |
|---|---|---|---|---|---|---|---|
| Option | Mass | Cost | Risk Assessment | Maintainability | Manufacturability | Sustainability | Safety |
| 0 | 3.3 | 4.82 | 5 | 4 | 4 | 3 | 4 |
| 1(140) | 3.8 | 4.35 | 5 | 4 | 4 | 3 | 4 |
| 1(284) | 4.2 | 5 | 5 | 4 | 4 | 3 | 4 |
| 2 | 5 | 3.75 | 2.1 | 2 | 2 | 4 | 3 |
| 3 | 4.5 | 4 | 2.1 | 2 | 3 | 4 | 3 |

Table 2.2: Scores of each Attribute for the different Design Options

The final attractiveness that was obtained for each design option can be seen in Table 2.3. It can be observed that the third design option (option 1(284)) has the highest obtained attractiveness and thus is the concept that will be selected for detailed design.

| Option | Attractiveness |
|---|---|
| 0 | 20.79 |
| 1(140) | 20.82 |
| 1(284) | 21.87 |
| 2 | 15.85 |
| 3 | 16.27 |

Table 2.3: Total Attractiveness of each Design Option

## 2.4 Detailed design description

The redesign of the large freighter fuselage section is done in a quite conventional way. This results in a not completely new design, but an evolution of the current design.
Lower risk and lower investment and certification costs where the main motives for this decision. The improvements are other materials, a new structural layout and new assembly techniques. These subjects are described below.

In the current section the aluminium alloys Al6013 and Al2524 and Glare are used. The materials of the redesign are Al2091, Al8090, Glare and a FML with Zylon fibres.
With Al2091, an aluminium-lithium alloy, a weight reduction can be achieved. Besides this, the material has better corrosion resistance. The aluminium parts (sides and keel) as well as the Glare parts (top) can be seen in figure 2.3, also the distinction between top and sides and keel will be clear. In the same figure the panel division can be seen.

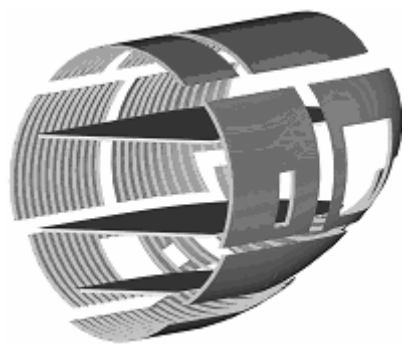


Figure 2.3: Exploded view of section 18

The Zylon fibre is used since it has a higher modulus of elasticity and a lower density compared to the HS Glass fibre used in the current design.

After an optimization the amount of stiffeners and frames changed, while keeping approximately the same stiffness. The amount of stiffeners increased from 140 to 176 and the amount of frames increased from 22 to 24.
Besides this a shifted door location contributes to the new structural layout, this can be seen in figures 2.4 and 2.5. The idea was to align the aft side of one cargo door with the front side of the other, so both end at the same frame. Consequently the reinforcements can be combined, which can save weight.

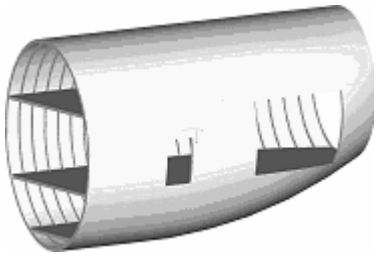


Figure 2.4: Left side of fuselage section 18

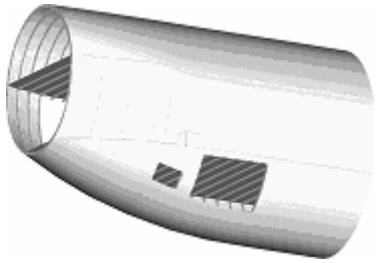


Figure 2.5: Right side of fuselage section 18

In addition to different materials and a new structural layout, new assembly techniques will be applied like friction stir welding. The main idea was to reduce the amount of rivets. Rivets weaken the structure, which requires the skin to be padded up. Materials will be

less sensitive to corrosion as well. For the same reasons adhesive bonding will be applied where possible.

## 2.5 Conclusions and recommendations

**Conclusions**

The main characteristics of the new design are its layout, material selection and assembly techniques. The main deck cargo door has been placed towards the back of the section instead of at the front. The main driver for the placement was the occurrence of the lowest structural loads. These occur toward the back of the section. In fact, the locations of the passenger door and cargo door have been interchanged.

In the redesigned section, less use is being made of Glare. Glare panels are only applied to the top, because that location is the most susceptible to fatigue, since it is loaded in tension. The rest of the section is built up of panels of aluminium lithium alloy (AL2091).

A third major change with respect to the Airbus design is considering the skin-to-skin assembly. It is suggested to apply friction stir welding to connect the aluminium sheets to each other. The application of this technique does not require the use of riveting. Friction stir welding leads to a reduction in structural mass and costs. Furthermore it is a more sustainable technique, since it produces less noise.

The applied optimizations have led to a total mass of 4,856kg. Compared to the mass estimation of the Airbus design of 5,557kg, the redesign has achieved a mass reduction of 13%.
The total cost of the redesign has been estimated at $19,947,000. This results in a total cost reduction of 3.2% with respect to the current design that was estimated at $20.598.000. Especially the cost reduction estimation should be considered with care, since the cost of the current Airbus design was not exactly known and an estimate had to be made.

The overall conclusion can be drawn that the new design as stated, is potentially an improvement over the current Airbus designs. One of the major improvements is the lower mass, achieved by the use of more advanced materials. This lower mass results in lower operating

costs, since less fuel needs to be burnt during flight. This makes the aircraft more sustainable in operations.
Other improvements are a lower manufacturing cost price per section and better performances with respect to manufacturing, fatigue and maintenance.

**Recommendations**
The design, created during the project, is of course not completely ready to be produced in the Airbus plant, and further optimizations can still be performed. These improvements are listed below:

- Structural mass:
  - A local optimization of the skin thickness based on the occurring stresses. Currently, a uniform skin thickness has been assumed from the front to back of the section.
  - The number of stiffeners can be reduced towards the end of the section. Right now the 176 stiffeners run over the whole length of the section.
  - The cut-out reinforcements have been sized conservatively until now. This leaves also room for optimizations.

- Structural Analysis: Use a full-scale FEM Analysis instead of the Excel tool based on engineering bending theory.
- Assembly: More knowledge should be obtained about the friction stir welding process. How this process affects the mechanical properties of a skin panel is a question that is not completely answered yet.
- Detailed design:
  - Perform a more accurate sizing of the elements.
  - Perform a more accurate mass estimation of individual components.

# 3. FLOATING SOLAR CHIMNEY

*Students:* M.S. Conen, M. Drijgers, K. El-Bachraoui, R.P. Huijser, J. de Klerk, S.J.J.K. Meysen, D. Sons, M.J. de Vlieger, H.J.B. van de Wal, S. van de Water

*Project tutor:* ir. V. Antonelli

*Coaches:* ir. A.H. van Zuijlen, dr.ir. M.C.M. Bakker

## 3.1 Introduction

5:57 AM, Chief of Maintenance Julio Rodriguez's alarm clock still has three minutes before doing its job. But Julio is already woken up by the light of the morning sun falling through his bedroom window. Sometimes this light suddenly turns into darkness for a few moments by a column shaped shadow that sweeps over the city of Deming.
Driving in his pick-up truck through the desert towards the slowly from left to right swaying chimney, he thought back of his childhood. Back then he wasn't afraid of heights and never hesitated to climb in the highest trees he could find. Now all that has changed and he doesn't envy the guys who have to go up there.

While turning right into 'the green mile' – the distance from the collector/*green*house entrance to the Turbine Maintenance Room (TMR) is almost exactly 1 mile – Julio turns the A/C on. Even now when the collector is at it's coolest, the heat storage tanks make sure the temperature under the collector never drops below 30 degrees. Back in the summer of 2009 he once made the mistake of doing his check-up during the afternoon. His truck overheated and broke down while driving in, and he had to spend the night in the TMR. The tow

truck had to wait for the next morning before the collector temperature was low enough again to enter.
The most uncomfortable part of Julio's morning routine is the 20 meter walk through the heat from his truck to the TMR and back. The breeze of air that drives the turbine doesn't exactly help cooling the human body down because that would require an air temperature lower than 37 degrees.

When he checked the status of the turbines at home on the internet all systems showed an 'OK' status. The turbines ran smoothly and generator power output levels still remain in the top 3 of all Solar Power Chimney's of this class around the world. However when checking the turbines manually he discovers No.11 is a little low on oil. Although not required Julio decides to top it up with some of his own expensive Mobil 1 instead of that synthetic crap which is normally used. After all June 23rd, 2033 is a special day. 'Rosa' turns 25 today…

Returned home, Julio finds his wife and children anxiously waiting. He is startled at first, but then remembers that on this special day, as a family tradition, he has to tell all about the history of 'Rosa' and its success.

Julio grabs a chair, opens a beer and after turning down the light, he begins to tell:

Once upon a time, approximately 27 years ago, the world was facing a huge problem.

More than a century ago during the industrialization, human effort was replaced by energy from fossil fuels. In the 20th century, technical and social development increased rapidly and energy needs from fossil fuels were never to decrease since then. Around the turn of the century, mankind predicted that, taking their current energy consumption and its increase into account, the world's oil reserves would be exhausted around the year 2040. Julio's children look at him with great unbelief, 'that would have been within ten years!' San Miguel, Julio's youngest son shouts.
Julio smiles: 'Yes my son, we must therefore be grateful that, at the beginning of the millennium, a highly motivated group of aeronautical engineering students designed a successful renewable alternative. The

alternative freed us from our dependence upon non-renewable and accompanied pollutant emissions and greenhouse gasses.

San Miguel, interested in technology as always, reminds his dad about a red book named the 'Delft Aerospace Design Projects 2006', by pointing at a bookshelf.

Julio reaches for the book and instantaneously opens it on this page. A weird but satisfying feeling comes up. What seemed revolutionary those days has become common practice nowadays.

The following has been taken from this historical document.

## 3.2 Working principle solar chimney

The working principle of the solar chimney (figure 3.1) is based on the combination of solar radiation and induced convective flow. Air is heated by solar radiation under a glass roof open at the periphery; this and the ground below it form a hot air collector with a diameter of 3140 m. The greenhouses covering lets the short-wave solar radiation pass through and retain long-wave radiation from the heated ground, also known as the greenhouse effect. This heated air expands and induces a pressure difference, forcing the flow to move into the direction of the base of chimney. The circular shape of the greenhouse realises that the inflow towards the chimney is uniform.
At the chimney base the air is diverted from a horizontal to a vertical flow with minimum friction loss. The chimney**,** with a height of 2940 m, can be seen as a tube that provides a pressure difference. The internal air is sucked up the chimney, due to the existing density difference with the external air.

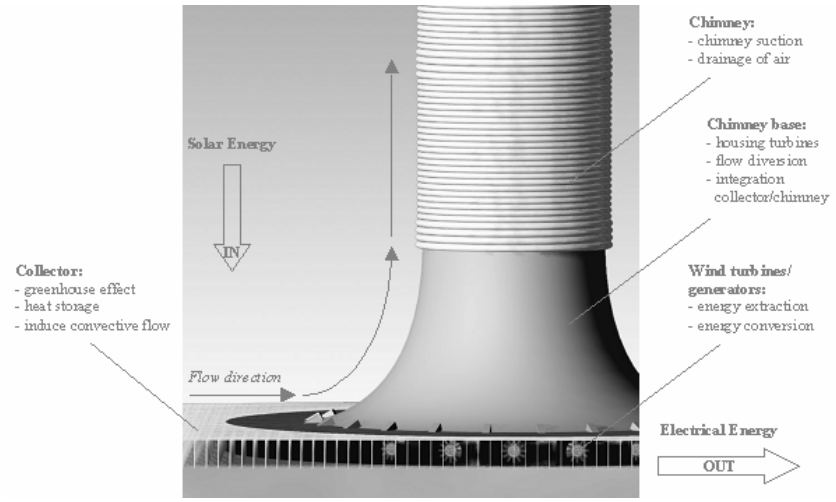



Figure 3.1: Working principle

The upward thrust of the air, heated in the collector, is approximately proportional to the air temperature rise in the collector and the volume and height of the chimney. The chimney suction facilitates the velocity of the up drafting air stream whilst cold air comes in from the outer perimeter of the collector.

The pressure energy of the air is converted into rotational energy by 24 pressure-staged wind turbines, with a diameter of 12.62m, surrounding the base of the chimney. The rotational energy is then converted into electrical energy by conventional generators. During the day a considerable part of the heat is stored into water containers placed inside the collector. This storage system enables heat to be radiated during night, ensuring a continuous 24-hours operation and level power output.

## 3.3 Mission statement

This statement summarizes the objective that has to be achieved during the Design Synthesis Exercise:

*"Ten students have to design within ten weeks a lightweight and commercially attractive solar chimney power station that operates continuously, with a peak power of 200 MW"*

## 3.4 Project requirements and constraints

In order to start the design process, the Project Objective Statement has to be translated into a clear list of requirements (table 3.1). Of course the '*peak power of 200 MW*' is a clear and important objective. '*Commercially attractive*' translates in a reasonable price for the electricity sold, while keeping the production and maintenance costs as low as possible. The '*lightweight*' characteristics of this large structure requires affordable manufacture and simplified construction.'*Operates continuously*' means operation 24 hours a day 7 days a week all year long. The solar energy collected during the day must be sufficient to keep the system operational throughout the night. Due to the size of the system and its vulnerability to external influences, it is constrained by many environmental characteristics.

| Description | Requirement |
|---|---|
| Peak power | 200MW @ 800W/m$^2$ |
| Price per kWh | ≤ 4 €ct/kWh |
| Continuous operation | 24h/day |
| Wind intensity | Negligible amount |
| Solar radiation intensity | >1950kWh/m²y |
| Rain intensity | Negligible amount |
| Producibility | Good |

Table 3.1: Requirements

## 3.5 Concept studies and trade-offs

The solar chimney consists of three main parts that are of massive size. They include the chimney, its base with integrated wind turbines and a collector. For all three subsystems numerous concepts have been looked at in detail. These studies have delivered the ability to select the winning concept for each subsystem based on sound arguments. These subsystems have then been integrated to represent the most effective solution to fulfill the above-mentioned mission statement.
The concept studies have been preceded by the determination of the optimal location for installment and operation.

**Location**

The options for optimal location, based on solar radiation level, are situated in:

- United States: California, Nevada, Arizona or New Mexico;
- Chili: Andean Plateau;
- Australia: Northwestern region.

The trade-off has been done with respect to the level of; solar radiation level, available space, power grid network, market opportunities, available knowledge/means, political environment/funding, meteorological conditions.
According to the trade-off made, New Mexico US is the most suitable global location.

**Chimney concepts**

For the chimney design, three variants were studied:

- Concrete chimney concept;
- Metal truss chimney concept;
- Floating chimney concept.

The trade-off has been done with respect to; overall costs, available experience and feasibility. Concrete and metal truss structures are used on large scales in constructing tall buildings, implying a high level of experience. However constructing a chimney with a length no other man-made structure has ever reached before is unique and considered almost infeasible with these options. Furthermore seen the required amount of concrete and metal and the increasing construction costs with height make these options a very expensive operation. For the floating chimney case the opposite holds. It is seen as low-cost, lightweight and challenging, but relatively simple solution, which excellently fulfills the project requirements.

**Collector concepts**

For the collector the following concept studies have been performed:

- Cover material: Glass, PolyCarbonate or Polyethylene;
- Heat storage: No heat storage, Passive heat storage or Active heat storage;
- Supporting structure layout: Flat shaped or Sawtooth shaped.

The trade-off on cover material has been done with respect to several relevant material characteristics; of which price, lifetime, fracture toughness, transmittance and density were considered most

important. Trade-offs showed that glass, especially with respect to its long lifetime and lasting high level of transmittance, is the most suitable.
The trade-off on what heat storage system to apply, was based on two questions; on one hand is it necessary for continuous operation and if so; is there any gain in applying a complex and expensive active system? The passive heat storage system consisting of steel containers filled with water prevailed.
The trade-off considering what layout would be the most effective was based on; shadow casting of structure, material usage, airflow obstruction and level of water drainage. The flat option showed to be by far the best, if special drainage facilities are incorporated in the design of the flat shaped layout.

**Turbines**
For the energy extraction the following concept studies have been performed:

- Single vertical axis turbine;
- Multiple vertical axis turbines;
- Multiple horizontal axis turbines.

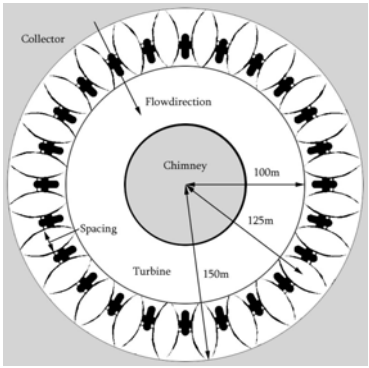



Figure 3.2: Turbine lay-out

These concepts differed in the number of turbines used and the positioning thereof.
A selection was made based upon a set of cost-, efficiency- and structure criteria.
The configuration with 24 horizontal axis turbines placed in a circle surrounding the chimney base was determined to be the most suitable one (figure 3.2).

## 3.6 Selected concept design

*The concept phase and associated trade-offs in combination with a extensive computational flow and performance analysis resulted in the most optimal solution to achieve our mission statement.*

**Chimney**

The design criteria have to be set in such a way that the chimney is able to resist the highest velocity winds in New Mexico. This problem is counter acted by letting the chimney rotate at its base. During normal wind conditions the chimney will have a maximal deflection angle of 25.8 degrees.

At the root of the chimney a concrete base is constructed which grounds the chimney and houses the turbines. In the middle of the base there is a large concrete counterweight cone, which is connected to the chimney with a carbon fiber cable (figure 3.3). This cable is attached to the supporting rings that are placed inside the chimney. These rings have besides keeping the chimney attached to the ground a supportive function. The supporting rings with spokes (figure 3.4) are made out of glass-fiber, which give the chimney a rigid characteristic.

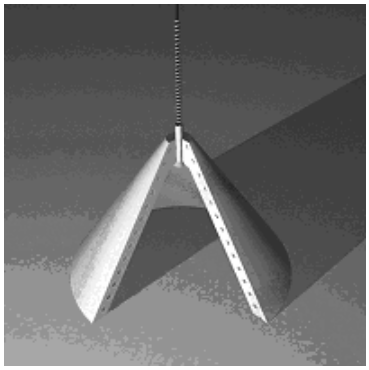


Figure 3.3: The base and cable

Hydrogen filled balloons attached to the inner wall fabric ensures that the chimney 'floats'. Seen the fact that the chimney may tilt due to external wind forces, more lifting force is required to assure that the chimney maintains its effective height. This lifting force is generated

with the use of these hydrogen filled lifting balloons. The balloons are circular shaped and placed at the outside of the chimney (figure 3.1). The diameter of the balloons varies with height from 3.2 meters at the base to 4.3 meters at the chimney top respectively. On higher altitudes more hydrogen is required because of the lower air density and the higher wind speeds. The balloons are made of a specific polyamide with an inner and outer coating; the inner coating prevents the hydrogen from escaping whilst the outer coating reflects the UV-radiation that potentially degrades the fabric.

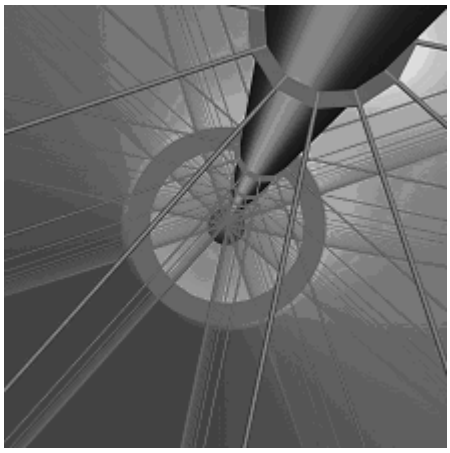


Figure 3.4: Cable with spoked supporting rings

**Collector**

Building the collector is a huge challenge because of the large diameter. But for the collector a simple design is used and no high-tech solutions are present in the collector. The maximum size of the glass plates is 3 by 3 meters with a thickness of 10 mm. With this size the plate is capable of carrying a 9 cm snowload with a safety-factor of 1.5.

The design of the collector can be seen in figure 3.5 and the maximum length of the vertical poles has been calculated taking in account the Euler-buckling. To make it as cheap as possible the minimum sizes of the vertical poles range from 4-10 mm thickness and 70-150 mm diameter. The I-beams supporting the glass have a dimension of 126 by 76 mm and on top of these I-beams are rubber mats to support the glass, allow for and make the connection airtight.

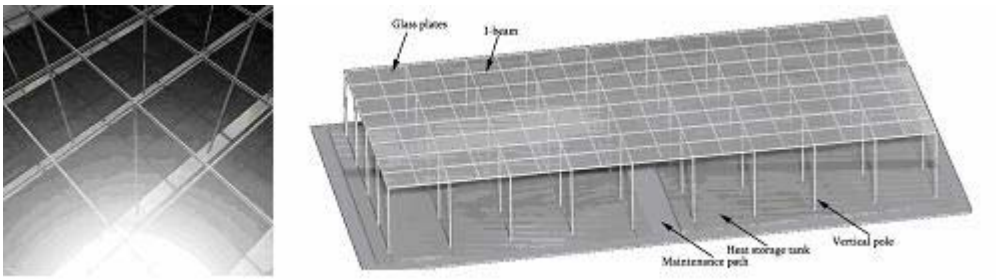



Figure 3.5: Collector overview

Heat storage in the form of water tanks is used in the collector to make sure that the solar chimney can operate continuously during the night. The heat that enters the collector during the day is stored in water-tanks, which contain in total 2.5 billion liters of water. Because of the heat storage the peak power of 115 MW is reached at 4:30 in the morning because of the highest temperature difference between the collector and the outside temperature. The average output is 95 MW and the total output per day is 2.29 GWh.

| **Solar chimney power station** | | | | |
|---|---|---|---|---|
| Height | 2940 m | Average day power output | 81 – 115 MW | |
| Diameter: | 3140 m | Maximum power output: | 157 MW | |
| Total system costs: | €573 million | Average day energy output: | 2.29 GWh/day | |
| Design wind velocity: | 4.5 m/s | Electricity sale price: | €0.04 – €0.06, €0.05 on average | |
| Maximum wind velocity: | 30 m/s | | | |
| **Location** | | | | |
| New Mexico, US | Near the city of Deming | Very high solar radiation | Average wind speed | 4.5 m/s |
| Average low rainfall | Low chance small earthquakes | No major earthquakes | Maximum wind speed | 23 m/s |
| **Collector** | | | | |
| Circular shape | Flat roof | Glass roof | Glass plates | 3 x 3 m x 10 mm |
| Diameter: | 3140 m | Steel structure | I-beams: | 127x76mm x6mx13 kg/m |
| Height collector: | 2m – 15m | Terrace shaped layout | Thickness tubes: | 4 mm – 10 mm |
| | | | Diameter tubes | 70 mm – |

| | | | | |
|---|---|---|---|---|
| | | | | 150 mm |
| **Heat storage** | | | | |
| Black steel containers | 34088 large containers | Dimensions large | 27 x 5.85 x 0.4 m | |
| 2,500,000 $m^3$ of water | 17044 small containers | Dimensions large | 27 x 1.425 x 0.4 m | |
| **Chimney** | | | | |
| Height: | 2940 m | Chimney deflection at $V_{wind}$ = 4.5 m/s | 25.8° | |
| Inner diameter: | 95 m | Chimney deflection at $V_{wind}$ = 30 m/s | 77° | |
| Outer diameter: | 101.4 m – 102.5 m | Lifting gas | hydrogen | |
| | | Cross sectional diameter lifting balloons | 3.2 m – 4.3 m | |
| Coated polyamide | Inner coating: impermeable aluminium | | Outer coating: UV protective | |
| **Chimney supporting rings** | | | | |
| 12 carbon fiber spokes | Glass fiber ring | Cross sectional diameter | 40 mm | |
| | | Wall thickness | 5 mm | |
| **Chimney base** | | | | |
| Inner diameter concrete base: | 200 m | Diameter counterweight cone: | 40 m | |
| Outer diameter concrete base: | 300 m | Height counterweight cone: | 26.4 m | |
| Mass concrete counterweight: | 20,000,000 kg | Wall thickness cone: | 3.25 m | |
| Maximum tensional load cone: | 100 MN | Steel spring cable attachment length: | 17.8 m | |
| Maximum moment cone: | 4000 MNm | | | |
| **Cable** | | | | |
| High Tensile Strength Carbon fiber | | Maximum diameter: | 244 mm | |
| **Turbines/generators** | | | | |
| 24 horizontal axis turbines | Maximum power output per turbine | 6.54 MW | Placement: | 125 m from center |
| Converging-diverging channel | Diameter turbines | 12.62 m | | |

Table 3.2: Design parameters

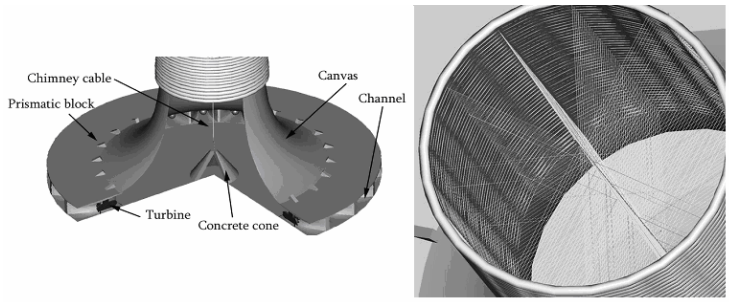



Figure 3.6: Integration base and chimney

## 3.7 Business plan

The solar chimney generates on average an output of 2.29 GWh per day and the solar chimney itself will have a lifetime of 30 years. The price of the complete solar chimney is 527 million euros with an annual operating price of 12.5 million euros. To compete with the other energy sources, such as wind energy or nuclear energy, the price of the electricity per KWh is 4 cents. The price of the electricity produced by the solar chimney will be around 4-7 cents per KWh. With this price per KWh, the break even point of the solar chimney will be reached after 15 operating years. After these 15 years there will be a profit as can be seen in figure 3.7.

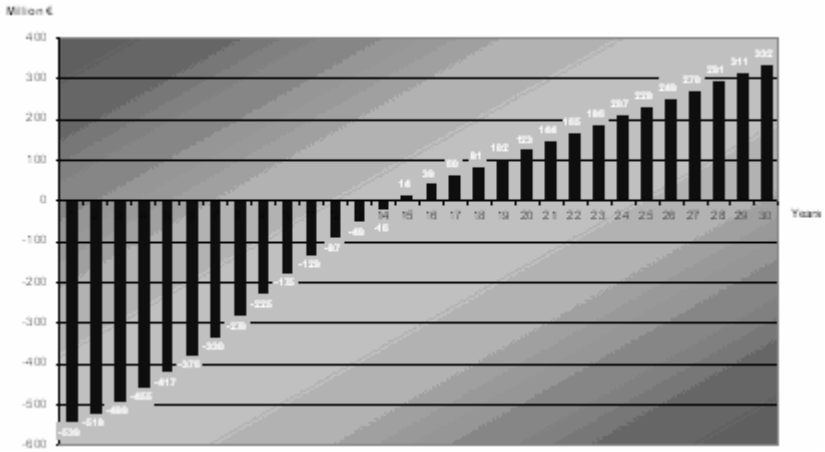



Figure 3.7: Profit

## 3.8 Conclusions and recommendations

The huge dimensions of the Solar Chimney make the design a real challenge. Nevertheless it can be concluded that the Floating Solar Chimney is a feasible, clean and renewable energy source. With the capability of delivering the affordable electricity so vital for maintaining the high living standards of the 21st century to over 100.000 homes, it can be concluded that the Solar Power Chimney is a real competitor on the energy market of the future. Additional future research must be done with respect to: dynamic stability, integrating the chimney-parts, thermal expansion, lighting influences, water and rain influences on the chimney and the final construction method of the floating chimney.

# 4. UNMANNED AIRBORNE GRAVIMETRIC SURVEYING OF THE OCEANS

*Students:* N.M.L. De Backer, S. Molenaar, L.Q. Nguyen, W.P. Otto, S. De Ridder, G.G.J.Rigot, S.S. Siregar, M.B. Tayara, M.M. Willaert, T. Yuyung Liauw.

*Project tutor:* dr.ir. P. Ditmar

*Coaches:* dr. M.O. Kechine, ir. O. Stroosma

## 4.1 Introduction

The geoid of the Earth is defined as an equipotential surface which (approximately) coincides with the mean ocean surface. If there would be no ocean currents, then the sea surface would correspond to the geoidal surface. In the past satellite missions have been designed such that they can measure the geoid of the Earth. These missions include CHAMP and GRACE. Also in 2007 the GOCE mission will be deployed, which will provide the most accurate geoid model yet. However, the spatial resolution in combination with the geoid height accuracy is limited when using satellites, since it is dependent on the flight altitude. So then efforts have to be made to try to obtain more accurate results other than with satellite missions.

## 4.2 Mission objective

A group of ten students has therefore been assigned to come up with a mission concept that will determine the geoid with this higher spatial resolution in combination with high accuracy. All the ten group members are students at the Faculty of Aerospace Engineering at Delft University of Technology. To complete their B.Sc. degree all students have to complete the Design Synthesis Exercise (DSE). The mission concept design for unmanned airborne gravimetric surveying of the oceans is part of the DSE 2006.

The objective of this project has been to present a mission concept that will determine the geoid of the oceans with a much higher accuracy than can be achieved with the aforementioned satellite missions.

## 4.3 Top-level requirements and mission need statement

The project had to be completed in ten weeks by a group of ten students. There were a number of top-level requirements of vital importance to the project:

- The mission shall be performed using one or more unmanned airborne vehicles.
- The geoid shall be measured with an accuracy of 3 cm in combination with a spatial resolution that is better then 70 km (the target value is 30 km).
- The entire ocean surface shall be covered without spatial gaps.
- The mission shall be performed within a budget of 100 million euros.
- The total mission shall be performed within a period of 12 years.

This gave rise to the formulation of the following mission need statement:

*"Design an unmanned airborne mission, with a duration of 12 years, for global gravimetric surveying of the oceans, within a budget of 100 million euros, in a group of 10 students within a time span of 10 weeks."*

## 4.4 Concepts study and trade-off

The total mission to determine the geoid model of the oceans consists of a number of elements. First of all a payload needs to be designed that supports the goal of performing gravimetric measurements. This payload then has to be integrated into an unmanned aerial vehicle (UAV). The UAVs are then used to perform the flight campaigns.

Concepts were studied for the two main payload systems: The gravimeter and the positioning system. A trade-off was performed for both these systems. Furthermore, six types of UAVs were examined and also the types of supporting stations for these UAVs. The last two were then combined to perform a trade-off for the flight campaign.

**Gravimeter**

To determine the geoid height of the global oceans, the gravity field of the oceans is needed. The device to carry out gravity measurements is the gravimeter. The concept of gravimetric measurement is as follows; a measurement by a gravimeter consists of the total acceleration undergone by the moving platform. To obtain the gravity acceleration at a particular measurement point, the local accelerations of the aircraft have to be subtracted from the total measured value.

There are various concepts of the gravimeter that have been assessed; and finally a trade-off has been performed to pick the best design option. This trade-off has been performed in two phases; the first and the second trade-off. The first trade-off had the purpose of eliminating the obvious losers among the design concepts for the gravimeter. The second trade-off has been carried out according to the following method; assigning weight factors to every criterion deemed important, then giving a score to each criteria for every gravimeter. The trade-off has been performed considering the most important requirements and criteria regarding the gravimeter; accuracy, operating temperature range, drift, stability, cost, weight.

The choice has become the LaCoste & Romberg air gravimeter system, which is manufactured in the United States. This type of gravimeter is widely used in airborne applications and the company has had a long history in manufacturing gravimeters of high quality. The gravimeter meets the requirements for accuracy of 1.0 mGal, has its own stabilizing platform that performs up to 22° pitch and 25° in roll. It can perform well under accelerations up to 100,000 mGal both horizontally and vertically.

The gravimeter is procured as a whole package, a complete system containing a thermal control system, stabilizing platform, software, monitor, human-machine interface allowing control by proxy, spare parts and basic maintenance tools. It is essentially a plug-and-play system. To initialize, set up the system and to perform basic maintenance, personnel need to be sent for training in the United States. When all is said and done, the LaCoste & Romberg air gravimeter system is the best choice for the mission and ensures the success of it. A picture of the LaCoste & Romberg gravimeter is shown in figure 4.1.

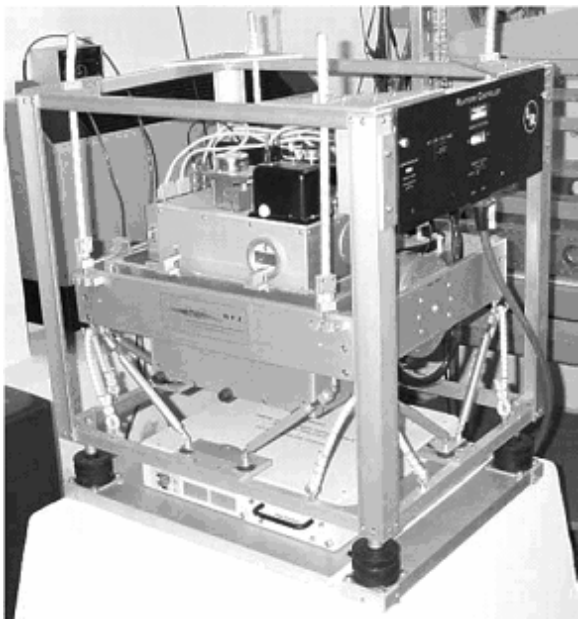


Figure 4.1: LaCoste & Romberg gravimeter

**Positioning system**

For our mission GPS is the most obvious choice for the scientific part of the positioning problem. High accuracy combined with global coverage makes it the perfect choice for the mission. GPS has also shown high reliability in airborne applications. There are however certain choices that must be made in order to determine which kind of GPS system to use and whether or not it should be augmented any further by other positioning devices. The most important ones that were considered are: Global Differential GPS (GDGPS), GPS + International GNSS System (IGS), GDGPS + Altimeter and finally plain GPS.

The result of the trade-off was that the only viable positioning system for this mission is the use of the GDGPS system. It has very good accuracy and also very important: global coverage. The costs are well within the limits of the budget and will probably not cause any problems in the total mission cost.

**Unmanned airborne platform**

The flight campaigns have to be flown using one or more UAVs. The UAV will have to fly largely autonomous, at various high altitudes and reasonable airspeed. The vehicles also have to be capable to carry a certain payload with certain weight. Considering all the available UAV designs, we have the following options: Rockets, fixed-wing UAVs, kites, balloons, helicopters and airships. Between these a trade-off has been made and it soon became very clear the balloon, the rocket, the helicopter and the kite were not an option. This was because they were either unstable, or not capable to fly at certain altitudes with the specific payload. The options left after the first trade-off were the fixed-wing UAV and the airship. When using airships, it was known from the start that multiple were needed because of their relatively low speeds compared to what fixed wing UAVs are capable of.

**Stations**

One or more stations support the UAVs in terms of take off and landing, maintenance and also checking the UAVs while they are in the air.

A number of stations can be distinguished, namely the ground-based station, the sea-based station and the air-based station. Each of the stations can also be stationary or mobile and there is also a choice in having multiple stations or just a single station. Several station options could be removed from further research early on:

- *Stationary ground stations:* Stationary ground stations are very inflexible in operation. UAVs must take off and land from the specific take-off and landing site the ground station is located. If a next flying mission has to start thousands of miles from the station, then a lot of time is lost flying to that area, before the actual measurements can be done.
- *Single ground station:* If a single ground station is used, then there is no redundancy. If the command and control hardware fails then the support of the UAVs cannot be monitored. Multiple ground stations can be located on both sides of the ocean or maybe multiple flight campaigns can be performed in different oceans at the same time.
- *Stationary sea stations:* Stationary sea stations (like oil platforms) are not an option for this mission. First of all, they are located too close to shore, so the advantage of having a station at sea diminishes. Next to that, it might prove very difficult, if not impossible, to buy or get access to such a platform.
- *Air stations:* All options that involve air stations will also not be examined any further. It is an option that might be feasible in the future, but there are too many uncertainties and high-risk elements involved to consider this as a feasible option now. The idea of having an air station above the ocean surface and smaller UAVs docking to and taking off again from this station is a very interesting option to do further research on. It is not feasible in the scope of this project.

**Flight campaign**

To perform a flight campaign, one or more UAVs are needed to fly along certain flight paths. The UAV options that remained were the airship and the fixed wing aircraft. The station options that remained were multiple mobile ground stations and one or more mobile sea stations. The characteristics of each option are shown in table 4.1.

| Combination | Characteristics |
|---|---|
| MMGS + Airships | Airships dock to and depart from ground station (truck). Landing and take-off sites can be wherever the trucks can move to. |
| MMGS + Fixed Wing | Landing and take-off from existing airstrips (runway needed). Limitations in the locations for take-off and landing. |
| MSS + Airships | The airships dock to a ship. This option is complex and expensive. |
| MSS + Fixed Wing | Principle of an aircraft carrier. Very high costs for just the sea station. |

MMGS = Multiple Mobile Ground Stations
MSS = Mobile Sea Station(s)

Table 4.1: Flight campaign options

Weight factors were assigned to different criteria. Then each option got a score for each criterion. In this way the best campaign option proved to be multiple airships in combination with multiple mobile ground stations. An artist impression of an airship flying over the ocean is presented in figure 4.2.

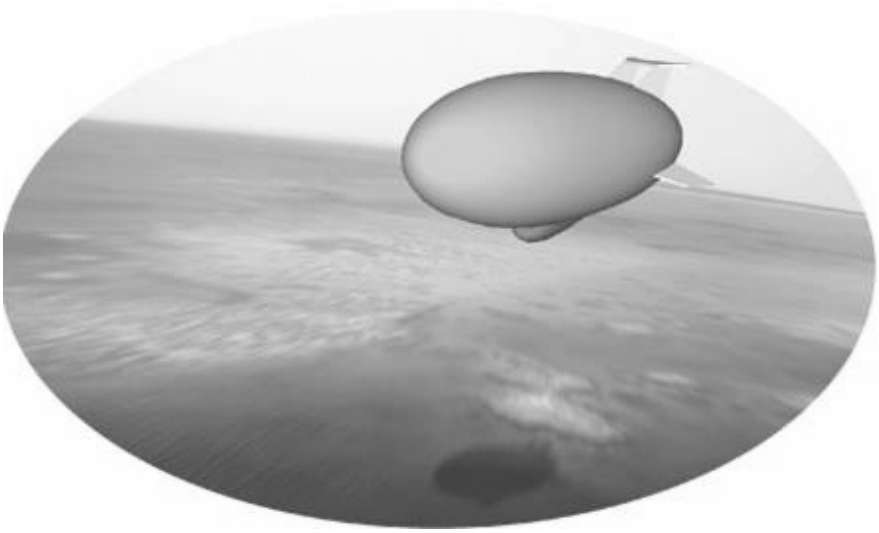


Figure 4.2: Artist impression of the designed airship flying over an ocean

## 4.5 Detailed design

**Communications system**

All the acquired data has to be sent to the Ground Station. For this we need a communication system on board the airship. The airship is going to fly for thousands of kilometers, because of this we need the airship to communicate via satellites for continuous communication. There will be a data rate uplink for telecommand of $R_{uplink}$=3840 bps and a data rate downlink for the gravimeter, GPS, and telemetry of $R_{downlink}$=25620 bps. To size the communication system we have to determine the received energy-per-bit to noise density from the Bit Error Rate we want to achieve. This parameter can also be calculated with the link budget and has to be compared to the required received energy-per-bit to noise density to check if the communication system achieves its goal. The link budget sizes the transmit power, P = 50 W, and antenna diameter, D = 0.70 m. With the transmit power we can determine the mass of the communication system, which is about 4 kg. If we include all other devices like for example a pointing device we will get an estimated mass of 10 kg.

**Storage device**

Although there is a communication system we still need a storage device to store the acquired data for 2 days as a back-up system. Then if the data is not send properly it can be send a second time. There will be a storage capacity needed of at least 553 Mb.

**Power production**

By using solar arrays, one can produce in a sustainable way the power for the airship. The airship is planned to fly only on days where the available solar power output is bigger or equal to 5000 $Wh/m^2$ (solar power amount where the airship is designed for). The batteries can deliver in that case 5000 $Wh/m^2$ (enough for 12 hours of flight during night operation or in case of solar array/extra power unit failure). For example, at the equator, one can fly without restrictions during the year (available solar power output is always bigger or equal to 5000 $Wh/m^2$). When progressing to the more northern and southern latitudes, one has fewer days to operate on. Another remarkable outcome of the simulations is the fact that one has to fly between 9 a.m. and 15 p.m. in an East-West progress direction. Outside these hours, one has to fly in a North-South progress direction.

**Airship performance analysis**

For this mission, an autonomous airship with extended mission endurance is needed and a solely powered airship would be beneficial in terms of this endurance. Such an airship uses solar energy to power all the systems and to propel the airship. It was investigated how such an airship looks like and if it is feasible. The resulting airship is displayed in figure 4.3.

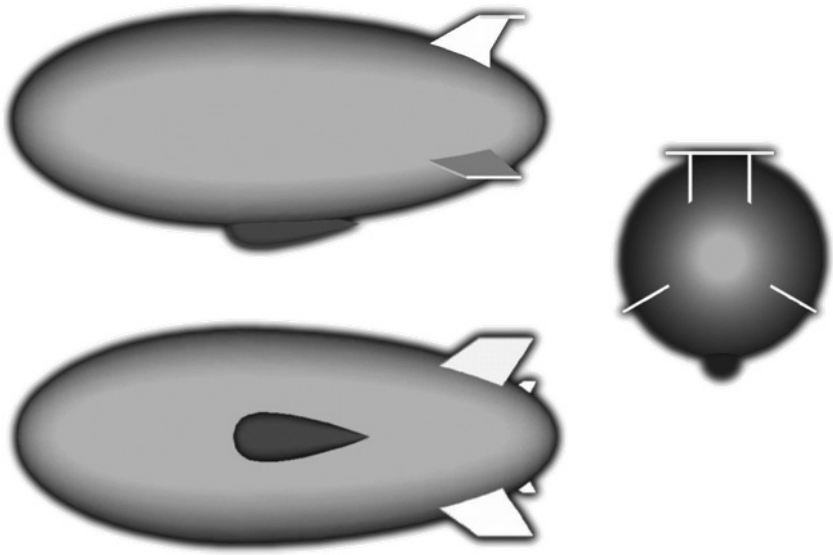


Figure 4.3: Three sided view of the airship

The following design strategy was used. First the gross lift is calculated as a function of the length and the airspeed and then the weight of the different components (payload, lifting gas, envelope, fins, structure) is subtracted. In this way, the net lift available for the power and the propulsion system is calculated as a function of length and airspeed. Inserting a specific airspeed, both the net lift available and the weight become only function of the length and one can make a cross plot of these functions. The net lift available should be equal or larger then the weight and where both graphs cross, the minimum length can be found. The chosen flight speed for which the cross plot is made, is obtained by investigating a constraint for the airship: the needed solar area should be equal or smaller then the available area (surface area of the hull / 2). In table 4.2, the characteristics and the

performance of the airship needed for the mission is summarized. These numbers were found using the above design strategy.

| Parameter | Value |
|---|---|
| Length | 147 m |
| Maximum airspeed | 23.5 m/s |
| Cruise speed | 21 m/s |
| Total mass | 15000 kg |
| Total fin area | 805 $m^2$ |
| Mass of lifting gas (helium) | 2250 kg |
| Solar area | 5425 $m^2$ |
| Mass of batteries (fuel cells) | 4650 kg |

Table 4.2: Important airship parameters and the corresponding values

Under idealized conditions, a solely solar powered airship is feasible. However in reality, there are no ideal conditions. Especially the wind is an important factor. The maximum airspeed is not sufficient to cope with extreme weather conditions. An additional power and propulsion system should be added to cope with those conditions, so further investigation is recommended.

**Stability and control**

The airship shows stable behavior around the chosen flight speed. However, there are not yet aerodynamic data available. In order to complete the stability analysis it would be necessary to obtain aerodynamic data for our airship, such the non-linear model can be completed and analysis can be performed accordingly.

**Integration**

The integration process has been described for eight main systems (gravimeter, fuel cells, flight control, GDGPS antenna, communication system, communication antenna, thermal control and positioning). The four main aspects investigated are mass, power supply, thermal control, and produced data of the main systems. All the systems are placed in the gondola except for the GDGPS antenna and the communication antenna, which are placed on a platform on top of the airship. In table 4.3 one can find the main systems with their characteristics. The values that are marked with a *, are values that have been guessed after research. The boxes that are empty could not be valued because we have too little knowledge about it.

| | Weight [kg] | External power | | Dimension | | | | Operational temperature | |
|---|---|---|---|---|---|---|---|---|---|
| | | Input voltage | Power consump. | L [mm] | B [mm] | H [mm] | Radius [mm] | min [°C] | max [°C] |
| GPS system | 1.81 | 10 – 30 Vdc | 8 W | 207.8 | 144 | 77.7 | - | -40 | +55 |
| GPS antenna | 0.45 | - | - | - | - | - | 146 | -40 | +85 |
| Gravimeter | 86+30 | 80 – 265 Vac @ 50 Hz | 450 W | 71 | 56 | 84 | - | 0 | +40 |
| Flight control system | 10* | 28 Vdc | 80* W | - | - | - | - | 0 | +40 |
| Fuel cells | 4650 | Output: 28 Vdc | Output: 8400 | - | - | - | - | +7 | +35 |
| Heater system | - | 28 Vdc | 2 W | - | - | - | - | - | - |
| Communication system | 10* | 10 – 30 Vdc | 40 W | - | - | - | - | 0 | +40 |
| Communication antenna | 1* | - | - | - | - | - | 70 | 0 | +40 |

Table 4.3: Payload and supporting subsystem specifications

**Flight campaign**

One of the top-level requirements is that the mission has to be completed within twelve years, including about two years of building and testing time. Using an airship velocity of 21 m/s, a flight path separation of 15 km and assuming the airships stay in the air effectively for 85 % of the time, then it would take five airships 9.23 years to cover the entire ocean surface without spatial gaps.

**Ground stations**

The mobile ground stations are all-terrain trucks, on which the airships can take-off and depart. The trucks are also for maintenance and repair purposes. Next to the trucks there should also be a command centre where the in-flight status of the airships can be monitored. This command centre can be either centrally located, or placed in the trucks themselves.

## 4.6 Conclusion and further development

**Conclusion**
Though there is still much that has to be investigated, from the so far obtained results can be concluded that the mission can be completed according to the mission requirements.

**Further Development**
After finishing the preliminary design of the mission, the first thing that has to be done is further research to develop the mission into detail. This can not be done during this project, so some recommendations are given for further study:

- The mission is now designed without taking into account the wind; at the height of 13.5 km there can be quite a lot of wind, and this has to be taken into account in all the simulations made.
- The airship has been assumed sufficiently stable for accurate gravimetric measurements, but this has to be investigated more into detail
- Investigation of the increase of the relative positioning accuracy.
- The rough ideas for the ground stations have to be worked out.
- Ground time is now set to 15 %, but this number is estimated. Additional research into ground time needs to be performed.
- Investigation of the legal aspects of performing the mission, like the flight restrictions per coastal area.

Of course these are not all things that have to be investigated. After the detailed design phase the actual development can start. The components are then tested: individually, at sub-assembly level and as a complete system. Together with these activities the legal requirements have to be sorted out to start the operation as fast as possible. After all data obtained during the operation has been collected and processed it has to be archived and distributed among the scientific community.

# 5. SENSOR NETWORKS FOR TRAFFIC MONITORING

*Students:* J.H.J. Gestels, A.E. Nguyen, T.M. van Opstal, R. van der Pol, M.G. Poorthuis, P.H.M. van Riet, D.J.D. de Ruijter, M. Strating, H.J. Vrijkorte, P.H.C. Wijkstra

*Project tutor:* dr.ir. B.G.H. Gorte

*Coaches:* A. Bucksch MSc, F. Karimi Nejadasl MSc

## 5.1 Introduction

Traffic congestion is a growing problem nowadays. One type of solution to this problem is the optimization of traffic flows using traffic models. Different macroscopic models exist that describe traffic flow. The major problem in solving traffic congestion, however, is the absence of microscopic scale data on traffic flow. Microscopic scale data is the registration of, amongst others, the behaviour of each individual vehicle. The collected data must contain a complete list of vehicles in the measured region at the time of measurement with, for each vehicle, a high-resolution trajectory in time.

The customer is the department of Dynamic Traffic Management at the Faculty of Civil Engineering at Delft University of Technology. They can use this microscopic data to determine the parameters of existing traffic flow models, such that the models can be used to effectively optimize traffic flow. The design of a system for the collection of microscopic data is what this project is primarily concerned with.

However, in the assignment two goals are set:

1. The design of a temporary traffic monitoring system, for the acquisition of microscopic traffic data as an input for behavioral research.
2. The design of a permanent traffic regulating system, which can provide real-time data for dynamic traffic regulation using electric road signs, traffic lights, etc.

The first goal is clearly labeled the primary goal of the project. Dividing attention amongst these two goals might lead to an insufficient level of detail in the design. In an early stage of the project it has therefore been decided to concentrate on designing a system according to the first goal, and keeping the second goal in mind as an extension of the system in the recommendations.

## 5.2 Mission need statement and requirements

The Mission Need Statement (MNS) has therefore been formulated as follows:

*"Design within two months a flexible system for the monitoring of individual motorized vehicle movements."*

The most important terms in this statement are clarified below:

| | |
|---|---|
| Design: | This exercise is narrowed down to the design of a system, not the construction and certification of it. |
| Two months: | This refers to the limited amount of time available for the project. |
| Flexible: | The term 'flexible' is chosen because it covers a lot of aspects the system needs. The system should monitor on different kinds of roads (highways as well as city traffic). Also, the system should be mobile and extendable so it can be used at more locations when needed. However, the term flexibility is limited in this discussion, and does not include operation at night, for instance. |

Monitoring: The output parameters are traffic movements, not the analysis and consequent dynamic traffic regulation.

Individual: The most important thing is that the system is able to follow the trajectory of different vehicles individually, i.e. traffic flow in microscopic detail.

The MNS forms the basis for the requirements, designing a system that fulfils all the requirements is designing a system that complies with the MNS and ultimately answers the customer's wishes. The most important requirements are:

- Flexibility: the system should be mobile and re-scalable.
- Accelerations should be measured with an accuracy of 2 m/s2 or better.
- Temporal resolution should be at least 10 Hz.
- 4 hours of measurement should be possible.
- Operation at temperatures between –15 and 35 °C, rainfall of up to 30 mm/h and hover at 6 Bft (or 13.8 m/s) should be possible.

## 5.3 Concepts

In this project, three concepts have been studied (see figure 5.1): (1) Fixed Optics, (2) Airborne Optics and (3) Airborne Hyperspectral Imaging (HSI). To determine these concepts, a sensor driven approach was used. When feasible sensors were discovered, the best suitable platform was searched for. The only sensors that appeared feasible are optical and hyper spectral cameras. This is due to their capability of taking images with a high resolution and high enough frame rate (10 Hz).

Figure 5.1: The three concepts. From left to right: (1) Fixed Optics, (2) Airborne Optics and (3) Airborne HSI.

**Fixed Optics**

In this concept, optical cameras mounted on posts or fixed objects monitor traffic. Something fixed with enough height is desired, so posts seem to be the most efficient. Available light posts and buildings can be used. When these are not available, a post has to be placed on the side of the road. The cameras are placed at a height of 40 m. The posts are placed at a distance of 150 m from each other. Data storage and transmission is done by a local data storage system, which sends its data to a central data system. Here the data can be processed. Costs are roughly € 350.000 per km (excluding operational costs).

Advantages of this system are the low operational costs and the permanent availability of the system. This makes it suitable for real-time traffic information. A disadvantage of this system is the relative immobility compared to the other concepts.

**Airborne Optics**

In this concept, optical cameras are mounted on unmanned airships, since a hovering and fuel-efficient platform is desired. These airships, flying at an altitude of 500 m, carry multiple cameras and can measure a 750 m stretch of highway. With a certain overlap area, a virtually unlimited number of ships can be combined to measure the desired distance. The maximum measuring time is four hours. To guide the airships, a ground station is present to watch what happens and to take action if necessary. Images are recorded on hard disks that will be read and processed afterwards in a research centre. The costs are roughly € 130.000 per km (excluding operating costs).

The airships are highly flexible in the sense that they can fly to any location. Due to the fact that the cameras can be rotated, even complex shaped roads can be monitored. The relatively high operational costs are a disadvantage.

**Airborne Hyperspectral Imaging**

Hyperspectral Imaging (HSI) is a technique in which a camera takes multi-spectral images. Physical materials can be distinguished by analyzing their spectral signature. For example asphalt and metal have different spectral signatures. This is advantageous for car detection.
The balloons (filled with helium) carry one HSI camera each. Just like for the Airborne Optics concept, a hovering and fuel-efficient platform is desired. Contrary to a lighter-than-air vehicle, a balloon can have a connection to the ground and it does not use fuel at all. The road distance covered by one balloon is about 45 m, so 22 balloons are needed for a one kilometre stretch of highway. The balloons float at an altitude of 100 m and are anchored to a ground control unit. Data transmission to the ground is possible through a wire. The ground units have wireless communication with the overall control unit to report the status of the balloon as well as their own status. The hard disks with the recorded data are removed from the ground stations and transported to a data processing centre. The costs are roughly € 650.000 per kilometre.

The balloons and small ground units can be transported with trucks. This takes some effort but, to a certain extent, this system is mobile. The biggest advantage of this system is the earlier mentioned capability to analyze images at different spectra. This will make the image processing a lot easier. The costs are a disadvantage, which are considerably higher than the other two options.

## 5.4 Trade-off

The trade-off criteria are listed in table 5.1. Also, the weight factors and (relative) scores are given.

| | | Weight Factor | Concept | | |
|---|---|---|---|---|---|
| | | | Optical ground | Optical airborne | HSI airborne |
| Costs | fixed | 2.5 | 3 | 5 | 1 |
| | operating | 2.5 | 5 | 3 | 1 |
| Performance | spatial resolution | 0.8 | 5 | 4 | 4 |
| | detection: intensity | 0.8 | 4 | 2 | 3 |
| | detection: shadowing | 0.8 | 2 | 4 | 4 |
| | temporal resolution | 0.8 | 3 | 3 | 3 |
| | operating conditions | 0.8 | 4 | 2 | 4 |
| Mobility | costs | 1 | 1 | 4 | 2 |
| | time | 1 | 1 | 5 | 2 |
| Safety | | 1 | 5 | 3 | 2 |
| Regulations | | 1 | 4 | 2 | 3 |
| Lifetime | | 1 | 5 | 2 | 3 |
| Maintenance | | 1 | 4 | 1 | 2 |
| | Total Score | | 54.4 | 49 | 33.4 |
| | Relative Score | | 0.73 | 0.65 | 0.45 |

Table 5.1: Trade-off results.

In this trade-off, the fixed optical variant wins. However, the customer was not satisfied with this choice, mainly because of the lack of innovation: mounting cameras on posts is already widely applied. Therefore, in agreement with both the customer and the project group, it was decided to work on the optical airborne variant in the final phase.

## 5.5 Detailed design of the airship

The system comprises of several components. First the airship and its subsystems are discussed. Then the ground components are described. Finally, operations, costs and the image processing are discussed.

**Airship**

In the design of the airship an unconventional double-hull configuration was chosen, based on the “Nautilus” concept developed by the Polytechnic University of Turin and three companies. The “Nautilus” airship was chosen primarily for the increased hover capabilities. Conventional airships are difficult to control at low

speeds because then the control surfaces are ineffective at low speeds. Moreover, the increased surface area makes a conventional airship more sensitive to disturbances. Instead of by control surfaces, the "Nautilus" is controlled using propellers that can be vectored in the horizontal plane.

The main features and dimensions of the airship are shown in figure 5.2, and clarified below:

1. The hulls have the same function as in conventional airships; they contain helium for buoyancy force and ballonets that can be filled with air to control the lifting force.
2. The central plane connects all components and houses the payload of the airship
3. The propellers are used for positioning and movement. Two are positioned above and two below the airship and pointed horizontally. The mounting arms of these four propellers can rotate along the vertical axis and are unbounded.
4. The two propellers located in the central plane are used for altitude corrections, for example during traffic monitoring operations when precise station keeping is desired.
5. The fourteen sensors are mounted underneath the central plane. This subsystem is discussed in the next paragraph.

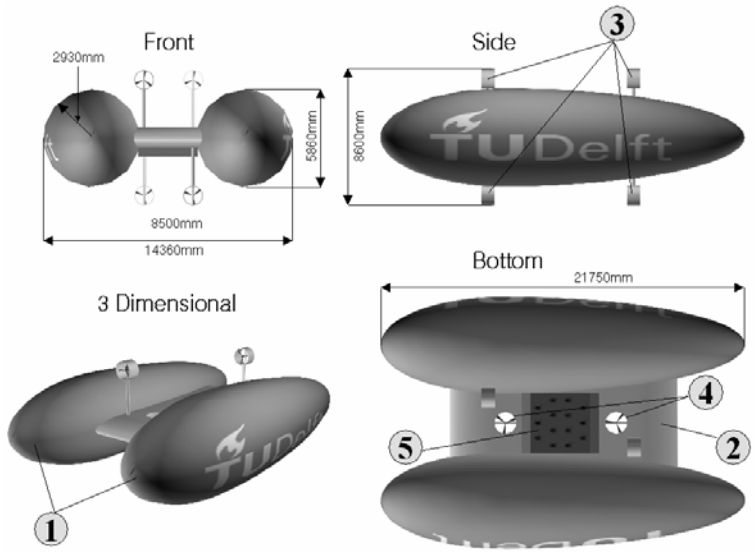



Figure 5.2: 3-View of the airship and dimensions.

**Sensor**

Multiple sensors are suspended under the airship. From image deformation considerations it has been determined that the optimal amount of cameras is fourteen. These cameras can be individually pointed to monitor a region of arbitrary geometry. Three cases have been considered, of which two are shown in figures 5.3 and 5.4, but this is but a small selection of the broad scope of possibilities. In each of these figures the arrow gives the location and heading of the airship.

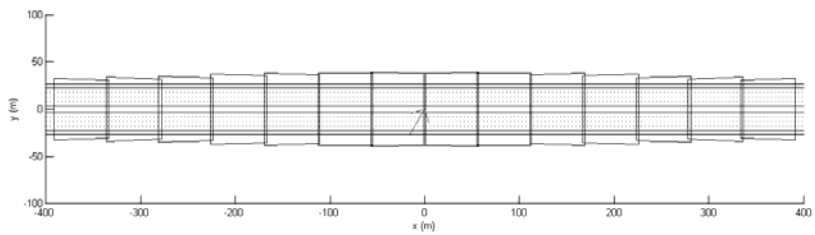



Figure 5.3: Camera layout for case 1; straight highway directly under the airship.

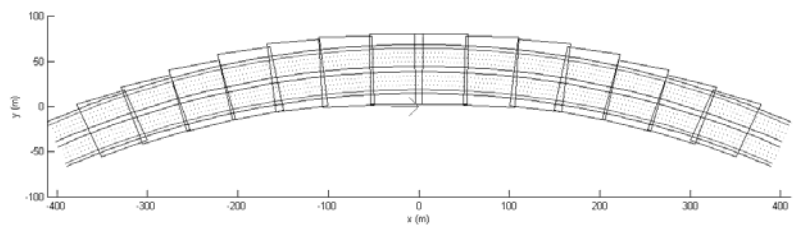



Figure 5.4: Camera layout for case 2; curved highway.

The sensor of the final concept is an optical video camera. The main criterion for the selection of the camera is the resolution, driven by the width of a road section and by the resolution with which this section is to be monitored.

A second criterion used for camera selection is that it produces monochrome images. In the trade-off between monochrome and colour images, monochrome images are chosen because of the lower data output. The images turn out to be as easy to process as colour images.

A camera is chosen with a resolution of $1600 \times 1200$ pixels, where the largest dimension is taken across the road. This has been done considering the deformation of the camera footprint (the ground

projected onto the CCD (Charge Coupled Device, a chip capable of converting light into an electrical signal) when the camera is turned in the direction of the road. It can clearly be seen in figure 5-3 that the footprints become parallelograms further from the centre of the image. To attain the required 5 cm resolution at the far end of the image, the margin is required to be this large to account for small disturbances.

By sweeping the camera away from the nadir direction the image distance inevitably increases. This means that the footprint increases and therefore the ground resolution deteriorates. To correct this, a zoom lens is mounted onto the camera. Because the pointing of the camera can be arbitrarily changed, as described above, a variable zoom lens is selected.

Finally, the cameras are mounted on a gimbal system, not directly to the platform. This is done for two reasons: first vibration and movement can be compensated for and secondly, the cameras can be pointed. This system, shown in figure 5.5, is an electrically controlled arm that can rotate around 3 axes.

Figure 5.5: The gimbal system.

**Power**

The power system supplies energy to the propulsion of the airship, cameras and all supportive equipment (e.g. flight computer, data storage, GPS receiver). In the context of sustainability it has been chosen to restrict the design options to non-polluting and renewable energy sources. A hydrogen fuel cell has been chosen, which emits water. As an energy carrier, hydrogen can be produced using electricity from renewable sources like solar and wind energy. The two most important components of the power system are briefly discussed.

From the requirements it can be seen that hovering at 13.8 m/s is required. To arrive at the measurement position with head-on wind, an airspeed of 17 m/s is used to dimension the fuel cell. Then the total power requirement is 36 kW.

From different fuel storage options, conventional pressure tanks are taken. The tanks are made of composite material. Compared to other options, this is a bulky solution, however, other methods are still in the research phase and bring considerable risk. The total volume of the tanks is 11.6 kg or, 282.9 L.

**The Modular Control Unit**

The automated control onboard of the airship is called the MCU (Modular Control Unit). On the ground an OCU (Overall Control Unit) controls all modules. This concept has been chosen to aid the extendibility of the system; modules can easily be added to the system without up-scaling the OCU, as long as the airships remain within 32 km; the range of the communication equipment. The MCU consists of avionics, control of camera pointing, image storage and communication with the OCU.

From stability analysis the short period motion and the oscillatory roll turn out to be unstable. To correct for this, an automatic flight control system is designed. The output is given to the propellers that control the airship movement.

Position and attitude determination is done by three systems. First, a GPS receiver with a resolution of 1.5 m determines the latitude and longitude of the airship. Secondly, a radar altimeter measures the altitude of the airship with an accuracy of 12.5 cm, as GPS cannot perform this accurately enough. Finally an attitude and heading reference system records the attitude of the airship.

All image data will be stored directly onboard, without intermediate processing. This has been done to decrease the complexity of the system. Finding appropriate image processing algorithms and estimating their compression rate is very complex and is beyond the scope of this project. From the requirements, four hours of recordings should be stored, with the previously determined amount and type of cameras, the total data storage capacity is calculated at 3.5 TB per

module. Commercial components are used for the storage of this data, the most prominent of these being the eight hard disks of 0.5 TB each. The telecommunication link is a Radio Frequency Modem (RFM) operating at 2.4 GHz with a maximum range of 32 km.

## 5.6 Costs

The costs of the system consist of three parts: the purchasing costs of the airship, the operational costs and the ground station costs. Purchasing one airship will require € 400,000, mainly due to the costs of the platform, the cameras and the stabilization system. Furthermore, the operational costs are € 2000 per airship per research session. The largest part of these costs consists of labour. Finally the ground station costs are mainly determined by the cost of the van from which the operators control the system. These costs add up to € 55,000.

## 5.7 Image processing

After capturing the images, the position of all vehicles has to be extracted for each frame. From this information, speed and acceleration can be derived. To recognize a car, one does the following. An image is subtracted from its predecessor, that is, for each pixel light intensities are subtracted. The remaining picture shows the change of the objects in both images. Those changes are called “blobs”. This is illustrated in figure 5.6, where two objects have a different position and thus two blobs are present in the subtracted image.

For this project, the road is just like the black in the third image, except for the places where vehicles are present. In this way, vehicles can be detected. To keep track of the vehicles, two techniques can be combined. By using the position and the velocity of the vehicle on the previous frame, the position on the next frame can be predicted. The car closest to the guessed point is then the same car. When there is a

change in speed, the guess will be wrong and maybe another vehicle is detected. However, the distance of two consecutive vehicles is in general such that the guessed vehicle is the right one. When there is doubt, a second technique can be used. The brightness of each vehicle is different. By comparing this parameter in two consecutive images, vehicles can be tracked. Using this method, the number of rightly recognized vehicles will increase.

This processing is done in a research centre, which can be just a room with some computers. Ten regular desktop computers are capable of processing a four-hour monitoring session in three weeks. The processing can be speeded up by using more efficient algorithms, use more or more advanced computers.

Figure 5.6: Subtracting of images gives blobs.

## 5.8 Conclusions

The designed system is found to have fulfilled all the preset requirements that are applicable. It can therefore perform the Mission Need Statement: “Design within two months a flexible system for the monitoring of individual motorized vehicle movements”. Also, the innovative airborne concept has been chosen above the ground-based concept (the best option, according to the trade-off) because of its appeal to the customer. It is an exciting and progressive investment.

A more tangible aspect of this system is, first, the high level of flexibility. There are at least four dimensions to this flexibility. First, the airships store all data onboard, in this way the system can be extended by simply adding more airships to the fleet. At a certain point, of course, the OCU will be overloaded and the processing time may increase too much. At this point the OCU and research centre should be re-scaled. Also, the cameras can be pointed independently

to fit the geometry of the desired measurement region. Next, the airships can move relatively fast to a new measurement point; the maximum airspeed is nearly 17 m/s. Finally, the monitoring system can be applied in more situations; for instance the study of traffic in urban areas. But the scope can be taken even broader; monitoring of forest fires, crops, coast security (assisting lifeguards), et cetera. There is a myriad of possibilities.

A second aspect of the system design is the decision made to store all acquired image data without intermediate processing. Onboard processing of data requires power but reduces the storage capacity demand, finally reducing the weight. Power, however, is not the main issue in implementing data processing. The challenge is to find the correct algorithms that cost little processing power but deliver good reduction of data size, at sufficient quality.

Thirdly, the design of the power system is heavy. The main reason for this is the conservative choice of the fuel storage mode. Fuel tanks are in wide use; they are reliable, but also very heavy. There are much lighter concepts in development, which have yet to be fully developed but promise to be much lighter. Also, some components, like the propeller pylons and the frame for the fuel tanks are made of metal, not composite materials making the airship heavier. Decreasing the airship weight creates the possibility of decreasing dimensions, such that the airship can be stored more easily.

## 5.9 Recommendations

The detailed design of the traffic monitoring system led to the following recommendations:

- Introduce a weight reduction program. One of the options is producing the fuel system frame from composite material, like the primary structure of the airship. Also, the fuel storage tanks can be replaced by lighter metal hydride units.
- A lot of research still has to be done concerning image processing. As a part of the next design phase it is important to select algorithms and test them thoroughly. Special

attention may be directed to the onboard image processing algorithms as elaborated above.

- Together with the customer, the decision was made to concentrate on one mode of the system, namely the scientific data acquisition mode. Another mode was posed in the initial assignment, the traffic regulation mode, which can provide real-time data. The system could be extended to perform this mode.
- Use colour images to ease the process of correcting for shadows a lot more accurate and therefore decrease the number of errors made during image processing. Colour images will produce more data, so either more storage capacity should be installed (the power system and payload capacity should then be altered), or apply onboard image processing.
- Explore other applications for this system within the field of Earth Observation, and discover their commercial potential.

# 6. MICRO-SATELLITE FOR STEREO IMAGING LASER ALTIMETRY (MISILAT)

*Students:* G.J. van Silfhout, W.R. van Caspel, M.A. Gijzel, S. Brak, R. Grotens, M. Muilwijk, S. de Jong, P.A. Beishuizen, P.D.C ten Hoopen, P.H.W. van Westerveld

*Project tutor:* ir. R.J. Hamann

*Coaches:* ir. M.C. Naeije, dr. G.S. Gardner

## 6.1 Introduction

Nowadays there are many scientific, military and commercial satellites in space. Most of these satellites are rather large, heavy and expensive. These missions usually demand tremendous amounts of funds and are virtually impossible for smaller companies to realize. In order to make a mission more cost effective and affordable for the 'small players', it is necessary to make satellites smaller and lighter.

The MISILAT (Micro Satellite for Stereo Imaging Laser Altimetry) is a satellite that allows small companies to get their instruments tested and operated in space with reasonable costs. The satellite is designed as an Earth observation satellite and the payload is the SILAT, which is developed by Cosine Research BV, Leiden. This instrument is a highly integrated instrument with a laser altimeter and a high-resolution stereo colour camera to produce altitude measurements and 3D mapping. Not only is the satellite capable of accommodating state of the art payloads, it is also smaller, lighter, on demand available and has a reasonable low price tag.

Furthermore it will be possible to accommodate a wide, more diverse variety of payloads and missions than ever been seen before in the space industry.

## 6.2 Mission objective

The instrument that will be flown onboard the MISILAT uses a new, highly integrated technology and needs to be proven for space application. Therefore, the MISILAT Project Objective Statement is:

*"Provide a feasible micro satellite concept for an affordable technology demonstration mission for the SILAT instrument within 10 weeks".*

## 6.3 Requirements and constraints

The specified objectives will lead to requirements and constraints on the mission and satellite design. The transformation of objectives into requirements can be categorized into three broad areas:

*Operational Requirements:* These determine how the system operates and how users interacts with it to achieve its broad objectives (Table 6.1)

*Functional Requirements:* These define how well the system must perform to meet its objectives. (table 6.2)

*Constraints:* These are limiting aspects on cost, schedule time and implementation techniques available to the system designer (table 6.3). The following three tables give a concise summary of the most important requirements and constraints for the MISILAT project.

| Parameter | Requirement | Source |
|---|---|---|
| Life time | 3 years | Project description |
| Satellite disposure | within 25 years | Int. Gentlemen's Agreement |
| Orbit | max. 800 km | SILAT |

Table 6.1: Operational Requirements

| Parameter | Requirement | Source |
|---|---|---|
| Relative pointing error | 24 arcmin | SILAT |
| Absolute pointing error | 0.5 arcsec/ms | SILAT |
| Development time | 3 years (launch 2009) | Scientific relevance data |
| Orbit type | circular (LEO) | Customer |

Table 6.2: Functional Requirements

| Parameter | Requirement | Source |
|---|---|---|
| Power | 30 Watt | Project description |
| Mass | 25 kilogram | Project description |
| Mission costs | 10 million euro | Project description |
| Satelitte costs | 4 million euro | Project description |

Table 6.3: Constraints

## 6.4 Concept exploration

Primary to the satellite design, a mission has to be defined, because the mission gives important design drivers for the subsystem design of the satellite. Three concepts for the mission are set up and contain different fields of science measurements, which are defined with the design option tree.

The primary mission objective is to test the SILAT and investigate the possibilities of using the instrument in space. The second mission objective exists of two scientific mission objectives; one that can be fulfilled with the HRC and the S-CAM and one that can only be fulfilled with the complete working SILAT. Dividing the mission in two scientific mission objectives gives the advantage that the satellite

still can fulfil a mission objective after a laser failure, which is likely to occur within the operational lifetime of three years. The three mission concepts are:

- Measuring ice topography and volcano activity
- Measuring glaciers and vegetation / desert (growth / mapping)
- Measuring topography for cartography and generating data for the Digital Elevation Model

To make a trade-off, the three concepts are analyzed on different criteria. A short summary is presented in table 6.4.

| Concepts / Criteria | Cost | Application for laser usage | Application for camera usage after laser failure | Need/relevance of Data | Uniqueness of delivered data | Commercial value of deliverable data | Possibility for future HIBRIS research | Astrodynamic characteristics | Altitude | Orbit | Operations & logistics concept | Launcher | Ground station | Operational in three years | Spacecraft system characteristics (communication requirements) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weighing factor | 7 | 8 | 4 | | 9 | 4 | 5 | | 4 | 4 | | 5 | 6 | 9 | 4 |
| Ice meter and volcano | | + | 0 | | + | 0 | + | | + | + | | + | + | | + |
| Vega & land ice | | + | 0 | | + | 0 | 0 | | + | + | | 0 | 0 | | 0 |
| DEM & cartography | | + | + | | 0 | + | 0 | | + | + | | 0 | 0 | | 0 |

| | |
|---|---|
| + | good satisfaction of the criterion |
| - | failed completely on the criterion |
| 0 | critically on the criterion |
| | no conclusion possible / no + or - |

Table 6.4: The trade-off table for the mission

The criteria have been composed from the important design drivers, the main requirements and the fulfilment of the main mission objectives. This trade-off table shows that the ice and volcano mission has less drawbacks and therefore this mission will be developed in detail.

After having defined the mission, a similar concept generation could be made for the satellite. Since the chosen mission concept specified the orbit to a large extent, now focus was placed primarily on the communication architecture to select a concept for the satellite. First of all, to be able to make a well-considered trade-off, the impact of the communication architecture on the subsystems has to be studied. The typical subsystems considered are Attitude Determination & Control, Telemetry Tracking and Command and Data Handling. Not only are these subsystems specified in the risk assessment as failure prone, the communication architecture has the biggest impact on the design of these subsystems as well. The following options for the communication architecture were considered:

- Making use of one or more data relay satellites
- Using just one ground station in Delft
- Using two ground stations, Svalbard (North Pole) and a McMurdo (South Pole) ground stations

Table 6.5 gives a concise overview of the satellite trade-off results. The trade-off resulted in the concept of using (at least) two ground stations, Svalbard and McMurdo were used for the initial investigations. The main reason for this was that this would be the easiest and most cost effective way to get the vast amounts of data down to Earth.

| Concepts | Criteria | Mission accomplishment | Power consumption | Payload integration | Volume | Mass | Cost | Design feasibility and simplicity | Durability/reliability |
|---|---|---|---|---|---|---|---|---|---|
| | Subsystem / Weight factor | 9 | 8 | | 6 | | 5 | 4 | 3 |
| 1 Relay satellites | Data handling | + | - | + | + | 0 | - | | + |
| | AD&C | + | 0 | + | + | + | 0 | + | 0 |
| | Power | | 0 | | 0 | 0 | 0 | 0 | |
| | Total | + | - | + | 0 | 0 | - | 0 | 0 |
| | | | | | | | | | |
| 2 Delft as single | Data handling | - | 0 | 0 | + | 0 | + | + | |
| G/S | AD&C | | 0 | | 0 | 0 | 0 | 0 | 0 |
| | Power | | 0 | | | 0 | 0 | + | + |
| | Total | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | | |
| 3 Svalbard & | Data handling | + | + | + | + | + | 0 | 0 | |
| Mc Murdo G/S | AD&C | | 0 | + | 0 | | | + | |
| | Power | | + | | + | | + | + | |
| | Total | + | 0 | + | 0 | + | 0 | 0 | |

Table 6.5: The trade-off table for the satellite

## 6.5 Mission design

In the conceptual design, the so-called ”ICE mission” is chosen. The primary observation targets of this mission are measuring ice volume changes within the Arctic and Antarctic circles and collecting data on volcanoes around the world. Looking at instrument characteristics, cross tracks, coverage, launcher availability and satellite complexity, the most convenient orbit for this mission turned out to be a sun-synchronous orbit with an altitude of 500 km at begin of life. The repeat track of this sun-synchronous orbit is not exactly a repeat track,

since the ascending node differs a little from the starting ascending node.

The choice is made not to perform orbit maintenance, which will result in a decaying orbit that will deviate in time from the exact sun-synchronous orbit. It turns out that, except from the shift of the ascending node, differences in the orbit parameters will be small. Only in the last three months big differences in orbit altitude and eccentricity begin to occur.

The orbit is divided in different phases, which can be seen in figure 6.1. This is just a general idea and is used in the satellite design.
To get the satellite into orbit, a launcher is needed. Several launchers are discarded due to unreliability or cost issues. Finally four piggyback launchers remain which are the Ariane 5 with the ASAP adaptor, the Dnepr with its piggyback ring, the PSLV and the Eurockot with its Breeze adaptor. To keep all options open and to ensure increased launch possibilities the MISILAT should be designed to be compatible with all four launchers. Since the Ariane 5 is the most demanding launcher, its requirements are taken as the requirements for the satellite structural analysis.

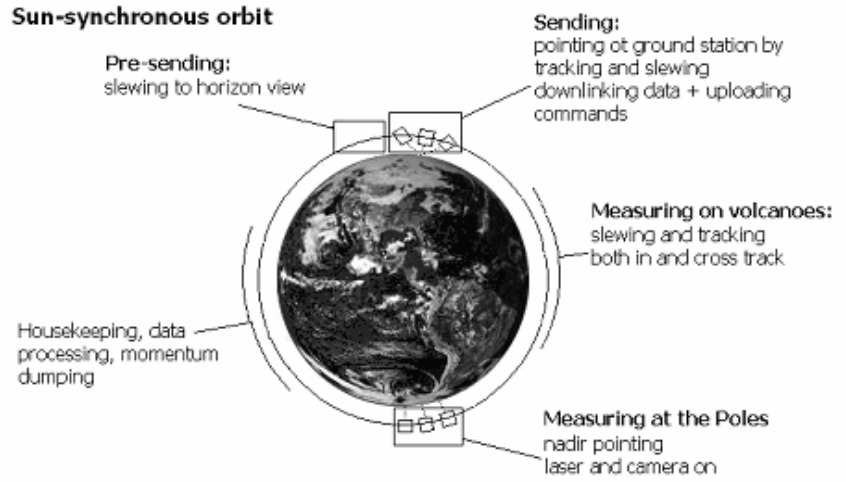



Figure 6.1 General phasing of an orbit

## 6.6 Satellite design

The satellite design was done on subsystem level and after that a conceptual configuration was made. The numbers behind the components match with the numbers in figure 6.2.

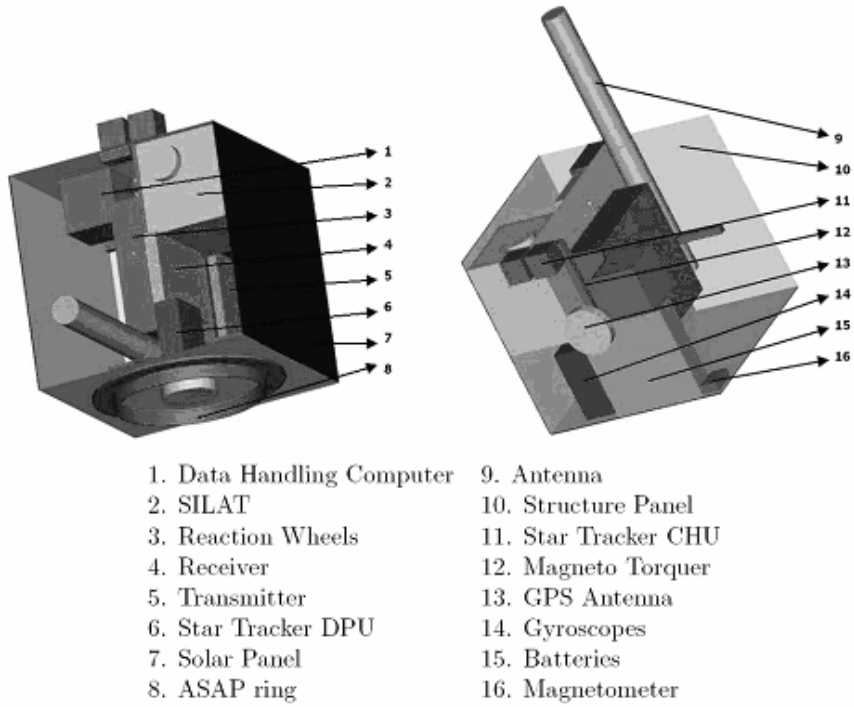



Figure 6.2: The conceptual layout and configuration of the satellite

The following subsystems were defined and designed:

**Attitude determination and control**

For the attitude determination a system of gyroscopes, magnetometers and star trackers is used. The gyroscopes determine the relative attitude and the magnetometers and star trackers are used to eliminate the long term errors of the gyroscopes. The star trackers also determine the absolute attitude. Since a rather high pointing accuracy is needed, the satellite inevitably needs a three-axis control system, which leads to the selection of reaction wheels. To be able to dump the generated momentum and to desaturate the reaction wheels, magnetic torquers will be used.

**Telemetry, tracking and command**

The onboard computer used by the MISILAT has to be able to handle large amounts of data. Cosine has already provided for a Digital Processing Unit easily capable of performing these tasks, however as it is still in design together with the SILAT, it is not space-proven. For this reason a commercial-off-the-shelf space-proven computer is also integrated, which can also easily handle these data rates and increases the reliability of the system. For the down linking and receiving of commands use is made of a helix antenna. For the housekeeping data that has to be sent down, also two simple low-gain patch antennae will be used. These antennae will be there for continuously sending down the housekeeping data. By using a simple off-the-shelf GPS receiver the satellite orbit can be measured within an accuracy of 10 meters. However, if the GPS data is stored and down linked to Earth for post processing it is possible to attain the desired accuracy of several centimetres.

**Electrical power system**

In the MISILAT satellite the primary power source are photovoltaic GaAs solar cells. As secondary power source (power storage) Lithium ion batteries are used. For charging and discharging the batteries a controller is needed to ensure proper working and to avoid damage to the batteries.

**Spacecraft structure**

For the spacecraft structure a cube layout is used with body mounted solar panels. An extra structural panel will be placed inside the satellite, to provide a mounting point close to the centre of gravity. No mechanisms or deployables will be used in the construction itself, however the helix antenna will require a linear mechanism to be deployed in space.

**Thermal subsystem**

During one orbit the internal and external heat production varies. However, no active heat system has to be installed. The SILAT is the only exception, because a heater will have to be installed near the payload to keep the SILAT within the desired temperature range. The passive heat system exists of radiators, insulation and a cold finger.

**Configuration**
The conceptual configuration and layout is presented in figure 6.2.

**Cost modelling**
To define the total mission cost, a cost breakdown is made. From this breakdown it appeared that the cost of the downlink via the ground stations forms a major part of the operational cost. Combined with the estimates for the remainder of the project (excluding the satellite), the mission cost are likely to exceed the 6 M€ (FY06) goal by 1-1.5 M€ By specifically aiming for a scientific mission this can however be reduced and the 6 million goal can be achieved. The satellite cost will amount approximately 4 M€ according to cost estimation relationships. The limited amount of actual cost data that has been collected indicates that this estimate is realistic or might even be on the high side. Combining the total cost will be about 10 M€. The total mission costs are however a rough estimation which are based on incomplete cost information.

**Lifetime phasing**
After the satellite concept has been defined, a payload test program is set up for the mission. The purpose of the payload test program is to test the SILAT on all of its aspects and consists of three experiments:

- Begin Of Life experiment: Close monitoring of SILAT by the Health Monitoring System (HMS) to check if it meets specifications.
- ICE experiment: Generate useful scientific data of measurements of ice volume and volcanoes during three years.
- End Of Life experiment: Intentional provocation of SILAT failures under close observation of the Health Monitoring System to provide knowledge on possible failures.

## 6.7 Conclusions and recommendations

The most important conclusion of the MISILAT project is that the study clearly indicates that the SILAT proof-of-concept for space use is feasible.

Much has still to be done for a complete and detailed mission and satellite design for the MISILAT project. The following recommendations are set up for future design teams:

- More investigation needs to be done on launch availability to the lower altitudes, possible due to the higher than assumed mass over area ratio.
- A more detailed position model of land-ice sheets needs to be created and integrated in the satellite software for better knowledge of start and end points of measurement per orbit.
- More data about non-polar glaciers needs to be obtained to be able to perform measurements in those regions as well.
- Cosine would like to design the star trackers in combination with the SILAT on a base plate, for better alignment and lower mass. This modular design possibility needs to be investigated further.
- The launch and operation of the MISILAT should preferably be before the operation of the Cryosat 2, because of the uniqueness of the data.
- Although the selected ice and volcano mission will probably be the best mission for the MISILAT, other mission possibilities still have to be investigated for possible combinations with the current mission.
- Investigate other possibilities for ground station use besides McMurdo and Svalbard. For example, if Delft would obtain a larger antenna, the ground operations cost reduction will be high. However the storage capacity of the satellite will have to increase, would this option be used.
- Receiving government funding for the project will be made easier if all subsystem elements would come from Dutch manufacturers. More investigation needs to be performed in this direction.
- More information on subsystems and their cost is necessary for a better cost estimation model.
- More research still has to be performed on risk and consequence of laser failure.

# 7. SAILTUG

*Students:* D.C. van den Berg, L.J. Buijs, P. Hermes,
J. van den Heuvel, M.C.W. van Loon,
L.P.P. Rammos, M.W. Schepers, N. Speelman,
A.A. van der Stelt, K.K. Tsoi, N. al Zuhairy

*Project tutor:* ir. J.A. Melkert

*Coaches:* prof.dr. W.J. Ockels, ir. M.B. Zaaijer, ir. M. Nawijn,
ir. B. Lansdorp

## 7.1 Objectives and requirements

The SailTUG is a system that will use advanced aerodynamic means in order to pull ships and other heavy objects, like drilling platforms, at sea. These aerodynamic means can be traditional sails or kites making use of larger wind speeds at higher altitudes. When the wind is favourable, the tug uses its Wind Propulsion Device to generate part of its propulsive power.

To be able to perform the mission described above, a Mission Need Statement was defined. The Mission Need Statement for the SailTUG project was defined as follows:

*In 10 weeks time and with 11 students, design a tug that uses the wind to generate at least 50% of the power commercially available tugs do, that can operate at wind speeds varying for 4 Bft up to and including 10 Bft and up to 60 degrees to the wind, and that can be developed and operated in a safe and sustainable way.*

Listed below are all the requirements and constraints that apply to the concepts. In the final design, some of the requirements were adjusted, which means the Mission Need Statement was altered as well. This will be explained later.

- The tug must be able to operate in wind speeds varying from 6.7 m/s up to and including 26.0 m/s at a reference height of 10 meters;
- During one mission, the Wind Propulsion Device (WPD) should perform at least 50% of the total work, assuming random wind angles and the lowest wind speed. A parameter • was defined as the ratio between the work the WPD performs and the total work that is performed by the system. • should be 0.5 or more, averaged over the entire wind angle spectrum;
- The tug must be able to react in time to weather changes;
- The tug must be sufficiently stable in all expected weather conditions;
- The tug must be able to deliver 900 kN of propulsive force;
- The tug must be able to deliver its propulsive force at a sailing speed of 10 kts;
- The tug must be safe to personnel onboard the ship and to the operation of the ship.

## 7.2 Selection of most feasible concept

From all the design solutions for the WPD that were defined in the Design Option Tree, all but four were discarded due to obvious flaws. The four concepts that did make it to the conceptual trade-off stage are listed below.

- Sail;
- Vertical wing;
- Direct propulsion by means of kites;
- Direct propulsion and indirect propulsion (providing power to the propeller) using kites in a pumping Laddermill configuration.

These four WPD concepts were analyzed separately and depending on their required aerodynamic surface area, a suitable hull type was chosen. The concepts were simulated in MATLAB, resulting in required surface areas for the WPD. These simulations were programmed in such a way, that the surface area that they calculated would ensure • would equal exactly 0.5. In the following paragraphs, all concepts will be treated one by one, stating strengths and weaknesses.

**Sail concept**

The first concept focused on using one or multiple sails as WPD. The sail is a tried and tested system, which has been used for thousands of years. After simulation, a configuration was chosen with two regular sails with surface areas of 6600 and 3300 square meters and a spinnaker with a surface area of 6600 square meters, installed on a catamaran. The sail concept's strengths included high technical maturity and high safety. The sail concept's weaknesses included huge masts (165 meters), high draught (17 meters) due to the enormous keel, which would be required to counteract the lateral force induced by the WPD, and high cost.

**Vertical wing concept**

A tug with vertical wing propulsion uses solid wings, placed vertically on deck, to achieve higher lift than a sail can ever achieve. The downside is that the lift over drag ratio is lower for the vertical wing, causing larger lateral forces on the tug, thus requiring a larger keel. This would increase the draught of the tug, which is undesirable. The simulation provided a required surface area of 9200 square meters. Taking into account the influence multiple wings have on each other and the stability of the hull, a configuration with three 4600 square meter wings was chosen, positioned on top of a trimaran. The vertical wing's main advantage was that it is smaller than the sail. Weaknesses included high cost, low maintainability and a very wide and deep hull.

**Kite concept**

The kite concept uses multiple kites, attached to the tug using a 2000 meter long cable. This way, the kite basically acts like a three dimensional sail, but at much higher altitudes, which means it can make use of the higher wind speeds at these altitudes. The simulation

resulted in a required surface area of 9700 square meters, divided amongst 20 kites with a surface area of 500 square meters, attached to a conventional hull. The kites were positioned 40 meters away from each other in the range of 1600 to 2400 meters. Strengths of this concept included low cost, good performance at higher wind speeds and high maintainability. The great weakness was low technical maturity.

**Laddermill concept**

The Laddermill concept also uses kites to provide some direct propulsive force. However, its main power output is provided by its pumping cycle. The cable to which the kites are attached is constantly extracted and retracted, which causes rotary motion at the drum to which the cable is attached. This rotary motion can be translated into propulsive force using either a generator and an electric motor, or by using a gearbox to directly drive the propeller. The results from the simulation showed that this concept would require 3300 square meters of effective surface area, divided amongst 10 kites with a surface area of 330 square meters each, which are attached to a conventional hull. The kites are attached to the cable, distributed over a range of 1500 to 2500 meters. The Laddermill concept showed even better performance at higher wind speeds than the kites, and it showed better overall performance, when looking at the entire wind angle spectrum.

**Final dimensions of all concepts**

The table below states the final dimensions of all concepts.

| | Sail | Vertical wing | Kite | Laddermill |
|---|---|---|---|---|
| WPD surface area [m2] | 16500 | 13800 | 9700 | 3300 |
| Length of cable [m] | - | - | 2400 | 2500 |
| Type of hull | Catamaran | Trimaran | Conventional | Conventional |
| Max. Length [m] | 85 | 83 | 70 | 65 |
| Max. Width [m] | 30 | 85 | 12 | 12 |
| Max. Draught [m] | 17 | 15.5 | 17.5 | 12 |

Table 7.1: Final dimensions of all four concepts

**Trade-off results**

The four concepts were compared by analyzing their performance with respect to the trade-off criteria. The criteria that the concepts were judged on are given below.

- Safety: how safe is the concept for the load and the operating crew?
- Technical maturity: how well are the physics of the concept known?
- Crew cost: how much crew will be needed to operate the WPD?
- Fuel cost: how much fuel can be saved at higher wind speeds?
- Maintainability: how easy is it to repair the WPD or replace parts?
- Ownership cost: how expensive will the system be?
- Availability: what percentage of the time will the system be able to operate?
- Geographical market accessibility: can the system use major connecting canals and can it reach every important location?

The concepts received scores from 1 to 10 on each criterion, which means the final score can be anywhere between 10 and 100 (since the weight factors add up to 100%). The table below shows the scores all the concepts received and the total score for each concept.

| | Safety | TechnicalMaturity | Crew | Fuel | Maintainability | Ownership | Availability | Accessibilioty | Score |
|---|---|---|---|---|---|---|---|---|---|
| Weight factor [%] | 10 | 12.5 | 5 | 25 | 7.5 | 20 | 7.5 | 12.5 | |
| Sail | 6 | 7 | 7 | 5 | 6 | 6 | 7 | 3 | 56 |
| Vertical wing | 5 | 5 | 7 | 4 | 5 | 3 | 3 | 3 | 41 |
| Kite | 7 | 5 | 7 | 7 | 8 | 8 | 8 | 7 | 71 |
| Laddermill | 7 | 4 | 7 | 9 | 7 | 7 | 8 | 10 | 76 |

Table 7.2: Trade-off scores for all concepts

As can be seen, the Laddermill concept scored highest in the trade-off. However, the margin of five points with respect to the kite concept is very slim. Normally, this would mean additional research would need to be done into both concepts in order to determine the winner.

However, due to shortage of time and since the Design Synthesis Exercise focuses on innovative and challenging designs, the Laddermill was chosen as the preferred concept.

## 7.3 Preliminary design of Laddermill-powered SailTUG

The land bound version of the Laddermill system is meant to generate electricity by letting kites extract a cable that is wound around a drum. The drum is connected to a generator. The cable can be retracted again by temporarily dumping the lift on the kites, so it takes less energy to retract them than was generated during extraction. In the SailTUG's case, the Laddermill is placed on top of an ocean tug in order to provide part of its electric power, which is used to drive its propeller.

**Adjusted requirements**

A market analysis showed that the best market for the SailTUG would be towing Panamax-size bulk carriers. These vessels do have engines of their own, but would save fuel nonetheless. Choosing this particular market adds and adjusts several system constraints and requirements. The altered set of requirements is given below. It is important to note that the requirement on • has been discarded.

- The tug must be able to provide 1450 kN of propulsive force;
- The tug must be able to provide propulsive force at a sailing speed of 14 knots;
- The tug must be able to operate in wind speeds varying from 6.7 m/s up to and including 26.0 m/s at a reference height of 10 meters;
- During one mission, at least 30% of the power should be delivered by the Laddermill system, assuming random wind angles and the lowest wind speed. A parameter • was defined as the ratio between the power the SailTUG's auxiliary engine needs to deliver, compared to the power the bulk carrier's engine would need to provide if it were sailing by itself. • should be 0.7 or less, averaged over the entire wind angle spectrum.

**Kite design**

For the array of kites used in the Laddermill, a type of kite was designed with a projected aspect ratio of 6.8, effective span width of 40 meters and a surface area of 344 square meters. This kite uses RAM-air inflation, which means the wind inflates the kite as opposed to inflating it with a pump. The centre chord is 7 meters long and the tip chords are 2.45 meters each. The centre airfoil is a standard NACA2414-63 profile, which is a thick airfoil that generates relatively much lift. To counteract this profile's tendency to crash the kite when a gust occurs, the tip chord was chosen to have an mh78 profile, which is a so-called "reflex"-profile. The kite has a lift coefficient of 0.8 and a drag coefficient of 0.06, which means its aerodynamic efficiency equals approximately 13.

**Configuration**

The Laddermill uses an array of 34 kites, which are positioned above each other over a range of 1320 meters. The array is positioned at an altitude of 1500 meters and is elevated an additional 500 meters during the extraction phase. This means the top kite might reach a height of 3320 meters above the tug. The tug is 65 meters long, 16 meters wide and 5 meters deep.

The cable used to connect the kites to the drum is made of Ultra High Molecular Weight Polyethylene (UHMWPE). Its main advantages are its great strength-to-mass ratio and the fact that it is hardly affected by other chemical compounds, which makes it highly resistant to environmental influences that occur when performing offshore operations. The cable has a diameter of 178 millimetres at the lower 500 meters. After these first 500 meters, the cable splits into two cables with a diameter of 101 millimetres each, connected to all the kites. At the back end, the cable is connected to the cable drum. Even when the Laddermill is fully extracted, there should always be 8 windings on the drum in order to transfer the force into the drum. The cable material has bad properties when it is laterally compressed while under high tension. Therefore, retraction of the lower part should be done single-layered. In case of complete retraction, all of the cable can be stored on the drum. This is allowed because at this point, there is no tension in the cable anymore. The drum is 6 meters in length and has a flange diameter of 8 m. The Laddermill drum and generator are placed on a rotable platform, located partly below the deck of the tug.

Rotating the drum as a whole is required to position the kites at a proper horizontal angle.

The SailTUG will be using a conventional satellite positioning system, like Galileo or GPS. Such systems are also used by other tugs (as well as conventional ships). The communication system will also be the same as is being used on conventional tugs. Using a radio or even satellite Internet, the SailTUG will be able to communicate with its load or with any harbour or ship. Since the SailTUG is a more complex system than conventional tugs, the collision avoidance system should be more sophisticated. Using the positioning system and a radar system mounted on the ship, the accuracy and range of the collision avoidance system should be sufficient to ensure the SailTUG is safe enough in that matter. Prediction and measurement of the weather is very important for the correct usage of the Laddermill. The weather can be subdivided in factors like the wind, the rain, the temperature. These are all very important parameters for the steering, deployment and retraction of the kite. Part of the weather prediction can be obtained from the Internet. However, it is also important to obtain weather data for high altitudes, which cannot be obtained that easily from the Internet. For these data (wind strength, velocity and temperature for each kite) some measuring equipment should be placed up along with the kites, in the pods connecting the kites with the large cables. The most complicated measuring system will be the measuring system for the Laddermill's attitude. This will have to be able to measure the position and attitude of every kite. This will provide the control system with the necessary information to adjust or keep its configuration. These measurements will be performed using four small tracking devices on both the leading edges and the trailing edges of the wingtips.

**Operations**

The kites are required to move in so-called 8-loops to create crosswind power, which causes them to generate significantly more lift. In order to steer the kites during these loops, a 2-line steering system is used. The advantage of this system over a conventional 4-line system is the fact that it has a relatively low storage complexity, since it only uses two cables. Furthermore, it requires a relatively low force to control the kite, which is favourable for a system using multiple kites. When using two steering lines, sliding the cables back or forth along the tip

chord changes the angle of the wingtips. To make this happen, a sliding rail is placed on the kite along which the cable can be guided with the aid of a carriage. Another big advantage of this system is the fact that the control force is not in the same direction as the cable tension, but at an angle of 90 degrees. This means that the force required to control the kite is significantly lower than for a 4-line system.

The power extracted from the Laddermill is combined with power from two 9 MW diesel electric drives in order to create enough thrust with the two propellers. The total thrust consists of this propeller thrust and the horizontal component of the cable force. During retraction the thrust is only provided through the diesel electric drives. When sailing downwind, it might become more advantageous to not retract the Laddermill at all and just use its pulling force to assist in propelling the ship. In the case that retractions do take place, the tug and the bulk carrier being towed experience slight variations in speed. Because of the large mass of the vessels, this speed variation remains small. The bulk carrier decelerates even slower than the tug and should not be allowed to overtake it, which means that there is a minimum level of thrust required during both the retraction and extraction. The amount of diesel required per cycle may vary as the wind angle with respect to the ship changes. The total amount of diesel power required can be expressed by means of •. The average value of • over all wind angles should be the required value of 0.7.

Further operations include deploying, completely retracting and storing the Laddermill system. To allow for these operations, a number of systems are placed on deck, including a number of cranes, a separate drum to store the kites and launch poles to temporarily hold kites in place before deployment.

**Final configuration**

The figure below shows the final configuration of the SailTUG, which was designed to be able to meet all the requirements and perform all the required operations.

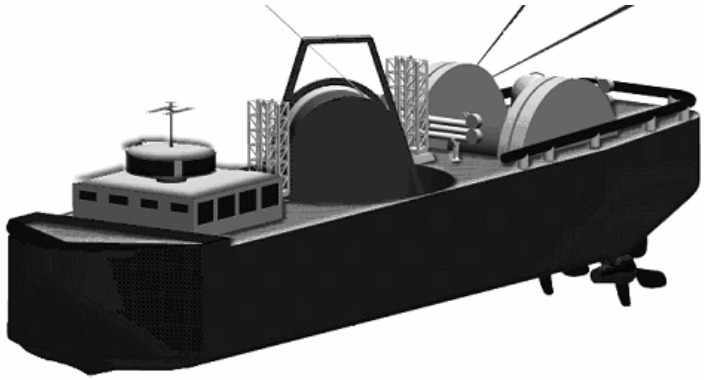


Figure 7.1: SailTUG final configuration

**Cost estimation**

After designing the SailTUG, a cost estimation was made which showed that the system would not be profitable at the current diesel and heavy fuel oil prices. The SailTUG will need to use diesel oil as its fuel, because the diesel-electric drives require high RPM engines. Bulk carriers currently use heavy fuel oil, which is cheaper than diesel oil, but also more polluting. Since the price of both heavy fuel oil and diesel oil depend on the crude oil price, the SailTUG will never become profitable as long as bulk carriers use heavy fuel oil. However, due to the extra pollution that occurs when using heavy fuel oil, it is feasible that this type of fuel will be forbidden in the near future. Should this be the case, the bulk carriers will also need to start using diesel oil engines. The figure below shows the cost for the bulk carrier if it would use diesel, as well as the cost it would encounter when using a SailTUG expressed in EUR per kWh.

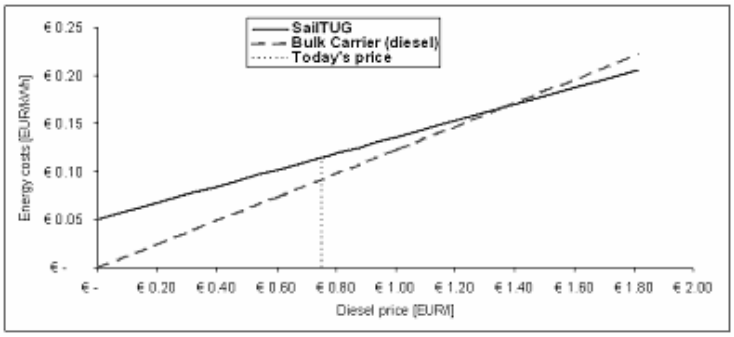



Figure 7.2: Cost of SailTUG and diesel-powered bulk carrier

The figure clearly shows that the SailTUG can become profitable if the diesel price would become approximately 1.40 EUR per litre, which would mean only an 80 percent increase is required.

## 7.4 Conclusions

The preliminary design has shown that it is technically possible for the SailTUG to meet the fuel saving requirement. The profitability of the system is not certain though, as it depends on future developments regarding fuel prices and government policies. However, it is not unrealistic to expect a future in which the environment will become so important that heavy fuel oil will be forbidden or much more expensive compared to diesel and the SailTUG will be profitable. As the price of a barrel of crude oil has risen above 70 USD, the importance of the research on sustainable development is justified once more. Regardless if it ever will be fully developed, the design of the SailTUG will hopefully initiate an increased engagement in sustainable development, enabling humanity to use the abundant energy provided by the wind (in this case) as a supplement or even an alternative for present day energy sources.

## 7.5 Recommendations

The first recommendation that can be made, is that the MATLAB model that was made needs to become more detailed, incorporating dynamic behavior, multiple kites and the effects these kites have on each other.

The design of the kites is still an important design aspect as well. Kite manufacturers have pointed out that the design has several downsides, including depowering problems. Together with the kite manufacturers, the kite design should be improved, as well as the 2-line steering mechanism and the control software.

Further research needs to be performed concerning the cables. Cables with these diameters, lengths and operating speeds are not quite

common. Tests will need to be performed and creep effects will also need to be studied.

Extreme conditions have not been incorporated in the design as much as they should have been. This is another field where a lot of additional research can be done in order to improve the design.

The final, and most important, recommendation is that it might pay off to develop a Laddermill on land first. When designing a land-based Laddermill, one does not experience dimensional constraints or problems concerning the cyclic operation, since multiple Laddermills can be used in series.

# 8. DESIGN OF A HUMAN POWERED HELICOPTER

*Students:* S. van Benten, B.C.T.M. Dirks, J.G. d'Engelbronner, J. Greeve, E. de Groot, S.C. van't Hoff, A.J.P. Jöbsis, B. Konneman, M. van Ruitenbeek, H.D. Watson

*Project tutor:* dr.ir. M.D. Bos-Pavel, prof.dr.ir. Th. Van Holten

*Coaches:* ir. I. Akkerman, ir. G. Larocca

## 8.1 Subject

Human powered flight has long been a dream of mankind. For fixed-wing aircraft it has been shown that it can be done, however vertical take-off and landing are impossible with fixed-wing (human powered) aircraft. Therefore it remains a challenge to also build a human powered rotary-wing aircraft. To further arouse interest for this design challenge the American Helicopter Society (AHS) has sponsored a contest with a $20,000 prize. The general requirements for the Sikorsky competition are:

- To remain airborne for 1 minute
- To momentarily reach an altitude of 3m
- To stay within a prescribed 10x10 m square
- Having at least one non-rotating crewmember

Although the contest already started in 1980, so far no one has been able to successfully fulfil the requirements of the AHS "Igor I. Sikorsky Human Powered Helicopter Competition".

The goal of this project was to present a design for a Human Powered Helicopter (HPH) which is consistent with the requirements as stated for the Sikorsky prize by the AHS. During the Design Synthesis Exercise 2006 this design process has been realised in the design of the 4NiCopter. The 4NiCopter is a four-rotor helicopter design with active stability control.

In this short summary of the design and design stages all relevant design parameters will be explained. The items that will be treated are the concept selection, the rotor design, the structure, the transmission and the control system.

## 8.2 Concept exploration

After the obvious losers are identified the following four concepts remain:

- Tip rotor design
- Coaxial design
- Tandem design
- Dual tandem design

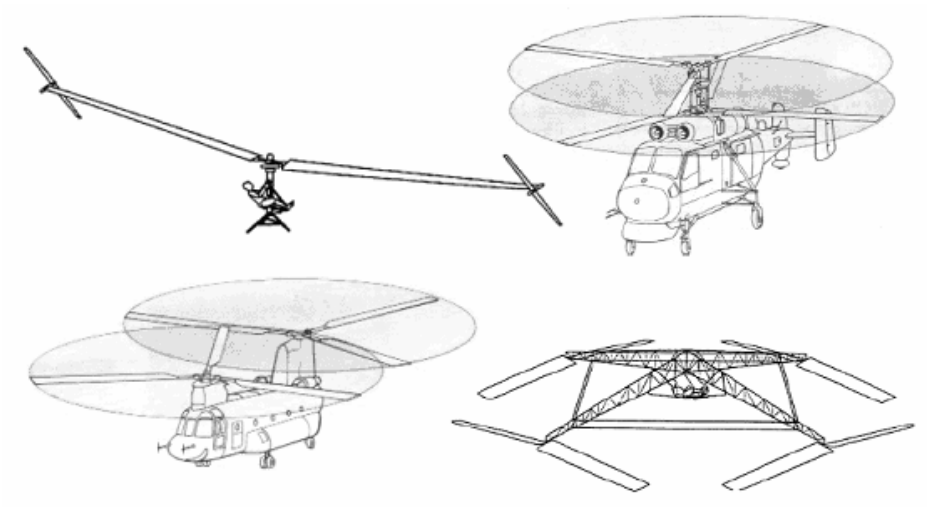


Figure 8.1: The four remaining concepts

First the *tip rotor concept* is considered. In the top-left of figure 8.1 the lay-out of the design is visualized. The design has two tip propellers that propel the rotor, which generates lift. The main advantage of this method is the absence of a resultant torque, so no counter-torque device is needed. Conventional helicopters have a tail rotor to cope with the torque. The disadvantage of the tip design is the increase of aerodynamic losses. Not only the rotor has losses but also the tip propeller. Because the design has one rotor the dimensions are large to be able to lift the total weight. The transmission distance is very large which results in high weight and a low efficiency.

In the top-right corner, the *coaxial design* can be seen. This design has two counter-rotating rotors above of each other. With this design no anti-torque solution is needed, because the torque of the two rotors cancel each other out. A major problem is the air inflow of the second rotor. The first rotor disturbs the normal steady inflow of the second rotor; therefore the efficiency of the second rotor is lower. An advantage is the low transmission loss because the rotors are situated close to the pilot.

In the lower-left of the figure, the *tandem design* is visualized. In the design non-intermeshing rotors are considered for simplicity. The rotors do not interact, no disturbances due to the other rotor. Because two rotors lift the weight the diameter can be smaller. The distance between the two rotors results in a high transmission weight and loss.

Finally, in the lower right corner the *dual tandem design* is shown. For the preliminary calculations the rotors do not intermesh. The diameter per rotor can be small, which results in smaller stresses in the rotor. Changing the collective pitch of one rotor might control the design better than the previous designs. The supporting structure is very large and therefore heavy. The distances covered by the transmission are large which results in relatively high transmission losses.

After a trade-off study the dual tandem design was chosen as the best possible option.

## 8.3 Rotor dimensioning.

Since a human is powering the HPH, a very low amount of power is available. Therefore a special rotor is needed for the HPH. A 75 kg heavy athlete can produce approximately 600 watts for 1 minute. This results in a very large rotor of 12 meters in radius, which rotates at a very low rate of 8 rpm. These propulsion parameters differ significantly from the parameters of a normal helicopter, where the rotors are not that large and rotate with far higher velocities (450 rpm). The difference lies in the available power. The rotor accelerates air downwards to lift the HPH. This can be done in several ways, producing the same amount of lift. Since the power to accelerate the air has a quadratic relation with the induced speed of the accelerated air, the large amount of air and low induced speed is the best option for the design. This is why the rotor is so large and rotates at a low rate. These parameters were the starting point of the optimization process.

In the optimization process, the structural weight was estimated 50 kilos and the blade's twist, taper and chord distributions are determined. Also an improved rotation speed and radius are calculated. The best combination of twist and taper makes the induced velocity uniform over the blade, resulting in the lowest induced drag. Since the induced drag is 75% of the total drag, it is necessary that the twist and taper are optimal. The twist is linear and 8 degrees pitch down towards the tip. The taper was chosen to approximate the ideal taper for hover. The taper can be seen in figure 8.2 in the next section. Iterating these parameters in MATLAB and choosing the rotor that required the least power to hover provided the final configuration. The total weight only increased 6 kilograms after one design loop.

## 8.4 Supporting structure

The HPH structure consists of two parts: supporting structure and rotor structure. Both have a tremendous share in the total weight of the HPH; therefore minimization of the weight is crucial for the success of the project. Since the general lay-out of the supporting

structure is fixed, variance can be applied in the cross section of the truss frame and the overall dimensions of the truss frame. In order to effectively analyze the effect of these variances, a Finite Element Model of the (potential) structure was created.

Three different types of truss structures were analyzed: a 2D truss frame, 3D truss frame with triangular cross-section and 3D truss frame with a rectangular cross-section. Each truss-structure is made out of the same material: Carbon Fibre M60J© with a quasi-isentropic lay-out. Furthermore, each model was subjected to several load cases and constraints. The load cases consisted of a landing, flight and misaligned thrust case. The constraints laid upon the structure are a maximal vertical and horizontal tip-deflection of 50 cm. After a few iterations, the 2D truss-frame was discarded due to the large deflections when a transverse load was applied. The 3D truss-frame with a triangular cross-section was incapable of bearing a misaligned thrust. Finally, the 3D truss-frame with a rectangular cross-section was able to withstand the different load cases most efficiently.

The next step was to optimize the total weight of the truss-frame by varying the diameter of the tubes in the truss-frame and tapering the structure. The optimization process was limited by two factors. The first factor is production techniques; these limited the tubular thickness of the truss-frames to 0.5 mm. The second factor that imposed a constraint on the structure was Euler buckling. In order to satisfy the buckling criteria, the tubular length had to be decreased and tube-diameter increased. Both actions have a negative effect on the overall weight. After a few optimization loops, the total supporting structure has an overall weight of 21.1 kg, including the joints.

The overall weight of the supporting structure can be brought down if more extensive, complex buckling analysis is carried out. This will allow a reduction of the safety factor.

## 8.5 Design of the rotor construction

The design of the rotor construction has to meet several strength and stiffness requirements that follow from the aerodynamic forces and the shape of the supporting structure. Of course it has to be strong enough to withstand the bending and torsional loads and, when subjected to these loads, hold an acceptable aerodynamic shape. In figure 8.2 the general design of the wing can be seen.

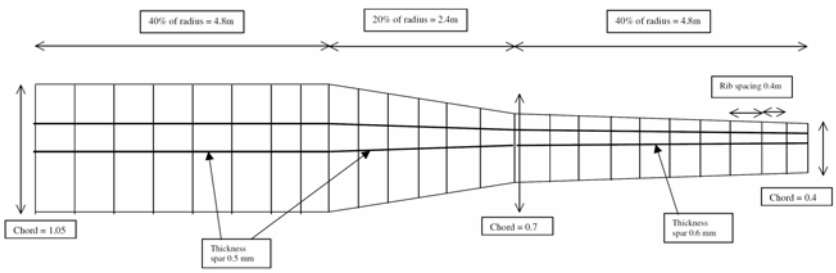



Figure 8.2: Wing structure lay-out

For the construction of the rotor use can be made of two principles, namely the stressed skin design and the spar and rib design. Calculations showed that if the stressed skin principle was applied the design had a weight in the order of 75 kg. This is far above the planned weight of 20 kg. Therefore it was chosen to use the spar and rib design. In this principle the spar handles all loads and the ribs provide the aerodynamic shape.

A tapered thin walled tube with circular cross section made from composite was used as the spar, namely carbon fibre M60J with a quasi-isentropic lay-out. The diameter of the spar follows from the maximum thickness of the airfoil, namely $t/c = 0.1$. The thickness of the wall of the tube is 0.5 mm. The ribs are made of extremely lightweight foam ($\rho = 12$ kg/m3) and the skin of the wing is a Mylar film with a thickness of 2 μm.

The supporting structure takes a deflection of the rotor blade of 1.2 m into account, where the calculated deflection is 1.0 m. Also the calculated buckling stress is 350 times higher than the actual stresses present in the construction. The total weight of the 8 rotor blades is approximately 21.5 kg.

## 8.6 Transmission

The pilot can only deliver a limited amount of power, so the transmission system must be as efficient and light as possible. An obvious problem is the large span of the 4NiCopter over which the power must be transmitted. Furthermore the variance of the power delivered from a cyclic motion was taken into account.

The transmission system basically consists out of three systems: the chain system, the bevel gears and the cable system. The chain system is connected to the feet of the pilot and rotates in a vertical plane. The bevel gears are needed to convert the rotational direction to the horizontal plane of the cable system, in which the rotors turn. The cable system provides the rotors their driving force.

The chain system contains commercially available bicycle parts, as these have improved much recently and are available in a wide range of weight and stiffness. The available parts have been selected with large scrutiny. Its main feature is a 52:12 gear reduction. The chain system also contains a one-way clutch, allowing the pilot to stop pedalling while the rotors keep rotating. This system weighs 935 g.

The bevel gears are selected for their high efficiency and low weight (2.02 kg). With a 3:1 ratio a total gear reduction of 13:1 is achieved. This allows the pilot to pedal with the most efficient rpm of 105 while the rotors turn at their optimal rate of 8 rpm.

Finally the cable system delivers the power to the four rotors. As the rotors are intermeshing, slip cannot be allowed. A chain-sprocket interaction is needed, however chains are too heavy due to the large span of the 4NiCopter. Therefore Dyneema is chosen as the cable material as it has the highest $\sigma_{specific}$. However it has a slippery surface and also no loop can be manufactured. Aluminium inserts are placed inside the cable with a 5 cm pitch to provide a relief, making for a chain like mechanism (see figure 8.3). Two rings are looped with the cable ends and provide enough friction force to make a connection. The cables run over spools which have a surface mated to the inserts. The cable weighs only 154 g while the spools account for 2 kg.

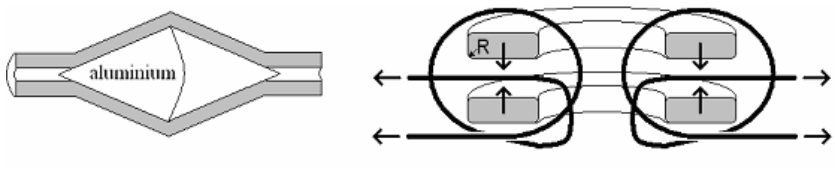



Figure 8.3: Insert and rings

The gears and spools are connected to carbon torsion tubes. Standard strength and stiffness calculations were performed to determine their dimensions. Together with the bearings that support the tubes these weigh 1.136 kg, giving a total weight for the transmission of 6.245 kg.

In previous attempts, the variance of the power produced by the pilot has proven to be a problem, as the light rotors are constantly accelerated and decelerated. Oval chain rings shorten the low power part of the pedal stroke and lengthen the high power part. Mating these gears with a flywheel solved the power problems for an earlier double tandem design. The rotors are significantly larger and heavier, so they will already act as flywheels themselves and the 4NiCopter will not need a separate flywheel.

## 8.7 Stability and control

Two important parameters in the design of a HPH are the stability and the controllability of the vehicle. The most successful design for a HPH until now has failed due to controllability issues. After a small disturbance the aircraft started drifting and collided with a wall. In order to prevent such failure modes in the 4NiCopter design a simulator with 3 degrees of freedom has been developed to analyze the behaviour in uncontrolled condition. After this analysis a control system has been developed to solve the problems.
From the 4NiCopter simulation it became clear that the least stable mode would be when the vehicle suffers from a gust of wind. In order to simulate this, an initial pitch rate was applied. The result of such a disturbance is a drifting in the horizontal plane, a decrease in altitude and a periodical pitching motion (see figure 8.4). It is important to

have the ability to counteract these motions and thus a control system has been developed.

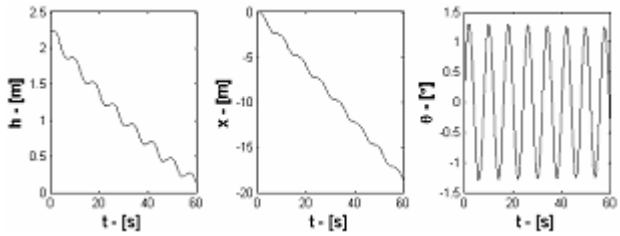



Figure 8.4: Gust behaviour for uncontrolled vehicle

The control systems proposed for the 4NiCopter is a system based on a centre of gravity shift. This system is capable of counteracting the gust as described above. In figure 8.5 it can be seen that in every degree of freedom the system is able to perform the necessary corrections. Even though a swash plate-controlled system gave more accurate results, that system is far too heavy to be included in a HPH.

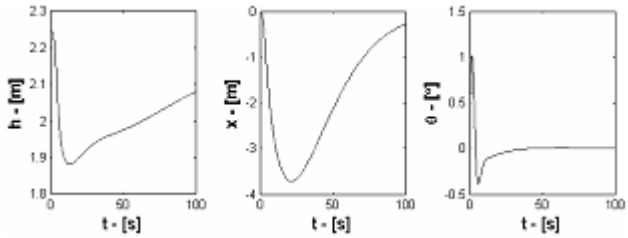



Figure 8.5: Gust behaviour for centre of gravity controlled vehicle

The centre of gravity shift used to control the vehicle is imposed by means of a 2 kg dead weight that has 2 degrees of freedom. The motion is driven by 2 servos, which are part of this dead weight. This control system can be realized with a weight of about 7 kg. The system can be seen in figure 8.6.

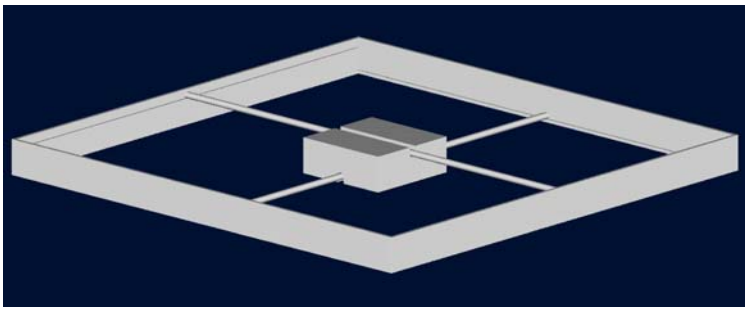


Figure 8.6: Centre of gravity shift control system

## 8.8 Conclusion

From previous attempts it shows that the requirements for a HPH as presented in the Sikorsky competition by the AHS are nearly impossible to meet. However, calculations on the 4NiCopter design show promising results.

In order to do all the dimensioning calculations, the 4NiCopter has been chosen to have a mass of 50 kg. An important factor in whether the design is feasible is the question whether the final design-mass is above this 50 kg. From the design calculations it has become clear that a mass of 56 kg is realistic for the 4NiCopter as it has been presented in this DSE. This excess mass of 6 kg is considered to be within limits and thus can be dealt with in later design stages.

The rotor has been developed to generate more lift than actually required. This means that the rotor can easily maintain the 56 kg weighing aircraft at an altitude of 1 meter. The rotor mass is slightly higher then the design-mass for the rotor.

The structure has a square cross-section and can easily satisfy the stiffness requirements. The structure mass of the structure is higher then the design-mass for the structure, but the structure can be improved further in future design stages.

The transmission of the 4NiCopter has been completely developed. The driving forces can be exchanged efficiently from pilot to rotors

and the system is lightweight. The system weighs more then the prescribed 5 kg.

The control system developed is fully capable of keeping the 4NiCopter on the designated location. The mass of the control system can be reduced drastically by further development and research. This means that even though the system is over weight, a solution is close at hand.

Since the total weight of the HPH design is higher then presumed during the rotor dimensioning, the rotor should be re-dimensioned and re-optimized for the actual achieved total weight. A larger rotor might well be capable of lifting the excess weight, including the weight increment caused by the rotor enlargement itself. The supporting structure could be developed more effectively.

## 8.9 Recommendations

For the supporting structure, a more extensive buckling analysis should be performed. This will allow the safety factor to be reduced and allow a lighter more optimized supporting structure. Furthermore, research on the effect of inclining the structure on structure stiffness should be looked into.

Also the rotor can be optimized further. The Reynolds number on the rotor is very variable; therefore the performances will differ a lot. The iteration steps might be extended and adapted. A performance analysis to differ the airfoil over the rotor can be done to optimize the performances of the rotor. To speed up optimization 3D plots can be made. A second optimization loop is needed to ensure that the most optimal setting of the rotor is used.

For the transmission, a promising new product is the Drivecord, an aramid cable with relief. As far as can be concluded from the webpage, this relief is constructed out of the same material. The patent-holder did not respond to the mail sent, so further information is not available now. Furthermore the torsion tubes must be optimized. They can be constructed more efficiently by optimizing the

radii. The off-the-shelf bicycle parts are also worthwhile redesigning and producing in-house. Although high-tech products are commercially available already, still considerable weight savings can be made (for instance on the spools). A more practical recommendation would be to make an effort to get sponsoring from DSM, the producer of Dyneema. DSM is seeking for ways to inform the public on the high-end possibilities of Dyneema and being part a record-breaking project would be a great way to accomplish this.

The control system can be dimensioned more effectively. The dimensioning in this report is a rough guess and fine-tuning will probably reveal that the control system requires less weight. The control algorithm could also be improved. The algorithm shows good recovery from gust loading, but the altitude loss could pose a problem.

In general the 4NiCopter can be called a success at this moment. The design has proven itself to be feasible and the results gathered in the past weeks look very good. Even though some problems have also been found, researching more in dept and making multiple design loops can solve all these problems. If the 4NiCopter will be built one day, it will fly and hover!

# 9. GRAVITATIONAL TRACTOR FOR TOWING ASTEROIDS

*Students:* C. van Beelen, M.V.C. Evertse, C.M. Evertsz, W.S. Huiskamp,.G.F. Huiszoon, G.T. Oud, L.A.J. Perez Lebbink, R. Reijnst, B.S.M. van Schie, R.M.C. Spiteri, G. Vanbavinckhove,

*Project tutor:* dr.ir. E.J.O. Schrama

*Coaches:* ir. G.F. Brouwer, dr. L.L.A. Vermeersen, ir. R. Amini

The mission states that the Earth has to be saved from a possible collision with an Asteroid, using a gravitational tractor. Both the concept for the mission as well as the concept for the spacecraft (named SET) will be presented.

## 9.1 Mission description

In the past, several theories about the existence and the evolution of asteroids have been conceived. Two main scenarios are generally considered. The first states that asteroids are debris from a planet that used to be in an orbit between Jupiter and Mars what nowadays is referred to as the asteroid main belt. It is believed that this planet fell apart (probably by an explosion) and that its remains are still in the same orbit. A second explanation is that asteroids are parts originating from the formation of the solar system that have not been able to form a solid planet (yet). However, there is still uncertainty about how planets were formed in the early years of the solar system.

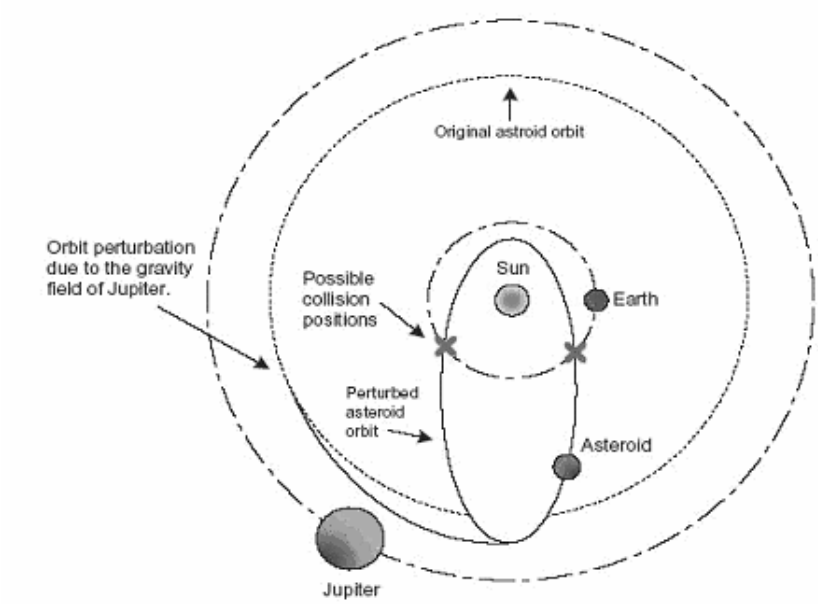



Figure 9.1: Overview of the orbit of an asteroid that is captured by Jupiter's gravity field (highly exaggerated)

Earth impact effects of asteroids and meteorites entering our atmosphere depend mainly on the projectile diameter and density, its entry velocity, the impact angle, and the target type (impact on land or ocean). The larger and more dense the asteroid, the deeper it will penetrate the Earth's atmosphere. On average the minimum size for an asteroid of rocky composition (the main bulk of the asteroid population) not to burn up in the atmosphere before impact is assumed to be 50 m diameter

The mission statement was formulated as follows:
*To deflect an asteroid bound for earth using a gravitational tractor, in order to save the Earth from a hazardous collision and to investigate the possibility of positioning one or more satellites near an asteroid such that its gravitational pull alters the asteroids trajectory.*

The gravity tractor approach uses Newton's law of gravitation. The relation between the required thrust $T$ and the distance $d$ from the centre of mass of the asteroid is

$$T\cos\left[\arcsin\left(\frac{r}{d}\right)+\phi\right]=G\cdot\frac{M\cdot m}{d^2}$$

Here, $r$ is the radius of the asteroid, $\phi$ is the thrust offset angle, $M$ is the asteroid mass and $m$ is the satellite mass. By applying this thrust force with the satellite the asteroid is towed out of its original orbit by the mutual attraction force between the satellite and the asteroid.

Out of all the hazardous near Earth objects (NEO's), Apophis was selected for the SET asteroid deflection mission (ADM). Apophis has certain characteristics that validate this choice. The dimensions of the target asteroid are important for the gravitational tractor concept to work. Apophis has a diameter of approximately 320 m. A direct hit from an intact Apophis would lead to destruction over a large local area, the blast equalling 880 MT of TNT, or 65,000 times the power of the nuclear bomb that destroyed Hiroshima in 1945. It therefore clearly meets the requirement of the target asteroid being hazardous. Apophis is large enough to pose a serious threat and not too large for the gravity tractor approach to work. A conclusion of asteroid Apophis' orbital elements posted on the NASA NEO page is that its orbit intersects the orbit of the Earth. This means that there is a possibility of Earth impact. For Apophis this means it makes a close approach to Earth every 7.8 years. This is Apophis' synodic period, or the time that it takes for the object to reappear at the same point in the sky, relative to the sun, as observed from Earth

There is a very close encounter on April 13, 2029. Apophis will pass the Earth at approximately six Earth radii. This is about 38,250 km. This means Apophis will actually make a swing-by of the Earth, altering its trajectory significantly. Most importantly, a small change in the swing by distance results in large changes in the altered orbit. The chance of an impact in 2029 is zero, the close pass in 2036 however could actually result Apophis impacting on Earth. This means Apophis poses a serious threat to Earth before 2050. It is the only known hazardous NEO for which this holds, making it the most logical target asteroid.

The total budget for the entire mission is 4 billion euros. Obviously the target asteroid needs to be deflected before its projected date of impact hazard. Because SET will be hovering at a relative low altitude above

the asteroid's surface the S/C position control system needs to be able to make reliable, accurate and consistent measurements and calculations to maintain the desired trajectories and orbits for the entire mission. The minimum amount of S/C (End-of-Life) power generation needed to operate SET has to be provided in a reliable way for the full duration of the mission
Although the satellite should have a high level of autonomy, during the mission constant communication with Earth has to be possible with a sufficient bandwidth.

The level of autonomy for the mission is a major indication to the level of command and telemetry communication needed at the ground segment of the mission, although a level of ground command should always be maintained in case of unexpected events.

## 9.2 Concepts studied and related trade-offs

In order to deflect Apophis, three possible mission concepts have been conceived and analysed:

- A single satellite, with a mass of 30,000 kg at Apophis, hovering for twenty months, with a pendulum configuration, launched by a Saturn V, using a Hohmann transfer orbit to travel to Apophis. It will be powered by a nuclear reactor, uses a high gain antenna and has a AOCS consisting of twelve ion engines
- An in space assembled satellite, with a mass of at least 30.000 kg at Apophis, hovering for twenty months, with a pendulum configuration built up by several cylinder shaped modules, launched by several Delta IV L/V's, using a Hohmann transfer orbit to travel to Apophis. It will be powered by a nuclear reactor, uses a high gain antenna and has a AOCS consisting of twelve ion thrusters, a CMG system and RCS hydrazine thrusters.
- A single satellite, with a mass of 1000 kg at Apophis, hovering for approximately one month, steering the swing-by of Apophis past Earth in the year 2029. It will be of a diamond configuration, launched by a Delta IV, using a Hohmann

transfer orbit to travel to Apophis. It will be powered by a combination of fuel cells and solar panels, uses a high-gain antenna and has a AOCS consisting of four ion thrusters, a CMG system and RCS hydrazine thrusters.

The first two concepts describe a solution to the deflection problem that is applicable to Apophis in every phase of its orbit history. The third concept however can only be used in combination with the swing by in the year 2029 as already described. This concept is with respect to satellite system design by far the most feasible and has therefore been chosen as the final design concept.

A combination of Fortran and MATLAB programming was applied to simulate the orbit of asteroid Apophis with respect to the solar system barycentre during the swing by phase. Use was made of the ephemerides of several solar system bodies, (Sun, Venus, Earth, Moon, Mars and Jupiter), provided by JPL. Making orbit estimations of a relatively small body such as Apophis is a complicated problem. It is highly dependant on the accuracy of the initial values of the asteroids position, the initial state vector. The results of the astrodynamic simulations show that Apophis will make a close approach to earth in the year 2029, as was indicated by various sources and that steering this close approach by positioning spacecraft SET in along track direction of the asteroid will have huge effects on its orbit. Therefore with respect to the astrodynamics the third concept is also feasible.

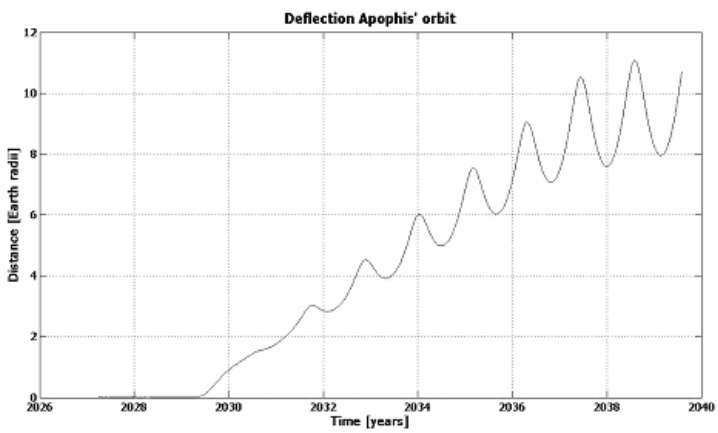



Figure 9.2: Deflection of Apophis in the year 2036

The simulation for the deflection of Apophis was performed using a gravitational tractor with a mass of 1000 kg and a hover period of one month, in November 2020. Figure 9.2 shows the perturbation in the orbit of Apophis due to the SET ADM: a deflection of six Earth radii is achieved, meeting the requirement of a deflection of at least one Earth radii by 2036. Note that the initial deflection at swing-by is about 2 km (0.0003 Earth radii). The swing-by has a deciding factor in the resulting orbit of Apophis.

## 9.3 Details of selected concept

If SET, with a mass of 1000 kg, starts its gravitational hover period in November 2020 and stays in position by thrusting in opposite direction of the gravity force by Apophis for 1 month, its gravity influence will result in a difference between the perturbed and unperturbed asteroid orbit in the range of 6 Earth radii in 2036. It is very unlikely Apophis has such a low density that spacecraft SET will tear it apart since the applied thrust is only 0.03 N and it has endured larger force during previous close approaches to Earth.

SET will be launched in April 2020 using a Delta IV-H. The most efficient transfer orbit to reach Apophis at the moment the hovering mission will begin is found to be a Hohmann transfer orbit. The total satellite mass at the beginning of the launch is 13500 kg. The Delta IV has a launch capability of 25000 kg in LEO. The upper stage of the satellite can deliver a maximum thrust of 110 kN, and is calculated using a $\Delta V$ of 6 km/s. The total $\Delta V$ needed for the Hohmann transfer orbit is only 2 km/s. This oversized design accounts for any contingencies.

Spacecraft SET is designed to have a cube shaped bus, with a diamond shaped side pointing towards the asteroid, so the thrusters can easily be positioned under a 30 degree angle with respect to the direction to Apophis. This is necessary to avoid ‘baking’ of the asteroid by the thruster exhaust and not to reduce the net towing force. The computer architecture on-board of SET has a capacity of 0.5 MIPS. The communication bandwidth has a maximum capacity of 425 kbits/s,

with a redundancy of 211 kbits/s for critical moments and possible software upload.

Star trackers and sun sensors will determine the position and attitude of the spacecraft while control moment gyroscopes (CMG) and hydrazine thrusters provide attitude control. A light intensity and ranging system will determine the altitude of satellite SET above the asteroid and map the asteroid surface. During normal operations, with 4 operating ion engines SET needs a power of 2682 W fully provided by solar panels. Thermal control onboard SET is maintained by 3 radiators with louvers, heating actively requiring a power of 121.1 W. SET will bring a multi-spectral imager to map the shape of Apophis, an infrared spectrometer to investigate its composition, and a magnetometer to measure its magnetic field.

For the ADM the total cost is estimated to be 1.7 billion Euros, where a 50 % redundancy has to be included. This gives a total cost of 2.5 billion dollars, well within budget. The technical performance parameters and risk values all give realistic numbers.

| | |
|---|---|
| Total budget | 4 billion euros |
| Total mission cost (incl. 50% redundancy ) | 2.5 billion euros |
| Launch date | April 2020 |
| Swing-by date of Apophis | April 14 2029 |
| Possible impact year of Apophis | 2036 |
| Deflection rate of Apophis in 2036 | 6 Earth radii or approx. 38,250 km |
| Launch vehicle | Delta IV-H |
| Required $\Delta V$ for Hohmann transfer | 2 km/s |
| Apophis diameter | 320 m |
| Required tractor force | 0.03 N |
| Duration of hover period | 1 month |

Table 9.1: Mission characteristics

| | |
|---|---|
| Spacecraft bus dimensions (*l x w x h*) [m] | 2 x 2 x 2 |
| Spacecraft mass [kg] | 1000 |
| Solar array area [$m^2$] | 14.4 |
| Required power [W] | 2682 |
| Attitude determination accuracy [arcsec] | 2.04 |
| Attitude control accuracy [arcsec] | 1.8 |
| Altitude accuracy [m] | 0.375 |
| Altitude control force [N] | 0.04 |
| Communication bandwidth [kbit/s] | 425 |
| Computer capacity [MIPS] | 0.5 |

Table 9.2: Spacecraft characteristics

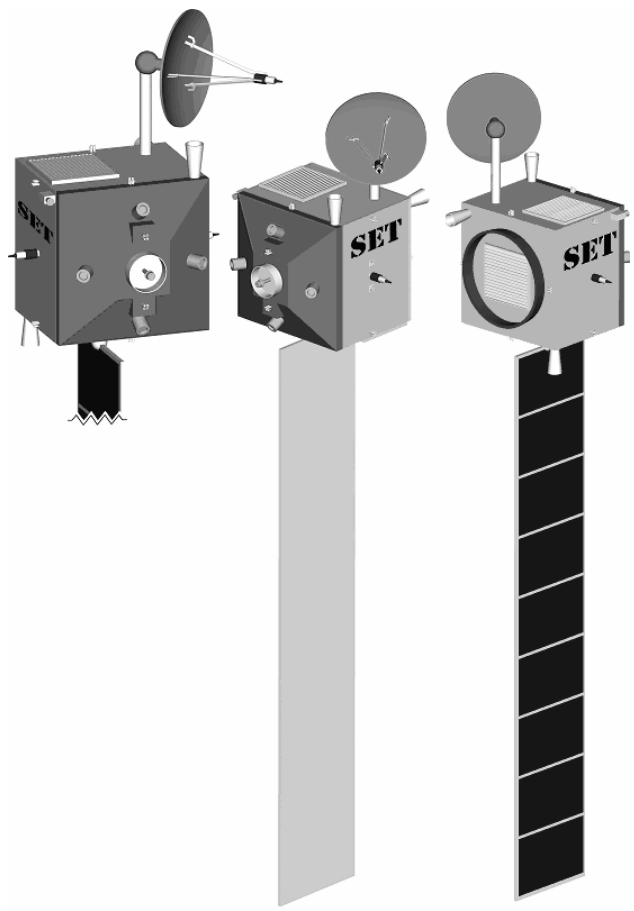



Figure 9.3: Satellite views

## 9.4 Conclusions and recommendations

Using a gravitational tractor to deflect the asteroid Apophis, which has a significant impact hazard in the year 2036, is a technically feasible solution. The concept, as designed for this particular asteroid, can however not be applied to most other asteroids due to the absence of a swing-by past Earth.

In the coming years several opportunities during relatively close approaches will occur for Apophis' orbit to be tracked more accurately with radar observations, for instance in 2013. It may happen that the risk of impact is then reduced to a level where a deflection mission is no longer necessary.

It is recommended that more accurate simulations, necessary to correctly predict the effects of the gravity tractor, are continued. A longer hover period might be required, which will have consequences for the SET spacecraft design (more fuel capacity for instance). A suggestion is to use a variance matrix of the initial state vector, instead of simply obtaining the initial values for Apophis' orbit from the online JPL DE405 solution. The variance matrix could include a stochastic Monte Carlo simulation (with generic algorithms) that takes variations of the initial state vector into account, based on the known spreading of the initial orbit elements. This approach would give a better representation of the statistical aspects of the chance of Earth impact in 2036 after the 2029 flyby.

New information on Apophis' albedo, shape, rotation and composition can be obtained by the extra instruments on SET or from research done by other space missions exploring asteroids. This should be used to improve the modelling of the influence of solar radiation pressure on the asteroid's orbit. The parameters that describe the solar radiation pressure in the simulations presented in this report are not yet realistic.

For the analysis of the Hohmann transfer orbit, development of the optimisation MATLAB program is needed. Working with the current optimisation algorithms for the trajectory simulations was a time consuming matter. With more time, this could be improved to a program that is fully automatic.

Further research on spacecraft SET itself should include analysis of the vibration (acoustic) loads on the structure and a more detailed layout of the internal satellite structure. Possible new technological developments in the space industry concerning the subsystems that are applied should be tracked. For instance, improved efficiency of solar cells and higher accuracy of sensors can be useful for the final ADM design.

Finally, a budget should remain available to maintain fulltime Near-Earth Object observation programs, also aiming for bodies smaller than 1 km in diameter.

# 10. SPACE FOR WIND

*Students:* W.J. Baars, W. Berkelaar, H.G. Bijlsma, M.P. Bouman, K.P. Damen, J.J.M. Dingemans, W.D. Ledegang, C. van Liere, M.W. Mulder, A. Thomopoulos

*Project tutor:* ir. W.A. Timmer

*Coaches:* ir. C. Ferreira, ir. W. Haans, ir.V.P. Brügemann

## 10.1 Introduction

At this moment, wind energy is the second leading source of renewable energy in the world. One of the most interesting points in this field is the exploration of wind energy in the urban environment while profiting from high wind velocities around buildings. The purpose of the project "Space for Wind" is to design a building integrated Wind Energy Conversion System that makes use of the high potential flow phenomena around the faculty of Aerospace Engineering.

The mission need statement of the project "Space for Wind" is:

*Conceptually design the Wind Energy Conversion System, integrated in the faculty of Aerospace Engineering, which economically facilitates both its energy production and research.*

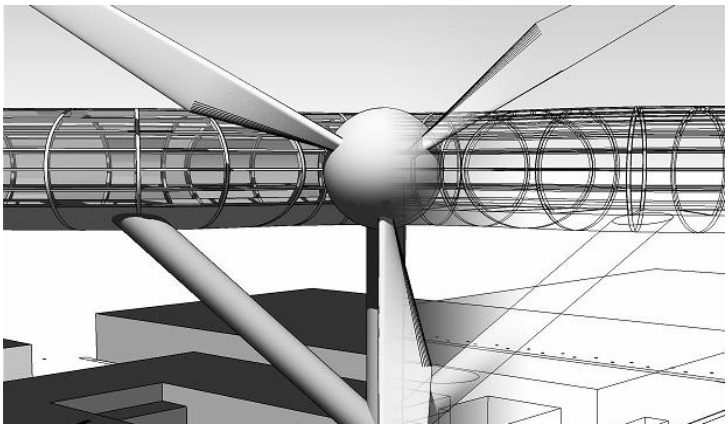


Figure 10.1: Impression of the Giant Ducted Turbine

## 10.2 Key requirements and constraints

The design of the Wind Energy Conversion System has to comply with a set of requirements and constraints. A selection of the most important requirements and constraints is given below.

Key requirements for the Wind Energy Conversion System are:

- Provide 30% of the faculties electrical power demand (135 kW)
- Provide electrical energy, costing less than € 0.20 per kWh
- Facilitate research on wind energy
- Create building integrated design

The most important constraints are:

- Risk; the hit probability for people in the vicinity should be lower than 10-6
- Noise; produce less than 40 dB(A) at the façade of the building and less than 35 dB(A) inside the surrounding buildings
- Visual; the system should not become a visual nuisance to people in the vicinity

## 10.3 Concepts

Following the mission need statement, five concepts are designed.

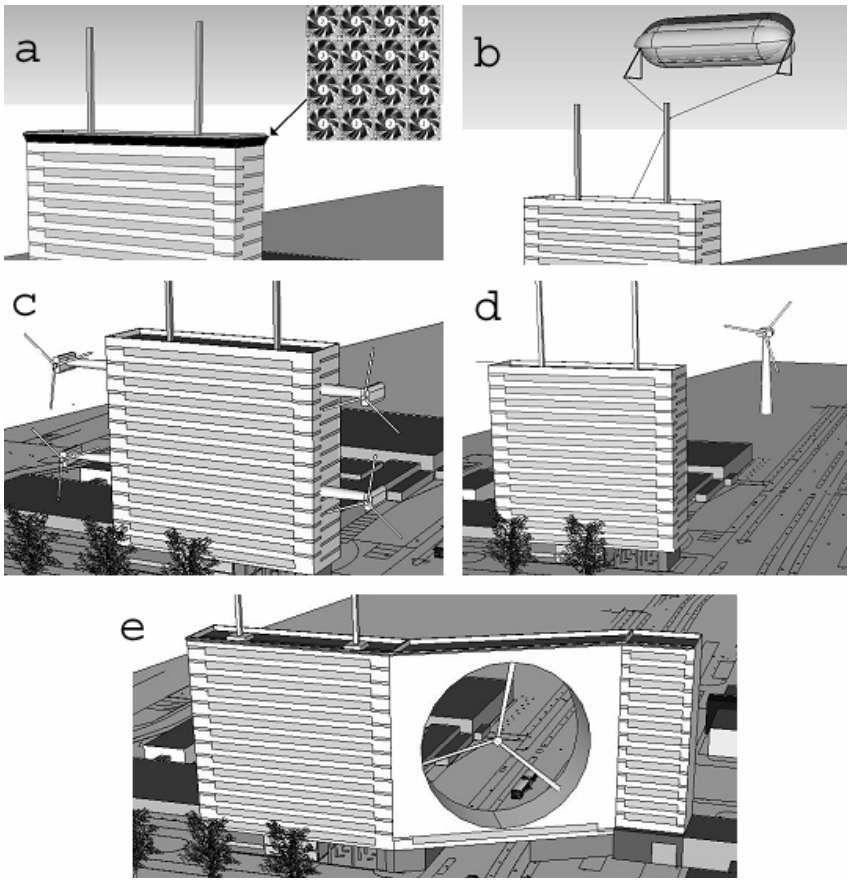



Figure 10.2: The five concepts; a) The Little J-Array, b) The Magenn Turbine, c) Side-Mounted Turbines, d) The Standard Turbine, e) The Giant Ducted Turbine

**The Little J-Array**

The current trend is to make larger wind turbines. However, the idea behind Little J-Array (figure 10.2a) is, "why go large and cheap, when you can go small and cheaper". The Little J-Array consists of arrays of very small turbines, comparable to the size of computer fans. In order to reduce the costs, the Little J-Array is made from very cheap components. Multiple arrays can be connected, which makes the

system scaleable to comply with the power demand. The Little J-Array can be constructed in such a way, that the aesthetics of the building are hardly affected.

**The Magenn Turbine**

A new type of wind energy conversion system is the Magenn Turbine (figure 10.2b). In essence, it is a helium-filled balloon with large scoops attached. Due to the drag difference of the scoops, the balloon rotates, generating power. The Magenn is connected to the ground by means of a cable. This cable can be attached to different locations of the Aerospace Engineering property. By changing the length of the cable, the Magenn can be placed at different heights. Disadvantages are the unproven design and its non-building integration.

**The Side-Mounted Turbines**

In the Side-Mounted Turbines concept (figure 10.2c), turbines are attached to the sides of the main building of the Aerospace Engineering faculty. The idea behind this concept is, that optimal use is made of the wind concentrator effects at the sides of the building.

**The Standard Turbine**

The Standard Turbine is, as the name hunches, a standard turbine located on the Aerospace Engineering faculty property (figure 10.2d). The main flaw of this concept is, that it does not fulfil the requirement of building integration. Hence, it does not use the concentrating effects of the building. This concept is used as a reference in the trade-off process.

**The Giant Ducted Turbine**

The Giant Ducted Turbine (figure 10.2e) consists of a large wind turbine in a duct, above the Kluyverweg. On the other side of the Kluyverweg, a new office building will be constructed. The Giant Ducted Turbine concept is not only effective for the generation of power. It also integrates wind energy in the built environment, making a statement to the world that the faculty of Aerospace Engineering is working on sustainable engineering.

## 10.4 Trade-off

During the trade-off process, one final concept is chosen. The trade criteria that are used in this process are; public opinion, costs of the system, the risk imposed on the people in the vicinity of the system, the average power generation, building integration of the design, the amount of maintenance and the environmental impact.

| | Public opinion | Costs | Risk | Power | Building integration | Maintenance | Environment hinder |
|---|---|---|---|---|---|---|---|
| Little J-Array | + | 0 | + | 0 | + | - | 0 |
| Magenn | 0 | 0 | - | - | - - | - | + |
| Giant Ducted Turbine | ++ | - | 0 | + | + | 0 | 0 |
| Standard Turbine | 0 | 0 | + | + | - - | + | 0 |
| Side Mounted Turbines | - | - | 0 | + | + | 0 | 0 |

Table 10.1: Trade-off table with five concepts and trade criteria

The paramount trade criterion in this trade-off is the public opinion. The public opinion was obtained with a questionnaire on our website (www.SpaceForWind.nl), over 300 people replied. From table 10.1, it becomes clear that the Giant Ducted Turbine is the best concept and will be further developed.

## 10.5 Details of the Giant Ducted Turbine

In figure 10.3, the final design of the Giant Ducted Turbine is presented. In this section the different components of the design will be discussed. These components are; the additional office building, the turbine, the duct structure, the pedestrian bridge inside the duct and the support structure.

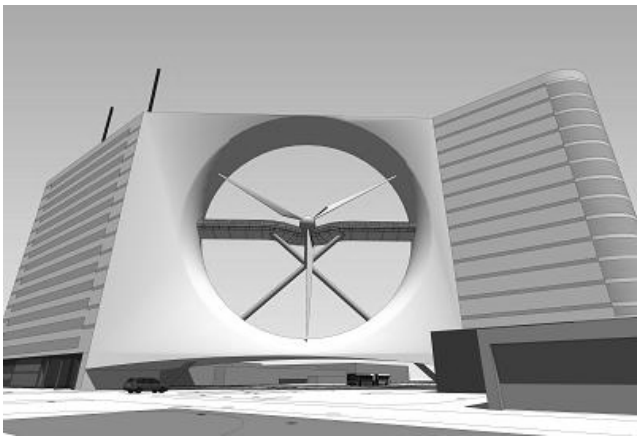


Figure 10.3: Final design of the Giant Ducted Turbine

**Additional office building**

There is a need for 1500 m2 extra office space within the Aerospace Engineering faculty. This need is incorporated in the design, creating 4100 m2 of new office space in an additional building with the same height as the main building. The remaining 2600 m2 of extra office space will be rented to external parties.

**Turbine**

It is chosen to use the Enercon E-44 turbine, because it has a high performance, state of the art wind turbine, with a power rating of 910 kW at a wind velocity of 15 m/s. The average power of 190 kW results in an annual energy production of 1.66 million kWh. This equals 50% of the faculty's electrical energy demand. The performance calculation is done using the following information:

- Hourly wind velocity and direction data of the last 25 years
- The turbine power curve
- An estimation of building effects incorporating different wind angles

Because of variations in wind velocity and power consumption, supply and demand will rarely be equal. The TU Delft Heat and Power plant will compensate for this shortage or excess of power at the faculty. Replacing 50% of the faculty's energy demand by green energy, results in a reduction of 3800 tonnes $CO_2$ emissions per year.

**Duct structure**

The duct structure has the same height as the current main building of the Aerospace Engineering faculty. The combination of the main building, new office building and the duct, will have a concentrating effect on the wind. Besides that, the duct structure integrates the wind turbine and new office building with the existing faculty building. An important feature of the duct structure is, that it is designed to be a stand-alone structure. This prevents turbine's vibrations from being introduced into the existing and new office buildings. A light truss structure supports the duct and its façade. The façade is mainly constructed using metal sheets. The double curved part is constructed using Styrofoam, for ease of construction.

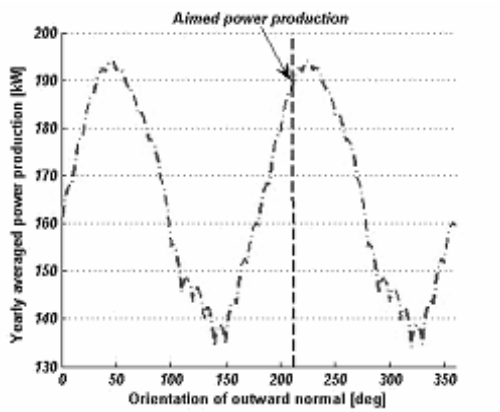



Figure 10.4: Average power production as a function of the duct orientation.

In the preliminary design phase, the duct was orientated in the optimal wind direction.

Building on top of the newly constructed Aerodynamics department building introduces difficulties. Therefore, at a later stage in the project it was decided to deviate from this optimal angle. The current building orientation causes a marginal decrease in average power production of 4 kW, as can be seen in figure 10.4.

**Pedestrian bridge**

The pedestrian bridge (figure 10.5) is an important component for the building integration aspect. This bridge connects the new office building and the existing building. Furthermore, students, employers

and visitors can see the turbine operating from up close. The pedestrian bridge is an ellipse, with a width of 6 m and a height of 3.5 m. The structure is mainly made out of glass. The pedestrian bridge is connected to the support structure by a roller support, in order to prevent sway vibrations that are induced by the turbine, from being introduced into the other buildings.

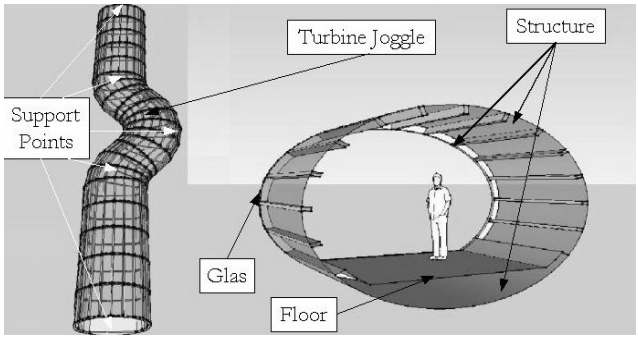



Figure 10.5: The pedestrian bridge

**Support Structure**

The support structure, consisting of two legs, carries the loads of the turbine and the pedestrian bridge. Regulations prescribe that the structure may not deflect more than 0.1 m. In accordance with the requirement that the maximum allowable stress should not be exceeded, the following parameters of the structure are determined. The struts of the support structure have a wall thickness of 0.02 m and an outer diameter of 1.00 m. The struts are made out of cold drawn AISI 1006 Steel. A detail of the support structure is given in figure 10.6

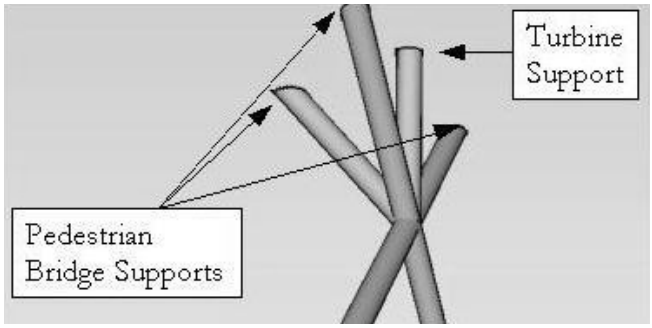



Figure 10.6: Detail of the support structure.

**Cost Breakdown**

In table 10.2, the cost breakdown of the Giant Ducted Turbine is given. From the investment costs and the estimated annual energy production of 1.66 million kWh, the energy price becomes € 0.15 / kWh. The costs of the new office building and the pedestrian bridge are not included in the energy price calculation, because they are not part of the power production system. The Facility Management and Real Estate department of the Delft University of Technology will fund these parts. The current electricity price for the faculty of Aerospace Engineering is € 0.12 / kWh. This electricity is generated with fossil fuels, of which the price increases at a higher rate than the inflation. In the future, it might be beneficial to use wind energy, instead of fossil fuels for generating electricity.

| Component | Costs |
|---|---:|
| Wind turbine (including support structure) | € 1,570,000 |
| Building around turbine | € 2,000,000 |
| Office building | € 5,000,000 |
| Bridge | € 480,000 |
| Project costs (start up) | € 8,400,000 |
| Maintenance and decommission costs | € 650,000 |
| Project costs (total life) | € 9,050,000 |

Table 10.2: Cost breakdown of the Giant Ducted Turbine

## 10.6 ModuLab

In the project objective statement, research and energy production are combined. To conduct research on small wind turbines at different locations around the faculty, the ModuLab concept is designed, as can be seen in figure 10.7. ModuLab consists of a platform on which the turbine and the necessary equipment can be installed. This platform, with force measuring capabilities, can be placed at various locations. It offers mobility, versatility and modularity. During the Design Synthesis Exercise, a functional split-up is made between research and energy production, because of the very different requirements. In the final phase of the project, the option was given to round off the

ModuLab and to focus on the technical design of the Giant Ducted Turbine.

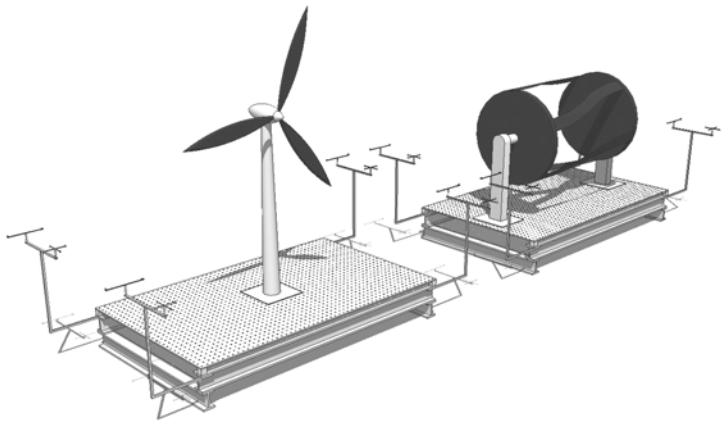


Figure 10.7: Visualization of ModuLab

## 10.7 Conclusions and recommendations

The Giant Ducted Turbine integrates wind energy in the built environment, making a statement of innovation and sustainability. But, does the Giant Ducted Turbine design meet all requirements?
The risk factor is in the same order of magnitude as the regulations prescribe. Safety equipment, like a safety net or cables through the blades, can be installed to lower risks even further.

As can be seen from table 10.3, there are two requirements for which compliance is uncertain. Noise and cast shadows demand further research. Noise is mainly produced by the vortex at the tip of the rotor blade. Since the turbine is placed in a duct, this tip vortex will develop in a totally different way, with respect to a standard turbine. It is assumed that this difference might reduce the sound significantly, because no specific data on the influence of a duct and the propagation of the tip noise is currently available. To comply with

governmental rules, further study should be performed on this noise aspect.

| Description | Requirement | Giant Ducted Turbine | Compliance |
|---|---|---|---|
| Electrical energy production goal | 30 % electrical energy production | 50% | ✓ |
| Electricity price | € 0.20 / kWh | € 0.15 / kWh | ✓ |
| Building integrated | Architect approval | Approved | ✓ |
| Risk | Comply with governmental norms | 3.42 10-6 | ✓ |
| Noise hindrance | Comply with governmental norms | Uncertainties in noise propagation | ✓/× |
| Cast Shadows | Comply with governmental norms | Flicker frequency = 1.7 Hz, but uncertainties in duration | ✓/× |

Table 10.3: Compliance matrix

The effect of cast shadows of the rotor blades consists of two parts; the flicker frequency and the duration. The flicker frequency fulfils the norms, however, research should be performed on the endurance of the cast shadows.

In the Giant Ducted Turbine, the Enercon E-44 turbine, which is designed for the open field, is placed in the built environment. Therefore, there are several aspects that demand further research. Because the turbine is yaw-fixed, research should be done on the effects that this characteristic has on the performance.

The Enercon E-44 normally has a hub height of 55 m. However, the Giant Ducted Turbine, with its 28 m hub-height, is placed relatively close to the ground. Closer to the ground the effects of the boundary layer increase, affecting the performance of the turbine. Besides these effects, also building-turbine interaction should be researched, using for example an extensive Computational Fluid Dynamics study. The Giant Ducted Turbine can also be used to conduct real time scientific research on wind energy in the built environment.

The start-up costs of the Giant Ducted Turbine are € 8,400,000. However, from a sustainable point of view, an adequate time horizon should be set to determine the payback of these investments. Other parties like wind turbine manufacturers and architects, can use the scientific research data of the Giant Ducted Turbine. The electricity price for the designed set-up of the Giant Ducted Turbine, is calculated to be € 0.15 / kWh. However, this price depends on the current design and further developments can lead to a lower price. Cooperation with other investors and subsidies of the government decrease the electricity price even further.

Overall, it can be concluded that the Giant Ducted Turbine is very effective in terms of sustainability, innovation and knowledge and also in terms of integration of offices and wind energy. The project is technologically and economically attainable. The Giant Ducted Turbine can be used as a good marketing tool for the Delft University of Technology, increasing the public awareness that wind energy in the built environment is feasible. The Giant Ducted Turbine has a high potential for actual implementation.

# 11. SKYRAFT: EMERGENCY ESCAPE SYSTEM FOR HIGH-RISE BUILDINGS

*Students:* F.P. van der Bas, E.T.C. Berix, P. Broos, I.P. van Dijk, J. van Eijck, M. de Jong, H.J.M. Kok, J.P. Kuiper, K. Tang, A.F.M. Vonk

*Project tutor:* ir. J. de Vries

*Coaches:* ir. C. Cerulli, ir. M.J.F. Jansen, ir. D. Richardson

## 11.1 Introduction

In the near future, high-rise construction is set to cross the 1 km height barrier and the number of people in such high buildings will rise accordingly. With offices, hotels and shopping centres all in one skyscraper, the capacity will easily rise above 25000 people, creating a situation with many people on a relatively small area.
At present day, people who need to escape from a high-rise building have to rely on stairs, fire doors and sprinklers. After the events of September 11th 2001, the need for alternative evacuating methods has increased even further and the belief has grown that a suitable escape system could have saved many lives if it were available.

The assignment for this Design Synthesis Project Group is to design a system that can provide a safe, fast and reliable way of escaping from a high-rise building. The Mission Need Statement, which serves as a guideline throughout the project, is stated as follows:

*'Design an airborne escape system evacuating all individuals, situated above the 25th floor of a skyscraper to a safe distance, in case of an emergency'*

## 11.2 Requirements and constraints

The requirements and constraints for a high-rise building follow from the Mission Need Statement. Due to the variety of options available for the emergency escape system, most requirements cannot be specified in measurable parameters. When the concepts are chosen, the requirements are updated where applicable.
The most important constraints and requirements are the driving and killer requirements. In order to evacuate all people from a high-rise building, these constraints and requirements have to be met. The driving and killer requirements are specified below:

- Get the people out alive;
- The system has to provide a larger capacity than the conventional stairs in order to make the evacuation less complex and chaotic;
- The size of the escape system inside the building has to be as small as possible, since more occupying space means a less affordable system;
- The cost of the system has to be less than 5% of the construction costs to make the system affordable;
- The detachment and flight phases have to be coordinated in order to perform a safe evacuation;
- The system has to be such that all people above the 25th floor can be evacuated;
- The whole building has to be evacuated within one hour;
- The evacuees do not need any training to use the emergency escape system.

Other requirements, which give direction to the design, are:

Constraints:
- Legal system
- Fly out of the building

- Architectural design
- Sustainable system
- Human endurance
- System costs

Technical requirements:

- Manufacturability
- Maintainable system
- No additional injuries during evacuation
- Requirements on performance

## 11.3 Concepts and trade-off

After the requirement analysis, a thorough brainstorm session was set up and approximately twenty different concepts were generated. A first trade-off followed between all these concepts from which the best were chosen. The following three concepts were worked out in further detail, while pictures are shown in figure 11.1, 11.2 and 11.3:

- An ejection system, already present in the building (the Flying Shell);
- A parachute / glider guided by a cable (the Hope Rope);
- A flying platform (the SkyRaft).

**The Flying Shell**

The Flying Shell is an evacuation system that flies people directly from the building to a safe place. On each floor in the building, a certain space is reserved for multiple escape shells. The people board and secure themselves in the shells after which a system checks if it is safe to launch. For safety reasons, the launch of the different shells takes place in different directions and at different moments. Shortly after launch, wings unfold such that the shell can reach a safe distance from the building, while being controlled by a computer system to manoeuvre. When a safe distance is reached, a parachute is deployed to land the shell safely.

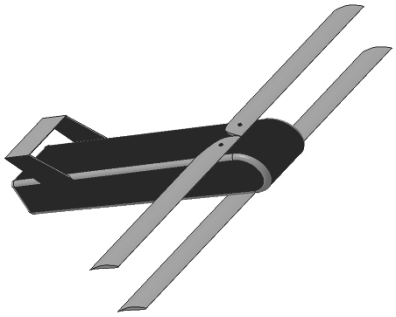


Figure 11.1: Concept sketch of the Flying Shell

**The Hope Rope**

The Hope Rope is based on the concept of transporting people out of the building along a cable, although the cable is strictly for guidance and does not carry the weight of the evacuees. Some device is needed to generate enough lift to glide along the cable with a safe velocity, but also a means of decelerating close to the ground is needed. First, the cable has to be deployed and transported to an attachment point by a vehicle. At the attachment point, ground personnel ensure that the cable is firmly attached. After the attachment is confirmed the actual evacuation can begin, where a crew assists the evacuees during landing.

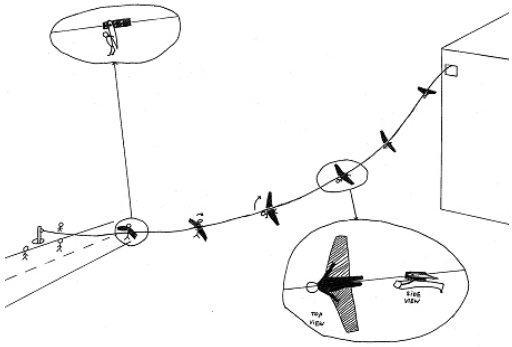


Figure 11.2: Concept sketch of the Hope Rope

**The SkyRaft**

The SkyRaft is a flying platform that can take off and land vertically. It is designed to carry 150 evacuees at once and can achieve a forward flight speed of 20 m/s. The SkyRaft is used as a shuttle system and is operated by a trained pilot. In case of an emergency the SkyRaft shuttles between the building and the landing spot. At every floor the

evacuees meet at a central point where facilities for boarding are present. Two crew members assist with boarding the evacuees. When ready, the SkyRaft flies towards the landing site and the evacuees are disembarked quickly. The SkyRaft takes off again and evacuates the next floor.

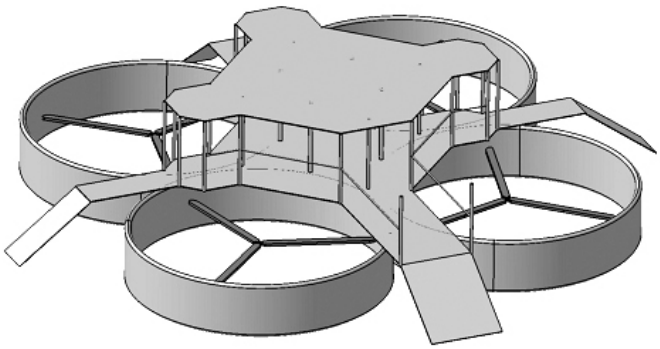


Figure 11.3 Concept sketch of the SkyRaft

**Trade-off**

To choose the final concept, the team created several selection criteria on which the three concepts needed to be evaluated on, differing in importance compared to each other. The criteria are: the size the systems take up inside the building, the evacuation time, the risks of the entire system, the inspection needed, the maintenance needed, the psychological barrier for evacuees, the sustainability, the costs of the system and the amount of training required from the evacuees.

After the trade-off, the SkyRaft seemed to score better than the other two concepts. The criteria on which the SkyRaft gained its higher score were the risk and the size it takes in a building. It has a relatively low risk compared to the others because it uses technology that is extrapolated from existing flight and the operational risks are low. The Flying Shell on the other hand, uses technology that is so far only feasible in theory and therefore it has a high development risk. The Hope Rope has a higher operational risk because the system is not totally autonomous and has a high psychological barrier.

As mentioned before, the SkyRaft requires no space in the building, while the others do. This is also a large advantage because the building does not have to be adapted for the escape system, making it

relatively easy to use for existing buildings as well. The only criterion on which the SkyRaft scored lower than the other two concepts is the cost criterion. The flying platform is a large investment, but it can be shared by a entire city because it is suitable for most buildings. By analyzing the weak points of the three concepts, it followed that the SkyRaft was indeed the best, also considering that it was the only concept without strong negative scoring. Therefore the SkyRaft was chosen as the best concept.

## 11.4 Design of the SkyRaft

From the trade-off it followed that the SkyRaft was the best option to evacuate high-rise buildings. In the next phase of the project, the SkyRaft was worked out in more detail and this section discusses main aspects of the design.

**Configuration and lay-out**

The final version of the SkyRaft is a hovering platform with main dimensions of 14.5 by 14.5 m and a height of 6 m. It uses rotors for lift and propulsion, which are surrounded by a duct for protection and a better airflow.

The SkyRaft can be divided in three main levels, where each level has specific functions that are clearly separated to ensure an optimal functioning of these various parts. The three levels are:

- System compartment
- Passenger cabin
- Cockpit

The system compartment is the space between the ducts and underneath the passenger cabin; it houses the main mechanical parts of the SkyRaft. The fuel tanks, the gearbox and the drive shafts are located here together with the two engines, which use the space between the ducts as air intake. The exhaust is directed downwards, into the downwash of the rotors. Figure 11.4 shows the bottom view of the SkyRaft with all mentioned components. All ducts are covered by inclined protecting gauze to prevent debris from damaging the rotors.

The passenger cabin is separated from the other parts to ensure maximum protection for the evacuees, with 4 bridges on the outside of the cabin. Inside the cabin enough securing capacity is available through vertical bars and overhead hand straps.
Above the passenger cabin the cockpit is located, giving the best view possible to the pilot. The SkyRaft is equipped with state-of-the-art flight and navigational instruments and uses helicopter-type control.

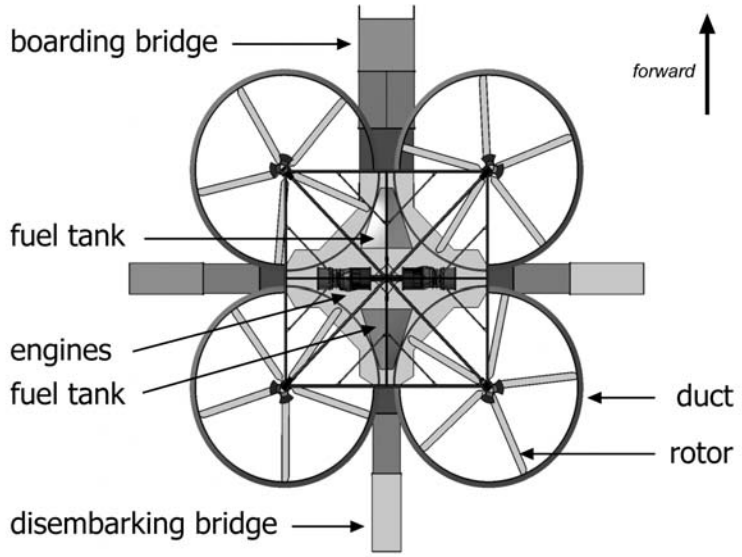



Figure 11.4: Bottom view of the SkyRaft

**Structure**
The main loads on the SkyRaft are carried by a pyramid form thin-walled truss structure, designed as such because it is very effective in carrying the vertical lift to the structure. In this way the truss structure remains lightweight. The bottom of the pyramid consists of two parallel frames with the rotors mounted halfway.
The passenger cabin has a capacity of more than 150 people, so the SkyRaft can evacuate an entire floor at once. The cabin is mainly constructed of lightweight aluminium honeycomb materials. There is one boarding bridge and three disembarking bridges connected to the cabin.

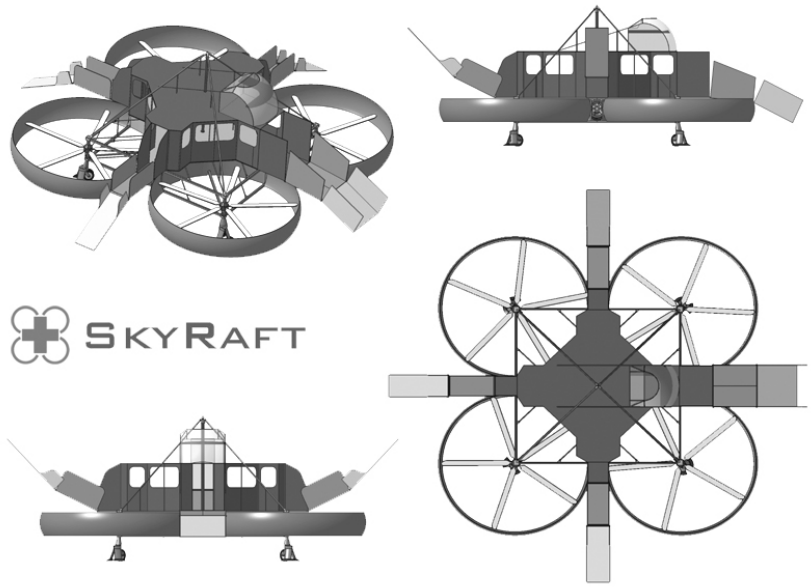



Figure 11.5 Different views of the SkyRaft

**Power**

At first the power required to fly was calculated without fixed dimensions for the rotor; it was found that the maximum power required occurred for the fully loaded climbing forward flight situation. Dimensioning the rotor for this flight situation resulted in a new maximum power required for the same flight condition with an empty load. The reason for this is the increase in drag due to the fixed chord length and blade loading for all flight situations. The maximum power required for this flight situation is 8416 kW.

**Aerodynamics**

A Vr-7 airfoil is used for the rotor blades of the SkyRaft; this airfoil is especially designed for helicopters and thus offers good performance for the SkyRaft. The airfoil is chosen because of its high lift and low drag characteristics as well as the nearly constant moment coefficient along the blade. The SkyRaft also features ducts around the rotors, which increase the mass flow through the rotor, increasing the thrust by as much as 6 %. The shape of the duct itself causes only a minor increase in thrust, in the order of 35 to 75 Newton depending on the flight condition. The duct has an diameter of 6.8 m at the top, 7.0 m in the middle and 6.6 m at the bottom; the height is 1 m.

**Drive train**

The drive train consists of all the components that generate power, including the two Rolls Royce AE1107 engines, the differential, the gearbox, the drive shafts, the four rotor hubs and the four rotors.

The working principle of the drive train can be described as follows: the two engines deliver a certain amount of power, with a maximum of 8416 kW in empty forward climb configuration. This rotation results in torque transmitted to the differential by the turbine shafts, which are rotating at a constant angular velocity of 15000 rpm. The differential provides the coupling of the two engines to each other. The differential is connected to the gearbox via the main shaft. The gearbox, with a gear ratio of 24.15, converts the high angular velocity of the turbine shafts and the main shaft into a much lower 621 rpm of the rotor shafts. The rotor shafts are connected to the rotor hubs, on which the rotor blades are attached.

**Stability and Control**

A flying platform is a naturally unstable configuration; therefore the SkyRaft needs a flight computer to constantly correct the disturbances. The computer registers the demands of the pilot and manoeuvres the platform safely to the desired flight condition. The input of the computer will be a combination of speed in forward, sideward and upward direction and a yaw-rate. This input is transferred to the pitch angles of the rotor blades.

The SkyRaft is equipped with the same controls as a helicopter. In this way helicopter pilots need little training before they can fly the SkyRaft. Since the controls are not linked to the orientation as in ordinary aircraft but to the velocities in the different direction, flying a SkyRaft is much easier. When the controls are released, they return to the neutral position and the SkyRaft levels off and stabilizes.

**Cost**

In order to determine whether the SkyRaft has any potential within the market, a cost estimation is necessary. The summation of all components of the SkyRaft is quite accurately estimated at € 5 million, in which the two engines have a large contribution by taking up 72 %. For the overall product cost price, aspects such as research and development, manufacturing, facilities and logistical support need to

be taken into account. The total costs are estimated by comparing the SkyRaft's payload with other aircraft to be around € 24 million per SkyRaft.

## 11.5 Conclusions and recommendations

**Conclusions**

After finishing the project, it can be concluded that no real barriers have come up during the design of the emergency escape system. This means that the SkyRaft can be controlled close to buildings such that all people can be evacuated in a safe way. Due to the increase in demand for safety, more money is available for rescue solutions. The result is that the SkyRaft can ensure global safety of high-rise buildings, since a large market for safety exists and the potential of the SkyRaft will only grow in the near future.

**Recommendations**

- In a further stage of this project, more focus on the placement of the engines within the frame is necessary. In the current design it would take a relatively large time to take the engine in or out during maintenance
- When alternative fuels like hydrogen or bio fuels are fully developed and readily available, the SkyRaft can be adapted to such a fuel to make it more sustainable
- The design of the duct and the airfoil can be optimized using CFD calculations. With these programs it would also be worthwhile to have a closer look at the drag of the complete SkyRaft during flight
- Even though the strength of the structure has been calculated, it can be improved by a FEM analysis

| **General characteristics** | |
|---|---|
| Dimensions (W x L x H) | 14.5 x 14.5 x 6 m |
| Operational Empty Weight | 7742 kg |
| Maximum Take Off Weight | 20122 kg |
| Payload | 12000 kg (150 passengers) |
| Cost | € 24 million |
| **Rotor characteristics** | |
| Number of rotors | 4 |
| Rotor diameter | 6.8 m |
| Number of blades | 5 |
| Profile | Vr-7 |
| Chord length | 0.27 m |
| Blade twist | -10° |
| **Drive train** | |
| Engine | Two 4392 kW Rolls Royce AE1107 |
| Gearbox | Main gearbox, gear ratio of 24.15 |
| Fuel tanks | Duel fuel tank, capacity 1350 litres each |
| **Performance** | |
| Maximum forward speed | 20 m/s (72 km/h) |
| Rate of climb (empty) | 20 m/s (72 km/h) |
| Rate of climb (full) | 2 m/s (7.2 km/h) |

Table 11.1: Description of the SkyRaft

# 12. ENVISENSE: DESIGN OF A $CO_2$-MEASURING MAV SWARM

*Students:* F.W.M. Dircken, L.K. Meijer, P.G.M. Rottier, S. Sieberling, M.M.A.G. van der Steen, D. Trips, M Uitendaal, R. Verspeek, M.J. Verveld, M.J.G. Wierema

*Project tutor:* ir. C. De Wagter

*Coaches:* ir. B. Bijnens, ir. B.T.C. Zandbergen


Figure 12.1: Artist impression of the ENVISense MAV, operation in an industrial area.

According to the "Nationaal Onderzoek Programma Mondiale Luchtverontreiniging en Klimaatverandering" (NOP) and the "Koninklijk Nederlands Meteorologisch Instituut" (KNMI), the Earth's surface temperature increased by about 0.55 degrees Celcius in the past century. The warming trend has even increased during the past

two decades. This emphasises that global warming has become a worldwide issue. In order to make accurate models of this phenomenon, atmospheric measurements need to be performed of prominent contributors of the greenhouse effect: the Greenhouse Gases. Some examples of these gases are $CO_2$, $CH_4$, $NO_x$ and the fluoride gases. Issues for which models are of great importance are the prediction and understanding of air quality, soil acidification and climate change. For this mission it has been decided to measure $CO_2$ concentrations only, simply because this is the only gas for which small and accurate sensors are available. The Mission Need Statement is formulated as follows:

*Safely measuring $CO_2$ gas concentrations for research and ultimately for government purposes.*

## 12.1 Project description

Several systems to measure $CO_2$ already exist. Figure 12.2 gives an overview of these systems. However, it can be stated that a Micro Aerial Vehicle (MAV) swarm distinguishes itself from its competitors, because it measures quickly, accurately and at different heights. This makes it suitable for missions where larger control volumes have to be measured.

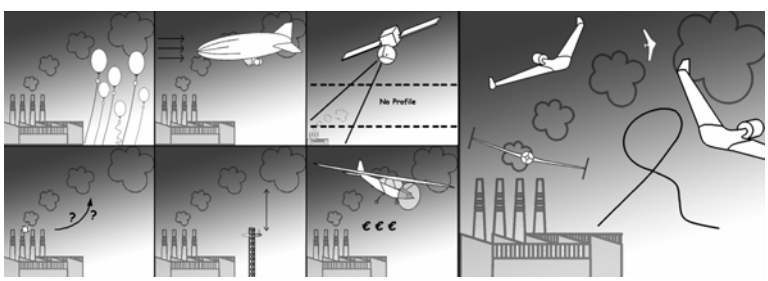



Figure 12.2: Overview of competing measurement systems and an impression of the ENVISense.

The requirements and constraints that the system has to operate in, are obtained from customer demands, sustainability issues and functional analysis. The requirements are divided into different levels of importance. The most important requirements are the killer

requirements followed closely by the key requirements. The killer requirements determine whether a project succeeds or fails, whereas the key requirements drive a design to a very large extend.

The killer requirements are:

- Safety; the system should be safe for people and objects on the ground. This is of importance because presently no legislation exists that allows autonomous unmanned aircraft to fly. To obtain a permit, the legislator must be convinced that the system is safe;
- Be able to measure; if the measurement of $CO_2$ concentrations fails the mission need statement has not been met;
- Be able to fly; in order to achieve the degree of flexibility required a flying sensor platform is required. Therefore, to fly is a primary requirement to be met;

The key requirements are:

- Endurance of 2 hours, flying in a 5 by 5 km area up to a height of 500 m;
- 6 prototypes and a preliminary ground station must be build for € 10,000.-;
- The MAV must be retrievable in case of a malfunction.
- The sensor must be modular, so it can be replaced by other sensors;
- Life span of 120 hours;

From the mission need statement and the requirements a system concept has been developed. Figure 12.3 gives a schematic overview of the system. The system is divided into a ground and an air segment. The task of the ground segment is to provide flight patterns for the MAVs. The air segment consisting of 6 MAVs measures the $CO_2$ concentration along these flight patterns. The development of the total system is divided into two major parts. The first part, the proof of concept phase must deliver a prototype system, which must proof its superiority to competitor systems. This phase must be concluded within the budget of € 10,000.-. The second part contains a system design into more detail. This phase is called the operational phase.

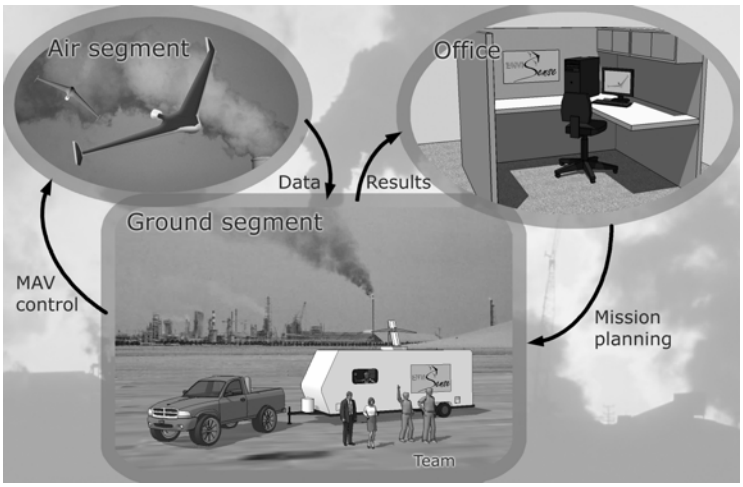



Figure 12.3: Global system overview of ENVISense.

The project objective statement for the DSE can now be summarized as follows:

*To design a safe autonomous swarm of at least 6 MAVs, within a budget of € 10,000 to measure $CO_2$ emissions in a prescribed volume, by 10 students in 9 weeks.*

## 12.2 Conceptual design

Concepts were generated for each part of the system. However most time was spend on the concept development of the MAVs. Three potential candidates were a *blimp*, a *conventional configuration MAV* and a *blended wing body MAV (BWB)*. Figure 12.4 presents the design option tree. The blimp was ruled out because of its sensitivity to wind. The remaining two concepts were worked out in more detail. The MAVs are designed to have minimal drag (minimal battery capacity) for a flight duration of 2 hours at 20 m/s, and thus it is as light as possible. Figure 12.5 presents the two concepts at the end of the conceptual design phase.

The first concept is the conventional configuration. It has a conventional tail and a high main wing. Furthermore it contains a

ducted push fan and is powered by Lithium-ion Polymer batteries. The second concept, the BWB, has a push prop and is also powered by Lithium-ion Polymer batteries. The major components are positioned in a small body compartment in the centre section.

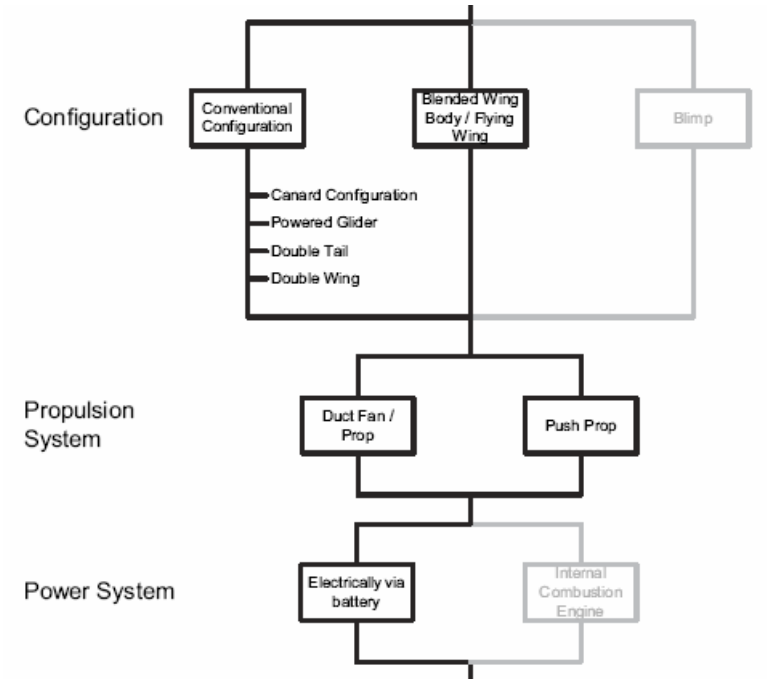



Figure 12.4: The design option tree for the MAVs of ENVISense.

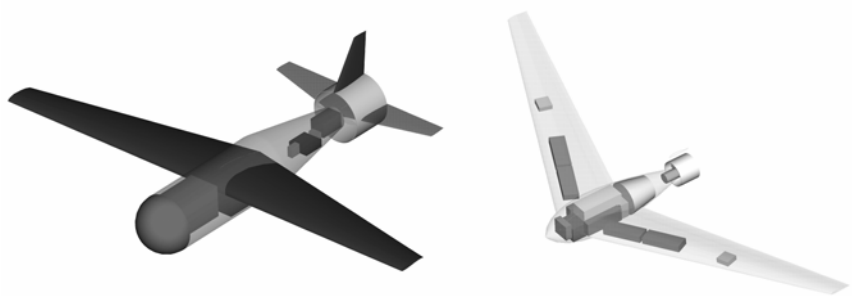


Figure 12.5: On the left, the conventional configuration concept, on the right the BWB concept.

## 12.3 Trade-off

For the trade-off a third concept is considered. This concept is the BWB with a ducted push fan instead of a push prop. The BWB with ducted push fan is selected by means of a trade-off. The major trade-off criteria are safety, performance, stability and launch and landing robustness as shown in table 12.1. All concepts have similar scores in the trade-off. However on the most important criteria the BWB with ducted push fan has better scores.

| Criterion and selection description | WF | Conv | BWB | BWB +DF |
|---|---|---|---|---|
| Safety. The ducted fan is considered safer than an open propeller. The same holds for low weight versus high weight | 5 | 4 | 3 | 5 |
| Performance. The BWB uses far less power in cruise conditions than the conventional configuration. | 5 | 3 | 5 | 5 |
| Stability. The conventional configuration is easier to design stable and does not suffer from a lack of lateral stabilization. | 4 | 4 | 3 | 3 |
| Launch and landing robustness. The BWB has less small and vulnerable parts on its outer shape. | 4 | 3 | 4 | 4 |

Table 12.1: Part of the trade-off table showing the four most important trade-off criteria. (The weight factor (WF) indicates the importance of the criteria. Conv = Conventional configuration and DF = Ducted Fan. The total is computed by multiplying the weight factor with the score and adding the scores of the individual criteria for each concept.)

## 12.4 Detailed design

In the detailed design the air segment and the ground segment are worked out into more detail. The final design of the MAV is presented in figure 12.1 and 12.7. Figure 12.7 also contains the specifications of the MAV. The sensor for $CO_2$ measurements is positioned in the centre section. The nose and the leading edge are made of Eperan® polypropylene, which is a soft material, to reduce the damage in case of a crash. The airfoils selected are S-curved airfoils, which provide a

low moment coefficient required for BWB. The winglets are added for control and stability issues. Figure 12.7 shows how the fuselage and the wing blend into a blended centre section. The MAV is controlled by a Flight Control Computer consisting of two main components: an autopilot and a navigation program as shown in figure 12.6. The navigation program solves for the flight pattern to be flown and the autopilot directs the control surface deflections using adaptive control.

In the detailed design the ground segment is further worked out as well. The most essential elements of the ground segment are operations and logistics, ground station, user interface, ground interface, flight patterns and telemetry. The ground station for the proof of concept phase consists of a laptop, telemetry and differential GPS. Later in the operational phase the ground station is translated into a mobile operations room. The user and the ground interface are both software. Their function is to control the MAV swarm. The user interface incorporates the user demands. The ground interface determines the flight patterns that have to be flown based on user wishes. The ground station and the MAV swarm are connected by means of telemetry. The telemetry is designed to reach MAV up to a distance of 8 km. Figure 12.6 indicates the system logic block diagram. All connections of the system are indicated in this diagram.

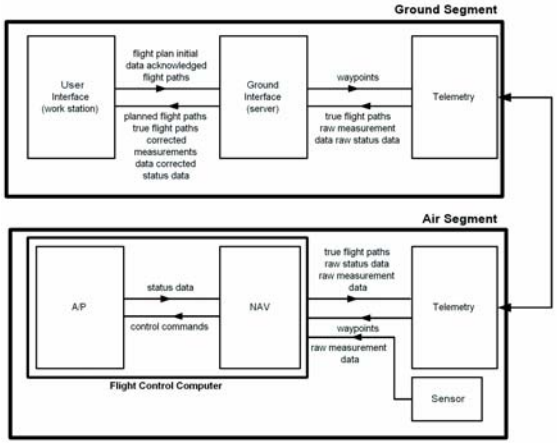
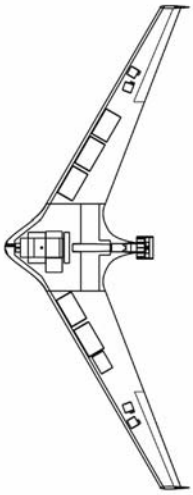



Figure 12.6 Logic block diagram of ENVISense. All communication links of the system are presented in this figure. Next to the lines the data that is send is indicated.

# MAV Specifications

***Dimensions***
Wing span: 1170 mm
Length: 449 mm
Height: 175 mm
Aspect ratio: 11

***Performance***
Cruising speed: 20 m/s
Max level speed: 32 m/s
Stall speed: 13.3 m/s
Landing speed (with parachute): 6.5-10 m/s
Max rate of climb: 2.7 m/s
Max range (Including climb to 500 m): 200 km
Turn around time: (With spare batteries): 10 min
(With recharging): 2 h 10 min



***Powerplant***
Type of propulsion: Ducted fan
Engine Power: Cruise: 17 W, Climb at 1 m/s: 38 W
Batteries: LiPo batteries 6 Ah at 7.4V

***Weights***
Maximum weight for 2 h flight: 1.5 kg

***Payload capabilities***
Payload bay dimensions: 110x56x45 mm
Max Payload weight for 2 h flight: 0.4 kg
$CO_2$ sensor: DX6200
Accuracy: For 1-2 Hz the accuracy is 10 ppm

***Airframe***
Materials: Eperan® Polypropylene and carbon or glass fibres in epoxy resin
Characteristics: Blended wing body design, midsection US1000, wings E182

***Command system***
- Real time status and data downlink, Real time command uplink
- Up to 50 kbit/s at a range of 8 km
- Adaptive control autopilot

***Operation conditions***
Altitude: 500 m
Wind conditions: 4 Beaufort
max no. of UAVs at same time: 25 MAVs per channel

***Safety measures***
Low weight, blunt soft nose and leading edge, ducted fan, autopilot and power failure triggers parachute and radio link failure triggers MAV to return to groundstation.

***Launch and landing***
Launch: Chainsystem arrangement
Landing: Parachute system

Figure 12.7 Specifications and a 3-view of the final design of the ENVISense MAV

## 12.5 Conclusion and recommendation

ENVISense functions as a true integrated whole: the MAVs listen to each other and to commands for other MAVs. The customer has the option to change the measurement site at any time. At any time any MAV can take care of itself if necessary as well. Based on these features, the system will be able to function in many circumstances and with great flexibility. The success of the design though, should of course be measured by the killer requirements:

**Safety**
In case an error is detected in the system, it will execute any of a variety of safety procedures, depending on the error. If all fails, the parachute will deploy and the MAV will gently oat back to the earth. Together with the soft front (nose and leading edges) of the MAV, this will make sure that a collision with a human being is unlikely to cause severe harm.

**Ability to fly**
The MAV is a highly efficient BWB type of aircraft. It is fitted with a propulsion system taking it to any point in the measurement block in a reasonable time and giving the MAV the agility to climb and descent at nice rates. The efficient shape does not demand much power though, so the amount of energy required is small and the MAV can fly for 2 hours easily during a normal mission.

**Ability to measure**
For the measurement of $CO_2$, a state-of-the-art sensor is selected, allowing fast and accurate measurements. Customers who want to measure something else have the flexibility to do that as well: only minor changes to the design are required as long as the sensor itself stays within certain mass and volume limits. And the formation flying behaviour allows for great flexibility of the way the measurements are performed.

The system fulfils all killer requirements that were set. The design as it is at this moment can thus be called a success. Remark though that this includes certain assumptions that need verification. The technical part of the design has several innovative features including: The measuring capabilities within a very small and low cost package, the endurance

of two hours for such a lightweight aircraft, autonomous flight in swarm formation. This makes ENVISense a very attractive system for further research and development and may ultimately be a competitive solution to measuring, surveillance and reconnaissance missions.

The major problem with the operation of ENVISense is legislation: Autonomous MAV swarms are a rather uncommon field of engineering for legislators. Therefore, there is no legislation readily available and design teams have to resort to other legislation, which is usually not suited for this application. It would be advisable to work with legislators to set up a set of rules for MAV applications (or UAV applications as a whole), taking into account the way these aircraft are controlled and used in practice. This will open a lot of possibilities for technically advanced applications and research, which now remains limited. At this stage ENVISense can however be used under certain circumstances. The proof of concept phase will therefore be concluded with a test flight program.

# 13. FASTCAT: THE FUTURE OF HIGH SPEED COMMERCIAL AIR TRAVEL

*Students:* ing. B. Boonacker, B.A.P. Bruggeman, M.V. van Dijk, D.J.M. Hendrix, T.E.M. Klein Tank, K. Lauwers, J.J.M. Luijten, S.G. van Oortmerssen, G.J. van der Straaten, O. Treur

*Project tutor:* dr.ir. B.W. van Oudheusden

*Coaches:* ir. G. Larocca, Dipl.-Ing. T.F. Wittwer, ir. J.L. Dalhuijsen, ir. E. Jesse

## 13.1 Introduction

Commercial air transport has brought a revolution in global travel, and flying has become the preferred way of long-distance travel - fast, safe, and comfortable. Technological advances in the field of high-speed aerodynamics and propulsion technology led to the introduction of the high-subsonic jet airliner in the 1950s. Not long thereafter, the Mach 2 Concorde entered the stage, reducing the flight time from Paris to New York to no more than 3.5 hours. The future of high-speed commercial air travel looked more promising than ever: it seemed just a matter of time before hypersonic flight could provide the ultimate speed in intercontinental travel.

Countless projects later and about 35 years after the first supersonic commercial flights, no successor has been fully developed and built. Economical and environmental concerns have plagued supersonic

development more than simple technical feasibility did. High development and manufacturing costs lead to high acquisition costs for airlines, and introduce market and development investment risks. Higher Mach numbers also introduce penalties associated with engine and airframe temperature cycles, while higher fuel consumption frustrates market acceptance through potentially higher fares. Environmental concerns include airport and community noise, sonic boom, and emissions.

Despite these difficulties, the dream of a new supersonic aircraft is still alive among many. The productivity increase, prestige for airlines, and the reduced flight times for passengers make super- and hypersonic, the latter meaning flying more than 5 times the speed of sound, means of transport still very valuable to pursue. After supersonic flight stood up, it was already running before it properly learned how to walk. A small supersonic aircraft, with easier solvable environmental, technical, and investment risks, could be the first step towards a new era of high-speed commercial transport. New materials and optimization tools make complex system design more feasible than in the past. Also, new configuration concepts, especially those optimized for both cruise speed at high Mach numbers and low speed operation, lead to higher efficiencies and improved environmental compatibility.

## 13.2 Mission statement

*Develop perspectives, strategies and concepts for supersonic/hypersonic passenger transport modes in the 21st century within 10 weeks, with a project group of 10 students.*

Within a period of 10 weeks, a report on the Future of Alternatives concerning Super/hypersonic Technologies for Commercial Air Transport was produced, in short: FAST CAT. This report is intended to inform clients about the possibilities and trends in the future of faster commercial air travel.
Project FAST CAT puts emphasis on the perspectives, required strategies, market opportunities, and concepts for a means of aerial transport that could someday accommodate the need for decreasing travel time.

## 13.3 A view on the market

In civil aviation, air travel is concerned with the shipping of goods to meet demand between market A and B, as far as the operation of shipping is within economical and societal constraints. In other words, air travel has to meet the market. In this simple representation many stakeholders play a part. Aircraft manufacturers as well as subcontractors, airlines, passengers, airports, environmentalists, governments and citizens all interact with each other and they all have various interests to protect.

The first aspect of the market that has been researched is economic feasibility. A criterion for economic feasibility of an aircraft is that it should return the commercial investment required to bring the aircraft and supporting systems into operation. Productivity it is the measure, which indicates the time needed to break-even on a cost basis. In essence, productivity is the speed times the number of seats times the flight hours flown expressed in seat-miles or seat-kilometres. The number of seats seems to have reached its upper limit with the new A380. Also, the number of flight hours per year seems to be limited to around 4000 hours. Therefore, to increase productivity, improvement in speed is sought. Another criterion for economic feasibility is fuel efficiency. Fuel efficiency is necessary, because higher fuel costs result in higher operational costs, thus extending the time before reaching a positive return on investment. High oil prices put a break on global economic growth, which in its turn reduces air transportation growth; oil prices decrease demand for transport and increase its cost. It is therefore imperative to keep an eye on fuel efficiency. Apart from that, the sheer depletion of fossil fuels itself makes research for alternative means of propulsion indispensable.

The second aspect of the market analysis was demand. Long term route and capacity development has been investigated, and showed that certain segments will develop in a favourable way for high-speed commercial aircraft. The category of business passengers has proven to be the most willing to spend more money on flight time reduction. As a consequence of this, routes that connect major world political and economical centres have been analysed with respect to their viability for high-speed air transport.

The final aspect of market that requires attention is the societal-environmental aspect.
Present day aircraft are already subject to various regulations concerning pollution, emission, and noise nuisance. Over time, these current regulations are expected to grow evermore stringent, although limits of supersonic speeds overland might be dropped if future technology provides lower sonic boom levels. The fact that high-speed aircraft operate at altitudes and flight speeds unfamiliar to normal aircraft means that much research will have to be done in this field. This to ensure that operation will stay within environmentally acceptable limits, even if they are not regulated yet.

## 13.4 Literature study

To create perspectives and background knowledge, a literature study was performed. Topics like structural materials, aerodynamics, aircraft configurations, propulsion systems, and previous supersonic commercial and military aircraft concepts were investigated. For the three main items, aircraft configuration, propulsion systems, and structural materials, a design option tree has been made, including the technology readiness and the applicable Mach number. The technology readiness is, synchronously with the scenarios discussed in section 13.5, divided into three time frames: short term (2025), mid term (2045), and long term (2065). The knowledge gained by this study, combined with the market outlook, led to the identification of possible future scenarios.

## 13.5 Scenarios and strategies

Now that that market analysis is done, and the future enabling technologies are investigated, a plan for the future is developed in order to design an economically viable and socially acceptable high-speed commercial concept. First, an inventory is made of the future world situations, followed by a division in three distinct periods: 2025, 2045, and 2065. This inventory resulted in 42 different possible

scenarios for the future. Next, the least probable scenarios were eliminated, resulting in three remaining scenarios; one for each period.

For 2025, this results in the situation of an economy boom, combined with lower social and economical acceptance (no sonic boom). The same applies to 2045, combined with a lack of fossil fuels. Finally, for 2065 again the beforehand mentioned situations occur, together with the fact that special airport adaptations to facilitate high-speed transport can be considered.

Subsequently, a set of boundary conditions were set up for each of the remaining scenarios, in order to clearly define them, combined with the technology possibilities and readiness. For the economy boom, the focus is on mass and business transport, and flight time reduction. The lower social and environmental acceptability results in the need for less emission and noise, and more difficulty to convince people of the new concepts. The fact that no fossil fuels are available results in the boundary conditions that alternative fuels must be found, and new engines developed. Also, other fuel storage techniques must be investigated. Since no sonic boom overland is allowed, boom strength reduction must be applied. Finally, when airports can be adapted, new layouts can be investigated, or airport handling can be optimized.

Following from these scenarios are the strategies, which will advise on the required number of passengers, cruise speed, and range, for each time period. Resulting from these three strategies, aircraft concepts were created that meet the requirements: SwingCAT for 2025, Obli-X for 2045, and HyperCAT for 2065.

## 13.6 Concept for 2025: SwingCAT

By the year 2025, current emerging economies in Asia, like China and India, will have grown immensely. Because of the relatively large stretches from Asia to Europe and the US, supersonic air travel will be an attractive solution to significantly decrease travel times. However, problems with flying supersonic overland, like the sonic boom, are not expected to be completely solved within a period of twenty years. Therefore, supersonic aircraft can be used on transpacific and transatlantic routes only. Because the required range of aircraft

operating on transpacific or transatlantic routes differ substantially, both categories of routes ask for different aircraft. In this section, a concept will be shown for a Mach 1.6 aircraft carrying 150 passengers with a range of 11,000 km, which is approximately the distance of transpacific routes between the west-coast of the US and China.
This choice is primarily based on the expectation that demand on transpacific routes will increase substantially in the next twenty years, and will be concentrated on a limited number of cities: Beijing, Shanghai and Guangzhou. Although the range of 11,000 km is mainly based on the transpacific routes, also other routes can be operated on. For example, transatlantic routes between Europe and the east coast of the US, which have been exploited by Concorde in the past. In table 13.1 the design requirements for this concept are shown.

| | |
|---|---|
| Range | 11,000 km |
| Cruise speed | Mach 1.6 |
| Number of passengers | 150 |

Table 13.1: SwingCAT design requirements

In figure 13.1, the layout of SwingCAT is shown. The variable sweep wing is chosen, because it combines excellent subsonic and supersonic performance. The reason for selecting an H-shape tail plane is that it shields the ground from noise produced by the engines, because the tail plane forms a box-like structure around the engines. This characteristic is essential, because we do not expect engines to be that silent to meet noise requirements, without such a shielding structure around them.

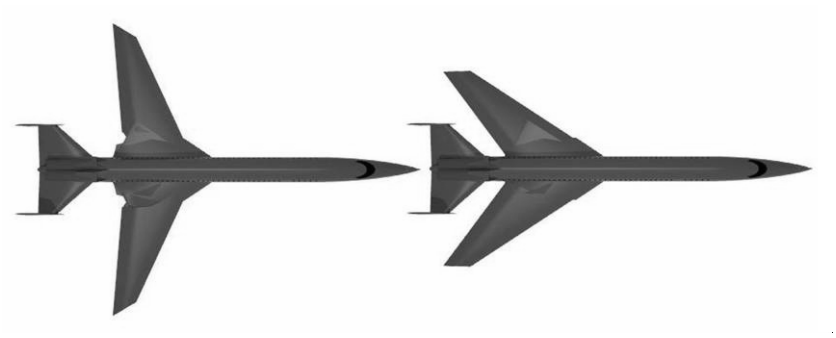


Figure 13.1 SwingCAT in landing and cruise configuration

## 13.7 Concept for 2045: Obli-X

A major design criterion for the 2045 concept was the absence of the availability of fossil fuels. Any aircraft, which is to enter service in 2045, and be operated for 20 to 30 years, most probably cannot depend on fossil fuels. Therefore, it is assumed that fossil fuels are no longer available by 2045, leaving hydrogen as most feasible fuel at this moment. A disadvantage of liquid hydrogen is that it requires four times the volume compared to kerosene, for the same energy content. Therefore, combined with the fact that transatlantic routes between various cities in Europe and the United States will be covered, a range of 7500 km is decided upon. A consequence of this is that the aircraft must be able to fly efficiently at subsonic speeds overland. A supersonic cruise speed of Mach 2.0 is needed to have a sufficient flight time reduction on these routes, a good productivity, and to be able to exploit the available technologies. To be able to store the required hydrogen for 7500 km, and have a sufficient number of passengers to fly efficiently, a number of passengers of 150 is chosen. In table 13.2, the range, speed and number of passengers are summarized.

| | |
|---|---|
| Range | 7.500 km |
| Cruise speed | Mach 2.0 |
| Number of passengers | 150 |

Table 13.2: Design requirements for Obli-X

In figure 13.2, the result of the conceptual design phase for 2045 is presented. As can be seen, the aircraft is designed with an oblique wing. Its major advantages are that it has a very good lift-over-drag ratio for both subsonic and supersonic flight. The wing is placed underneath the fuselage, in order to easily replace the wing if necessary, and to be able to incorporate the hinge mechanism in the bottom part of the fuselage. As the oblique wing pivots during flight, the engines are placed at the rear of the fuselage. A T-tail is used, since then the horizontal tail plane is out of the wake of the fuselage, and the engines can be attached to the fuselage. The length of the fuselage is approximately 92 m, to be able to incorporate all hydrogen needed for 7500 km. Hydrogen tanks are placed behind and underneath the passengers, and in the tail and nosecone. The materials used for the

structural parts of the aircraft (wing, fuselage, and tail) are PETI-5 materials, developed by NASA. PETI-5 is short for Phenyl Ethynyl Terminated Imide, and is the fifth formulation developed. It combines good mechanical properties and extreme durability with good producability, low cost, and environmental stability.

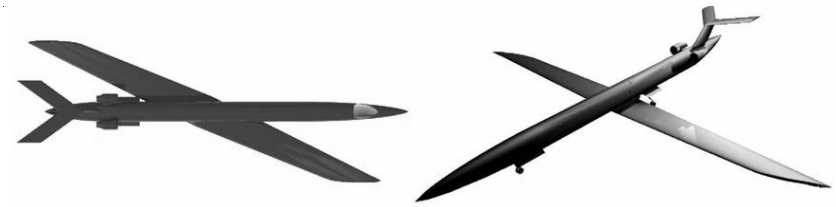


Figure 13.2: Top and perspective view of Obli-X

## 13.8 Concept 2065: HyperCAT

In 2065, air travel will be somewhat different from what is seen today. It is assumed that a mixed fleet will be operational; the traditional subsonic aircraft will still be present for short-range transport, complemented by supersonic transport for long-range travel. Because of ever-growing demand to save time on travel for some categories of passengers, a market exists to develop even faster concepts.

Technology will have matured too, as supersonic aircraft make use of new materials and propulsion techniques that stimulate research & development. When market meets these technologies, hypersonic aircraft will be conceived. For this timeframe, the HyperCAT was designed. The foundation of the HyperCAT concept was the market for businessmen who want to attend a meeting on another continent, and be home before dinner. This resulted in a range of 20,000 km, long enough to connect all important business city-pairs in the world. To make sure that the passenger is back home before dinner, significant time should be gained, resulting in a cruise speed of Mach 5. The cruise speed takes care of a time gain on London – Sydney of 20 hours. Because the aircraft should be exploited commercially, a capacity of 100 passengers was chosen. Table 13.3 shows the design requirements, which were set up for the HyperCAT concept.

| | |
|---|---|
| Range | 20.000 km |
| Cruise speed | Mach 5 |
| Number of passengers | 100 |

Table 13.3: HyperCAT design requirements

The HyperCAT has the configuration of a wave rider. The wave rider is a flying body, which benefits from the shockwaves emanating from the leading edges. Although a wave rider has a low subsonic lift-to-drag ratio, its particular shape, as shown in figure 13.3, is optimized for sub-, super-, and hypersonic lift-to-drag ratios, as well as for an optimized volume around the centreline. The engines are chosen to be turbo-ramjets, which combine the good subsonic efficiency of a turbojet, and the good supersonic efficiency of the ramjet. The HyperCAT, as the Obli-X, will be flying on hydrogen. Besides this, take-off and landing of the HyperCAT will be revolutionary. A magnetic runway will be used. The aircraft will taxi on a taxi-cart from the gate to the runway, and vice versa. Once on the runway, the aircraft will magnetically lift off the cart and accelerated, to encompass a silent take-off after which the turbojet will take over. The main structural material used for this aircraft is aluminium-titanium, with additional carbon-carbon and composites for high thermally loaded parts.

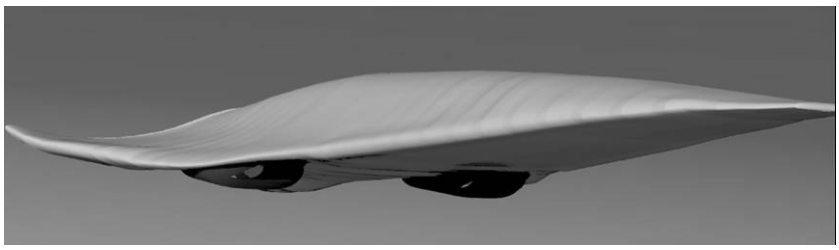


Figure 13.3: Perspective view of HyperCAT

## 13.9 Conclusion and recommendations

**Conclusions**

Flying super- or hypersonic can reduce flight times on long ranges significantly, and flying faster is a way to accommodate the expected growth in air transport by increasing efficiency. Next to the high

performance requirements (high speed, low drag, high lift), the aircraft must satisfy many social and environmental demands (low emissions, low noise, low cost). These requirements and demands are often conflicting.

The Concorde is actually the only supersonic airplane ever to have flown commercially. It was an engineering success, but due to its design focus on speed and prestige, it did not meet the high environmental and economical demands. Nevertheless, a lot of investigation on high-speed commercial air travel has been performed in several research projects.

There is certainly a need for speed, but new technologies are needed to make aircraft more economically and socially viable. Passengers are willing to pay a premium on their ticket price to fly supersonic, but airport handling must be accelerated to profit from the advantages of flight time reduction. It is only feasible to market high-speed aircraft when the world economy maintains a healthy, steady growth rate.
High-speed flight overland is assumed to remain prohibited in the following 20 to 40 years, because of the sonic boom. High-speed aircraft must be able to fly subsonic efficiently, to be able to cover not only coastal areas, but also inland city pairs.

The year 2040 is expected to be the economical turning point for kerosene in favour of liquid hydrogen. Changes in engine and airport infrastructure are needed to be able to make this step. Hydrogen requires a storage volume 4 times as large as kerosene, which conflicts with the performance requirement for supersonic aircraft, stating volume should be as small as possible.

**Recommendations**

A lot of further research on engine, wing, and material technology is needed, in order to make high-speed transport viable. The technologies used in the conceptual design of the SwingCAT, Obli-X, and HyperCAT are important for further development.

During this project, only little investigation has been done on sonic boom reduction. However, this is a very important issue and deserves more attention in follow-up research, as it may be possible to reduce sonic boom down to levels acceptable for overland supersonic flight.

Also, to be able to serve many city pairs, high-speed aircraft should be able to fly efficiently without sonic boom, either through sonic boom reduction, or subsonic flight. More research can be done on this hybrid cruise principle, i.e. cruise consisting of different flight speeds.
It is interesting to investigate new, larger versions of the SwingCAT, Obli-X, and HyperCAT; ticket prices could be reduced when the aircraft can transport more passengers.

During the development of HyperCAT, a magnetic catapult has been proposed as an alternative runway for hypersonic aircraft. The magnetic catapult in itself is a very interesting principle, perhaps worth investigating in another design syntheses exercise.

# 14. SPACE-BORNE TSUNAMI WARNING SYSTEM

*Students:* P.A.I. Brouwer, J.C.T. Gunneman, H.M. Jara Orué, M. Visser, B. Masselink, B.J.A. van Marwijk, M. BAldee, R.A. Molijn, T.C.K. Bermon

*Project tutor:* dr.ir. H. van der Marel

*Coach:* dr. R.C. Lindenberg, ir. P.W.L. van Barneveld

## 14.1 Mission need and relevance

The terrible Tsunami that hit the island of Sumatra and the countries around the Indian Ocean on December 26, 2004 killed over 250,000 people. It has painfully demonstrated the need for a reliable, fast and global Tsunami warning system. The aim of this study is to prove the feasibility of a global space-borne Tsunami early warning system that uses signals emitted by Global Navigation Satellite System (GNSS) satellites that are reflected by the ocean surface. This technique is known as GNSS-Reflections or GNSS-R and can in theory be used to measure sea level height. Nevertheless, at this time the concept of altimetry GNSS-R has still not been proven from space.

The mission need of the project can be summarized by the Mission Need Statement:

*"To design a feasible, global and competitive GNSS-R based space-borne Tsunami early warning system, including a detailed demonstrator satellite, within nine weeks."*

The objectives of the project are to:

1. Define the user and system requirements
2. Demonstrate the feasibility of using GNSS-R from space for accurate sea level height measurements
3. Study other applications of instrument data
4. Design a satellite constellation that satisfies the system requirements
5. Create a conceptual design for one of the constellation satellites
6. Make a detailed design of the demonstrator satellite

The project roughly consists of three phases, starting with the definition of the requirements, followed by the design of the total Space-borne Tsunami Warning System (STWS) and finally the demonstrator mission and satellite design.

## 14.2 Total system requirements

The requirements of the total system can be divided into three main categories, the constraints, functional requirements and operational requirements. The functional requirements apply to the performance of the system. They include among others the expected Signal-to-Noise Ratio (SNR) that is necessary for accurate measurements, but also the open-sea Tsunami detection threshold. The operational requirements mainly focus on reliability of the system, in terms of time availability and expected lifetime. The constraints are the restrictions that apply to the system, such as the maximum costs and the scarce time that is available. The most important requirements for the Space-borne Tsunami Warning System are listed in Table 14.1.

| | | |
|---|---|---|
| Functional Requirements | Acquire observation data | Sufficient SNR, data link and data storage |
| | Process data | Sufficient processing power |
| | Detection threshold | Detect Tsunami >10cm |
| | Timely warning | Warning < 30 min after Tsunami formation |
| Operational Requirements | Reliability | < 1 missed Tsunami in 1000 yrs<br>< 1 false warning in 3 yrs |
| | Time availability | > 99.9 % |
| Constraints | Cost competitive | ~ € 470 M in 20 years |
| | Time limit | Launch demonstrator within 3 yrs |
| | Client constraints | Space borne system |
| | | Global coverage |
| | | Use GNSS-R |

Table 14.1: Requirements for the Space-borne Tsunami Warning System

## 14.3 STWS design concept analysis and trade-off

After generating the design options for the system, all options that are clearly non-feasible are immediately discarded. The remaining design options are grouped into six independent categories in order to make the design concept analysis more efficient. These categories are shortly discussed below.

**Orbit and constellation**

The satellite altitude is restricted by the SNR of the reflected GNSS signals, which increases as the orbit altitude decreases. On the other hand, atmospheric drag determines the orbit decay rate and increases with decreasing altitude. A high orbit decay rate results in a shorter satellite lifetime or a higher need for orbit maintenance propellant.

An optimal altitude of 645 km is found for the STWS. Because of the height restriction in both directions, it is convenient to use a circular

orbit in order to keep the altitude of the satellite constant throughout the one fully revolution.

The design of the constellation, i.e. the number of satellites, number of orbital planes and the number of different inclinations is mainly determined by the required Tsunami detection time. The chosen constellation is based on the Walker Delta Pattern, using 40 satellites in 10 different orbital planes, with 66° inclinations. This inclination is chosen because the constellation will cover the area between –60 and + 60 degrees latitude, which in turn corresponds to the region where all Tsunamis are originated. The ground tracks of the constellation during a time lapse of 30 minutes are indicated in Figure 14.1. It can be seen that there are still some gaps around the equator and mid-latitude areas, because this constellation is merely used to get an indication of the required number of satellites. Further optimization of the constellation will provide full coverage of the relevant parts of the Earth surface within 30 minutes.

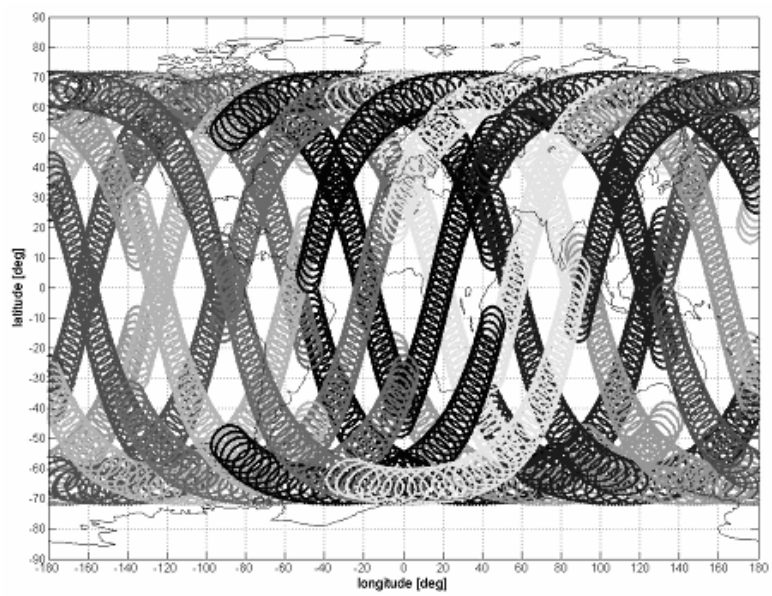



Figure 14.1: STWS 30-minute ground track

**Satellite bus**

Five concepts for the satellite bus were generated, mainly based on their attitude control system. Although each concept is expected to have a sufficiently long lifetime, the sustainability of the system was

considered to be an important factor for the choice of the attitude control system. Therefore, a concept was chosen which included thrusters, so the satellite can be de-orbited at End of Life. The satellite is stabilised by a momentum wheel, reaction wheels and thrusters, which in turn are also used for momentum dumping, orbit maintenance and during the disposal manoeuvre.

**Data processing**

An important design choice was the selection of the place where the acquired data would be processed; i.e. onboard or on ground. Fully data processing on ground is not feasible due to the high data rate required as a consequence of the continuous downlink. Processing only on board of the satellite is not possible, because there is not enough information on board of the satellite to perform all necessary corrections. The data needed to perform corrections, such as seismic data and GNSS satellite precise ephemeris data, is available on ground. Therefore, the data will be pre-processed on board so the downlink needs less bandwidth, while corrections and the resulting interpretation will be performed on ground.

**Payload**

In order to have sufficient gain for the GNSS-R antenna, an antenna array is needed. A digital beam steering array is chosen over a mechanical beam steering array for the sake of reliability and simplicity. The gain that is needed at an altitude of 645 km is ~26 dB. The corresponding SNR for the GNSS precision code, also called P code, is 6.5 dB.

**Mission data link**

The mission data link is crucial for the reaction time of the system, because when a Tsunami is detected, it is of key importance that this information is interpreted as soon as possible and therefore each satellite needs a continuous mission data link. The use of relay satellites for this purpose is reliable but expensive. Consequently for the data-link, the use of inter-satellite communication is chosen. In this manner, several satellites of the constellation will always be in direct contact with a ground station.

**Launch method**

The use of a dedicated launch for each satellite is not feasible because of the involved costs. On the other hand, because of scheduling problems it is not possible to use piggyback launches for 40 satellites. The most realistic option is to launch multiple STWS satellites at once. This implies that each satellite will carry a limited amount of fuel to make an orbit transfer to the desired place.

The chosen design options for the Space-borne Tsunami Warning System are listed in Table 14.2.

| Category | Characteristic |
|---|---|
| Orbit and constellation | |
| Altitude | 645 km |
| Inclination | 66° |
| Number of satellites | ~ 40 |
| Number of orbit planes | 10 |
| Payload | |
| GNSS-R antenna | Digital beam steering (phased array) |
| Antenna gain | 26.0 dB |
| Signal-to-noise ratio (P code) | 6.5 dB |
| Satellite bus concept | |
| Attitude control | Momentum wheel, reaction wheels and thrusters |
| Orbit maintenance | Included |
| Debris control | Structural protection |
| Data processing | |
| Pre-processing | On board |
| Corrections and verification | On ground |
| Mission data link | |
| Communication | Inter-satellite communication |
| Launch | |
| Launch method | Dedicated mission (multiple launches) |

Table 14.2: Space-borne Tsunami Warning System characteristics

## 14.4 The demonstrator satellite

The goal of the demonstrator satellite is to demonstrate and test the technical feasibility of GNSS-R for Tsunami detection. The design choices for this satellite are described below.

**Satellite orbit**

The altitude of the orbit of the demonstrator satellite will be 645 km, i.e. the same as the constellation satellites. An inclination of at least 66° is required in order to receive GNSS signals reflected from a point at 60° latitude. This difference is the consequence of the lower inclination of the GNSS constellations.

After the imposed 1-year lifetime, the satellite will be transferred to a disposal orbit with a perigee located at 175 km altitude. After approximately 2 years the satellite will reenter the Earth's atmosphere, satisfying the sustainability requirements imposed on the mission.

**Payload**

The orbit of the satellite and the link budget define the antenna gain required to perform the actual detection of Tsunami waves. In the case of the demonstrator satellite, an antenna gain of at least 25 dB is necessary in order to perform sea level height measurements. However, a larger gain is recommended because of the uncertainties present in the analysis of the link budget. The antenna gain in turn defines the size of the GNSS-R instrument; in other words, a gain of 25 dB corresponds to a diameter of approximately 1.4 meter. The passive GNSS-R instrument consists of a digital beam steering antenna and the receivers. In addition to this instrument, the payload also consists of a direct GNSS antenna and a receiver.

**Power and thermal control**

The payload is supported by the subsystems forming the satellite bus. The power subsystem provides all the necessary electric power to the payload and all other subsystems. In order to fulfil this functional requirement, the demonstrator satellite uses two solar arrays with a total surface area of 1.3 m2 and 4 Li-ion batteries.

The thermal subsystem ensures that all components of the satellite can operate within an acceptable temperature range. However, the selected passive thermal subsystem does not exactly satisfy this

functional requirement. This implies that the use of an active thermal system using radiators has to be considered for future design.

**Attitude determination and control**

Precise attitude determination is essential in order to accurately point the beams of the phased array antenna. The attitude determination subsystem provides an accuracy of 0.1° and consists of a sun sensor, an IR Earth sensor and an inertial measurement unit. The attitude control system does not need to be as accurate as the attitude determination. An attitude control accuracy of one degree is assumed to be sufficient for the nadir antenna. This subsystem consists of two reaction wheels, a momentum wheel and twelve thrusters.

**Propellant**

Besides attitude control manoeuvres, the demonstrator satellite uses propellant for orbit maintenance, disposal and orbit injection. The amount of propellant needed to maintain the satellite in orbit is very small since the atmospheric drag is very low at 645 km altitude. However, the propellant needed for the disposal manoeuvre is estimated to be 6.5 % of the total satellite mass. The injection propellant is necessary to perform a 245 km change in altitude and a 1° change in inclination. The amount of propellant required for this manoeuvre is approximately 7 % of the total injected mass.

**Data processing**

The demonstrator satellite will receive the GNSS signals from the Zenith pointing direct GNSS antenna and the Nadir pointing GNSS-R instrument. The data from both antennas is converted from analogue to digital, which is called level I data. Then the digital signal is pre-processed in order to obtain the difference in Pseudo Range ( PR) between the direct and reflected GNSS signals, Doppler shifts, Significant Wave Heights (SWH), Signal-to-Noise Ratio (SNR), the carrier phases and the time. This pre-processed data is called level II data and is combined with attitude determination & control data. The data is stored and sent down with a rate of 300 kbit/s when contact with the ground station is established. Subsequently, the data is sent to the mission control centre where it is combined with (seismological) verification data and IGS data, in order to perform orbit corrections. The communication link between the satellite and the ground station uses an X-band frequency.

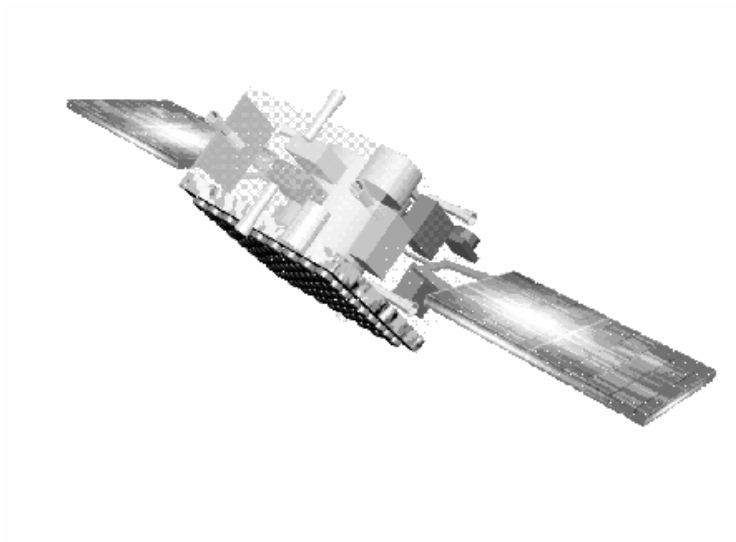


Figure 14.3: 3D view of the STWS demonstrator satellite

**Structure**

The structural subsystem mechanically supports all other spacecraft subsystems and attaches the spacecraft to the launch vehicle. The developed design satisfies all strength and stiffness requirements of the spacecraft by putting a cylindrical structure in the middle of the satellite. This aluminium cylinder has a diameter of 0.5 m, a height of 0.5 m and a thickness of 1 mm. This part of the structure, which carries most of the loads, is called the primary structure. The secondary structure consists mainly of a cubic box onto which all subsystems are attached. Figure 14.2 shows a 3D perspective of the STWS demonstrator satellite.

**Cost considerations**

Table 14.3 summarizes the resource budget allocation of the demonstrator satellite. The cost estimate for the demonstrator satellite is about € 15 million, but this will become more precise when cost specifications are obtained from the manufacturers and when the development of the instrument enters a mature stage.

**Expected accuracy**

One of the most important requirements imposed on both the STWS mission and the demonstrator mission, is the detection of a 10 cm

Tsunami wave at open sea. Calculations show that the C/A code is not precise enough to deliver the required accuracy. Consequently, the sea level height measurements have to make use of the P code, which delivers an altimetric accuracy of about 4.5 cm. Besides this, the observations will make use of the dual frequency characteristics of the available GNSS systems in order to reduce the error introduced by the ionosphere. Also weather models have to be used to reduce the tropospheric errors, especially those introduced by the presence of water vapour in the atmosphere.

| Subsystem | Elements/ Description | Mass [kg] | Power [W] |
|---|---|---|---|
| Payload | GNSS-R instrument, GNSS antenna, receiver | 40.6 | 57.0 |
| Power | 1.3 m2 solar array, 4 Li-ion batteries | 14.0 | 34.1 |
| Thermal | Passive system | 4.8 | - |
| Attitude determination | Sun sensor, Earth sensor, inertial measurement unit | 7.5 | 24.5 |
| Attitude control | Reaction wheels (2X), momentum wheel, thrusters | 9.2 | 5.7 |
| Propulsion | Thrusters, propellant tank | 7.6 | - |
| Command and data-handling | DSP platform, solid state recorder | 1.0 | 19.0 |
| Communication | Transmitters, receivers and antennas | 1.0 | 4.7 |
| Structures | Primary cylindrical structure, secondary box, joints | 20.3 | - |
| Propellant | Attitude control, orbit maintenance, disposal | 12.1 | - |
| Total mass | | 129.8 | 145.0 |

Table 14.3: Resource budget allocation of the demonstrator satellite

## 14.5 Conclusions and recommendations

**Conclusions**

The GNSS-Reflections based Space-borne Tsunami Warning System is a feasible alternative to the DART buoys system. In contrast to the DART system, the STWS could provide a nearly global coverage during a time period of 10 years. Coverage outside the latitude range -60° and 60° is not necessary. Therefore, the inclination of the orbit should be about 66°, in order to be able to observe GNSS reflections at 60° latitude.

A critical aspect of the STWS is the timely delivery of a warning signal. The detection of a Tsunami from space takes up the main part of the warning time, which is called the detection time. By using a constellation consisting of 40 satellites, global coverage within 30 minutes can be achieved. However, the present constellation design will not cover the whole surface of the Earth; hence attention has to be paid to the optimization of the constellation.
Inter-satellite communication will be used in order to minimize the time elapsed between the acquisition of the observation data by the satellite and the downlink of this data to an accessible ground station. The data downlink rate will be equal to 300 kbit/s.

Another critical aspect of the STWS is the required measurement accuracy. In order to detect a life-threatening Tsunami at open sea, an altimetric accuracy of at least 10 cm has to be achieved. This requirement implies that the measurement of reflected signals using the C/A code are not accurate enough to provide the required accuracy. As conclusion can be taken that only the use of the P code provides sufficient precision to be able to detect Tsunami waves at open sea.
The accuracy of the measurements is also partially dependent on the antenna gain. For altimetry applications, like the detection of a Tsunami wave, the required antenna gain will be approximately equal to 25 dB. However, an exact calculation of the link budget and hence a precise sizing of the antenna is still not available. This antenna gain defines the altitude of the satellite constellation to 645 km.

If the DART system would be extended to provide global coverage, the total cost over a period of twenty years is estimated to be € 470

million. The GNSS-R based satellite constellation will be slightly more expensive and has an estimated cost of € 540 million. On the other hand, revenues from other scientific and commercial applications could justify the higher cost of the STWS mission.

The demonstrator satellite is slightly different from the planned STWS-satellites. It will be heavier, due to the fact that the GNSS-R antenna is in an early stage of development and because the antenna is over dimensioned to ensure sufficient gain. The demonstrator will not make use of inter-satellite communication, but it will have the possibility to downlink the raw pseudo random noise. The demonstrator satellite is designed for a lifetime of one year, because it only needs to prove the principle of altimetry using reflected GNSS signals. Furthermore, the amount of observation data acquired during one year will be sufficient for scientific research and development purposes. The cost estimate for the demonstrator satellite is around € 15 million.

**Recommendations**

It is recommended to focus research on shortening the detection time by optimizing the constellation design. This implies reducing the existing gaps in the ground coverage and reducing the number of satellites if possible.

A critical part of the development is to define a well-established link budget for the GNSS-R instrument. This is the basis for the development and optimization of the phased array antenna. An optimized instrument design will lead to a lower instrument mass and power usage, which will in turn translate into a smaller satellite and therefore lower cost.

Tsunami intensity prediction models have to be developed to translate sea level height observations into accurate Tsunami warnings, as at this moment no accurate model exists that can accurately predict the local run-up height of a Tsunami wave at the shore. Also, the possible alternative applications of the obtained GNSS-R data need further investigation to be able to justify the cost of the mission in view of other commercial and scientific benefits.

# 15. SURYA – REUSABLE SHUTTLE FOR LOW ORBIT SPACE FLIGHT

*Students:* R.C. Baaten, S.Y. Go, S.S. Harrison, M.H.M. Kloosterman, J.H. Koning, D.J.W. Leusink, P. Perczynski, W. Stolk, G.A.A. Thuwis, J. Varkevisser

*Project tutor:* ir. J. Sinke

*Coaches:* dr. G.S. Gardner, ir. R. Noomen


## 15.1 Introduction

The expansion of mankind into space has progressed to the point at which real benefits are available from routine mission profiles, by reusable space vehicles. NASA has the only such vehicle in operation.

However, that programme is suffering the consequences of two fatal accidents in which the crews were lost. An example of a disposable space transfer and return vehicle is the Russian Soyuz capsule. This 1960's design is at the end of its expansion life and cannot be expected to adapt endlessly. Consequently, there is call for a new, manned space shuttle for low Earth orbit. In the last decade several projects have been conceived, like the cancelled European Hermes and more recently the Russian Kliper.

This project aims to design a small shuttle, capable of transporting personnel to a space station like the International Space Station (ISS), or on satellite maintenance missions. The shuttle should be low cost, have more than one launcher option, and have access to most low Earth orbits (LEO).

## 15.2 Mission statement

The mission statement can be formulated as follows:
*The Surya project aims to design a flexible, reusable shuttle allowing manned space flight in LEO competing in tomorrow's market. The shuttle should support space station docking or satellite repair. The first manned flight will be around 2020.*

## 15.3 Requirements

After negotiation on technical grounds, the following requirements were agreed:

- Fifty mission service life per vehicle, totalling 250 flights in 10 years.
- Capacity of 5 people and 1,000 kg of additional payload.
- Support of docking with space stations and support of satellite repair in LEO, at up to 1,000 km at inclinations between 3.5º and 98º.
- Controlled landing possible at any chosen location.

- Competitive price to the Soyuz and Space Shuttle, per mission per person.
- System for escape during launch.
- Relaunch within 20 working days after landing.
- Parts to be replaced after a mission to total 10% or less of gross mass.
- Compatibility with two launchers, of which one must be Ariane 5. The launcher should be or become rated for manned flight.
- Total launch mass not to exceed 20,000 kg.
- Life-cycle energy consumption to be at least 10% less than current options.

## 15.4 Concept exploration

With the requirements in mind, three configurations can be distinguished among the concepts. These are a capsule, a space plane, and a space plane with a space tug. The configurations are investigated with respect to structure, propulsion, aerodynamics and thermal protection. A brief description will be given in the next sections.

For all concepts, as required, the Ariane 5 ES and the Proton M are selected, because they do not require costly inclination changes to reach the ISS and because they can easily achieve a man-rated status.

**Capsule**

Based on previous designs, such as the Apollo, Soyuz or the new Crew Exploration Vehicle, this concept tries to combine the advantages exemplified by them. New technology is only included where it will yield clear benefits without convolution of the system as a whole. Structurally, the capsule will make use of a modular design, allowing parallel production and easier maintenance.

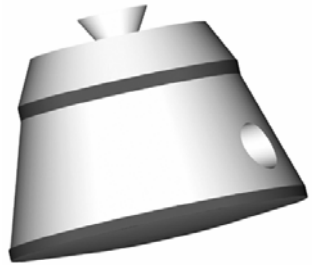


Fig 15.1: Capsule design

The capsule will have the same outer diameter as the Ariane 5 to fit on top of the launcher. Mono-methyl hydrazine and nitrogen tetroxide are chosen as propellants since this combination is well proven in space, and has ample performance. On re-entry it uses a disposable, ablative heat shield. Controlled flight and subsequently landing are achieved via a parafoil, and an inflatable impact attenuation device (airbag).

**Space plane**

In contrast to the capsule, the space plane is envisaged as a more challenging concept, open to more advanced solutions. It generates lift, like an aircraft, which allows it to optimise its flight path for smaller loads and enjoy a wider range of landing options. A space plane is characterised by small wings, control surfaces, and landing gear.

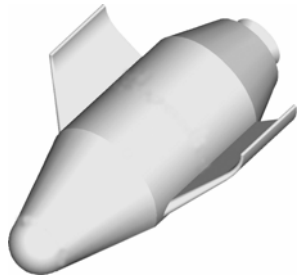


Fig 15.2: Space plane design

The oxidiser and fuel are oxygen and propyne respectively, with high performance, and compatibility with regenerative cooling which can improve the durability of the engine. The craft would be mounted in place of the cargo section of the launcher. During re-entry the space plane applies a combination of ceramics and hot-metallics in its

reusable Thermal Protection System (TPS). Due to controlled re-entry and the use of hot-metallics, maintenance efforts are expected to be moderate. Finally, the space plane enjoys an extensive landing envelope.

**Space tug**

Close to the previous concept, in fielding a lift generating body, the main difference is that this concept will not have an on-board engine. Instead there will be an engine in orbit, also known as a space tug. A major improvement, with respect to the space plane is reduced dry mass, allowing increased mass budget for crew, payload or fuel. The other design aspects are similar to those of the space plane.

## 15.5 Trade-off

Next step is the choice of a final concept. Notably, the third concept was explored briefly but appeared not to meet the requirements on altitude/inclination range. The trade-off was facilitated by quantitative, comparative analyses like those of cost against risk and complexity against benefit. This yielded little insight, even with variation of criterion weights to clarify dependencies and relationships. In table 15.1 qualitative strong and weak points are shown, on the strength of these, concept 2 is selected.

| Concept 1 | | Concept 2 | |
|---|---|---|---|
| Strong points | Weak points | Strong points | Weak points |
| Low costs | Less flexible during re-entry and gliding | Flexible re-entry | Relatively expensive |
| Common technology | Risk involved in parafoil, rotating seats | Limited disposable parts | Possible launcher instability |
| | Possible re-entry instability | Good flight performance | Relatively high-risk technology |
| | High disposable mass | | |

Table 15.1: Strong and weak points of the concepts

## 15.6 Detailed design

After the selection of the space plane, system characteristics were investigated by research on the sub-systems dealing with: stability and mass distribution, structure and TPS, escape system, risk, and cost. Figure 15.4 shows three views of the space vehicle Surya.

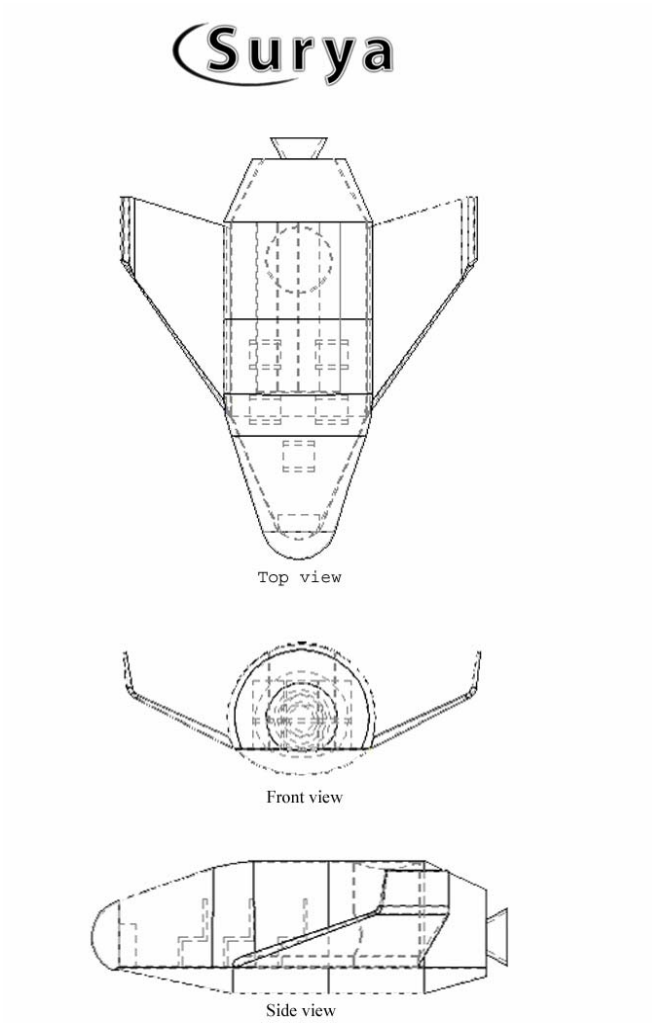



Figure 15.4: Space vehicle Surya configuration

**Stability and mass distribution**

Integration of the space plane with the launch vehicle requires that the centre of mass be less than 0.163 m from the centreline of the launcher and less than 2 m forward of the payload-adaptor. These requirements will be met if the payload is designed properly.

Stability of the launcher/spacecraft combination will be affected to some degree since the wings will cause an upward shift in the centre of pressure. This must be investigated further. Additional research is especially necessary on the influence of crosswinds during launch. During launch, for stability, thrust vectoring is necessary in the initial phase. Stability then improves due to a forward shift in centre of mass.

The spacecraft design is aimed at aerodynamic stability to ensure a safe return flight and lower complexity. The total length is 10 m, wingspan 8.5 m, and there is 34 m2 of lifting surface. The centre of mass is 5.5 m from the nose.

**Structure and TPS**

Objectives include withstanding loads during the different mission phases, such as pressure differences and thermal loading. Requirements follow from findings in stability and mass distribution, and from calculations made regarding launch conditions, which introduce the greatest loads.

The longitudinal quasi-static launch load is 4.55g while pressure differences in orbit introduce hoop stresses. On re-entry, maximum loads occur at the wing root, the craft dissipates 60 kJ on landing. Because of reuse, fatigue loads are of primary concern, especially in parts that oscillate.

Some details of the structural design:

- For the keel / inner wing, machined titanium alloy was selected.
- Primary upper wing-spars and bulkheads are constructed of forged titanium with composite core material.
- The loaded panels of the wings will be made of pressed aluminium alloy plates, reinforced by bonded extrusions.

- The engine shield and fairing will be designed for dual roles, those of aerodynamic fairing and of debris-shield for the engine and tanks.
- In the vicinity of hatches reinforcements are needed. They consist of titanium insets and aluminium frames.

Heat flows generated upon re-entry, cause temperatures at the nose and leading edges above 1,450 K, beyond which hot-metallics fail, therefore ceramic tiles are used. Elsewhere, hot-metallics are preferred, for maintenance and weight reasons.

**Emergency escape system**

A key requirement is an escape system, the derived requirements are:

- Escape to an altitude high enough to ensure a safe parachute deployment.
- Maximum allowable loads during escape acceleration not to be exceeded.
- Safe landing within crew tolerances.
- Separate to a region outside the possible fireball due to launcher explosion.
- Work fully automatically.

Based on this, three concepts have been developed. These are: ejection seats, ejection capsule, boosted separation of the entire craft.

A combination of an emergency boost and ejection seats is considered to be best, since the methods have complementary strengths and have a weight, which is still likely to be lower than a capsule. Escape is always possible up to about 650 km altitude, but not during re-entry. It gives a scope of escape options not seen in any previous space system, which is consistent with the requirement.

**Risk analysis**

After negotiation, acceptable risk was defined by the occurrence of no more than 3 life-threatening situations during 250 missions. Although overall risk is indeterminate at this stage, insight can be gathered about that of sub-systems, helping to isolate risk drivers. The analyses of reliability are qualitative, and are divided into two parts.

The first covers reliability monitoring during design, in which three steps are taken. The Technical Readiness Level (TRL) is determined for each sub-system under consideration. Based on that, procedures for design and verification are defined such as to increase TRLs. Finally, research is carried out into technological solutions to the resulting optimisation problem.

The second covers reliability optimisation during operations, again in three steps. Possible failures during each mission phase are isolated, failure impact estimated, and finally, parameters are defined to monitor failures. Procedures to be initiated in these eventualities are subsequently determined.

The reliabilities of the Ariane 5 ES and Proton M are also scrutinised. Initial estimates are known, and appear insufficient for manned missions. This must be rectified.

**Cost estimation**

To determine the costs of the space plane, two models are used, being the parametric cost model and the Transcost model. Using two different ways to approximate the mission cost will give possibly a more reliable cost estimation. Still, estimation of mission cost at this phase of design is difficult since only a few details are known and estimation is mostly dependent on historical data extrapolation.

The parametric cost model uses a combination of parameters that illustrate historical trends while maintaining statistical integrity. The Transcost model uses cost estimation relationships based directly on historical data.

The following values are found with the two models:

| Parametric cost estimation | Transcost model |
|---|---|
| € 190 M for Ariane 5 launch | € 230 M for Ariane 5 launch |
| € 130 M for Proton M launch | € 190 M for Proton M launch |

Table 15:2: Cost estimation

The requirements stated that Surya should be competitive in price with Space Shuttle and Soyuz. Figure 15.4 shows its compliance with

this, since the cost per launch per person is around the average of the Space Shuttle and the Soyuz.

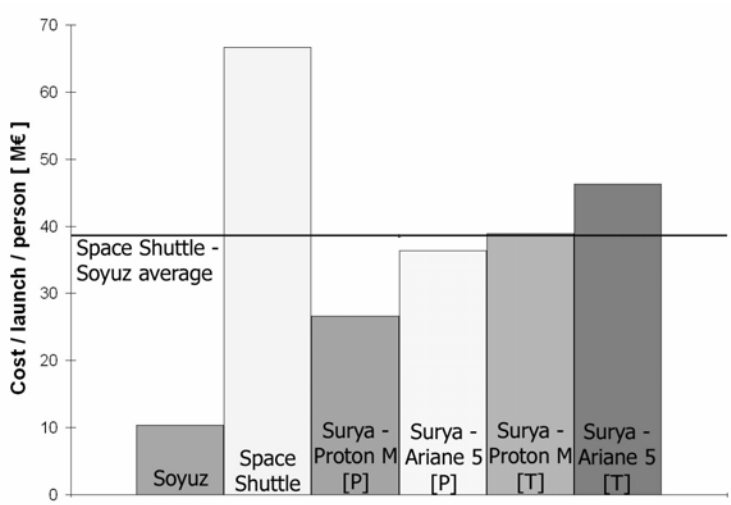



Figure 15.4 Cost comparison Soyuz, Space Shuttle and Surya ([P] Parametric cost estimation, [T] Transcost model)

## 15.7 Conclusions

The goal of this project is to conceptually design a reusable space vehicle, which can bring 5 people and 1,000 kg of payload to LEO. This shuttle should be reliable, cheap to operate, easy to maintain, and allow fast re-launch times.

From a variety of concepts, one has proven most likely to achieve these goals: the space plane design. This configuration has been elaborated upon. It can launch via Ariane 5 ES or Proton M and is designed with safety in mind, with the crew able to evacuate under most conditions. Aerodynamic stability minimises the risk of losing control.

Although there will always be risks involved in manned spaceflight, those associated with this project can be deemed acceptable. The reliability is expected, by the launch date, to be better than that of the

Space Shuttle. Moreover the launch price of about € 190 M per mission is between that of Soyuz and Space Shuttle and is thought to be competitive. Surya should see the light of day in 2020.

## 15.8 Recommendations

The following recommendations are given.
More details of the subsystems are required to make better analyses.
With respect to the structure, a finite element model is the logical next step, providing insight into load paths and allow for a first vibration analysis.
In the analysis of stability and mass distribution, attention should be paid to integration with Ariane 5 ES and Proton M.
To improve the evacuation analysis, research is required on the placement of the emergency boosters and on the structure around the ejection seats.
To obtain a more accurate risk analysis, actual testing is required, both for verification and improvement of reliability.
Regarding the cost analysis, more details will allow the use of more advanced models and will lead to a more accurate estimation.

# 16. SOLAR TURBINE POWER STATION

*Students:* G.W. Bakker, E.K. Driessen, M.G.L. Evers, T.T. Francken, K.A.A. van Ginderdeuren, H. Hujdurovic, J. Kruitwagen, P. Rijneveld, S. Waltmans, E.A. Zhukov

*Project tutor:* ir. O. van der Jagt

*Coaches:* dr. F. Micciché, ir. T. Rahman

## 16.1 Introduction

Energy consumption is increasing while conventional energy sources have been predicted to be exhausted within decades. Therefore the world needs to turn to alternative energy sources, such as: wind, water, sun or geothermal heat. The most promising of these is the unlimited capacity of the sun. Over the past few decades mankind has tried to collect this energy source in various ways, for example: solar pool heating, greenhouses, solar cells, et cetera. Greenhouse technology is the most widely used application to collect solar radiation.

The greenhouse technique combined with the natural phenomenon of convection currents form the basis on which a solar turbine power station (STPS) relies. A STPS produces energy from the generated warm airflow. Since a STPS relies on the sun, it does not deplete natural resources, nor does it produce carbon dioxide. Therefore STPS is a sustainable means of energy production. For a successful introduction in the energy market, a STPS should be an economically

attractive alternative. Therefore the system has to produce electricity at costs comparable to conventional power plants.

## 16.2 Project objective and requirements

The objective of the project can be stated as:

*Within ten weeks, ten students are to design a solar turbine power station with a floating chimney, which is able to produce 200 MW, optimized for economic profit. The final design will be presented to the client.*

This objective must be accomplished while meeting the requirements and wishes of the client. The main requirements are:

- The solar turbine power station must be capable of generating a maximum power output of 200 MW at a solar radiation intensity of 800 W / m2, if no heat storage is applied;
- The market price of the delivered energy must be competitive with other forms of energy generation, therefore the price should be no higher than 0.05 €/kWh;
- The break-even point must be reached within 20 years;
- The lifetime of the STPS should be at least 30 years.

Furthermore the client expressed the wish that fluctuations in the power output over a 24-hour period are minimized by the implementation of a storage device. The client also desired the STPS to be independent of a specific location, in order to retain the possibility of constructing the STPS in various countries.

## 16.3 Working principle of a STPS

Figure 16.1 outlines the basic concept of the STPS. A solar turbine power station is a combination of three well-known principals: a greenhouse, a turbine and a chimney. The chimney guides hot air from the collector below into the ambient atmosphere at its exit above.

Due to the difference in temperature of air inside the chimney and atmospheric air, there is also a difference in density between air inside the chimney and the open atmosphere. As a result the column of air inside the chimney is pushed in the upward direction by buoyancy forces. Simultaneously the pressure, lower than the ambient pressure, at the chimney entrance draws in the air around the collector. The air passing through the collector is heated until it reaches a maximum temperature at the chimney base.

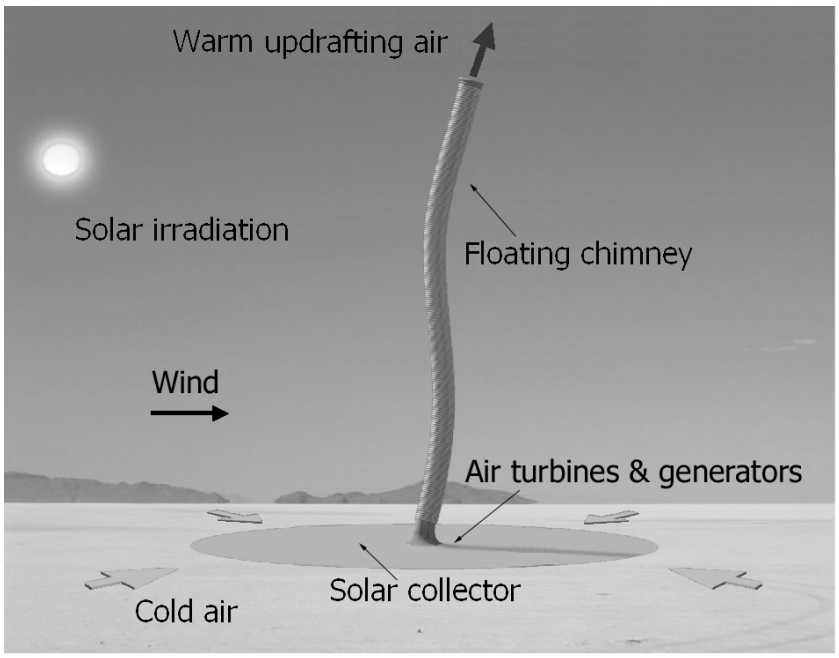



Figure 16.1: STPS general layout

Because of its extreme height the chimney needs to be 'lighter-than-air'. The application of aerospace expertise in composite materials, lightweight structures and aerodynamics, make the inflatable structure that forms the 'lighter-than-air' floating chimney possible.

Though a windmill is a nice analogy to the STPS turbines since they both extract power from moving air, there is an important difference in their extraction method. A windmill uses the kinetic energy within airflow. The STPS applies pressure-staged turbines that are placed near the centre of the collector, just before the chimney entrance. They convert the pressure difference over the entire system into mechanical

shaft-power. In turn the generators are driven and electrical power is delivered to the grid.

In order to reduce fluctuations in power production during insufficient solar irradiation, a thermal storage is implemented in the design. Part of the heat delivered by the sun is accumulated in a suitable medium (water); this heat will be released to the air inside the collector during low irradiance (night) ensuring a continuous power delivery.

## 16.4 Concept selection

Four different flow concepts are considered (figure 16.2.). The first concept of a single airflow is relatively straightforward. This concept is based on already existing prototypes of the STPS. The air intake is at the edge of the collector.
The second flow concept consists of a double flow where the air will be collected either at the top, or at a certain height of the chimney after which it will follow a double path through the collector. The idea being that a second pass along the collector results in a reduction of the required collector planar dimensions through a higher increase in passing air temperature. This concept may result in an increase in efficiency. It is however questionable whether the increase in efficiency outweighs the higher production costs and if the airflow can still be generated in spite of increasing aerodynamic drag.
The third and fourth concepts both rely on a second pass along the collector as well.

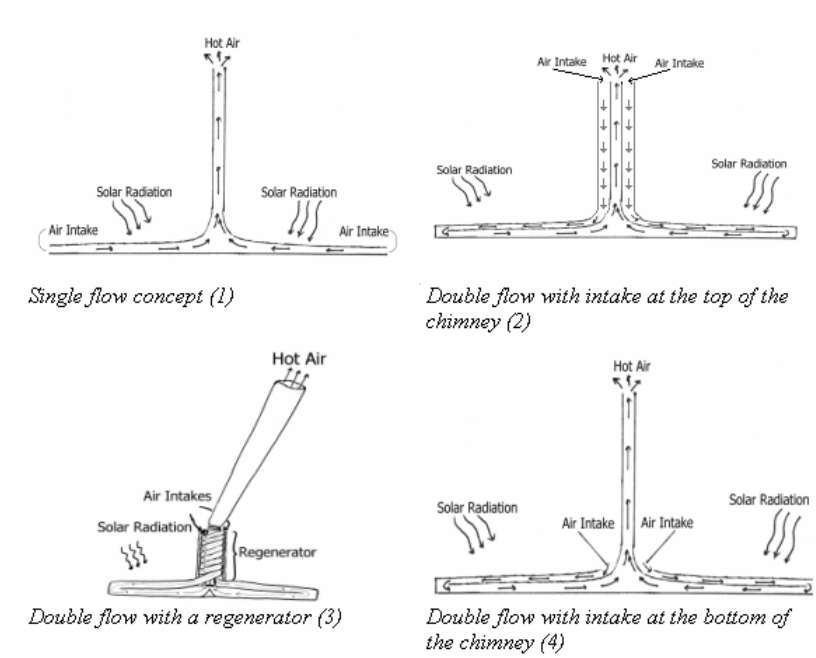



Figure 16.2: Flow concepts

A thorough analysis of these concepts was performed to be able to set trade-off criteria. The detailed study of these four concepts resulted in a trade-off. It can be concluded that the single flow concept (1) promises to be the most viable option to work out in detail.

## 16.5 Design overview

The detailed design phase lead to a final design of the STPS of which an overview is provided in the following section. The structural layout of the STPS design is shown in figure 16.3. In this figure the total STPS is depicted, including a detailed view of the base joint section with power generation assembly and the top of the chimney.

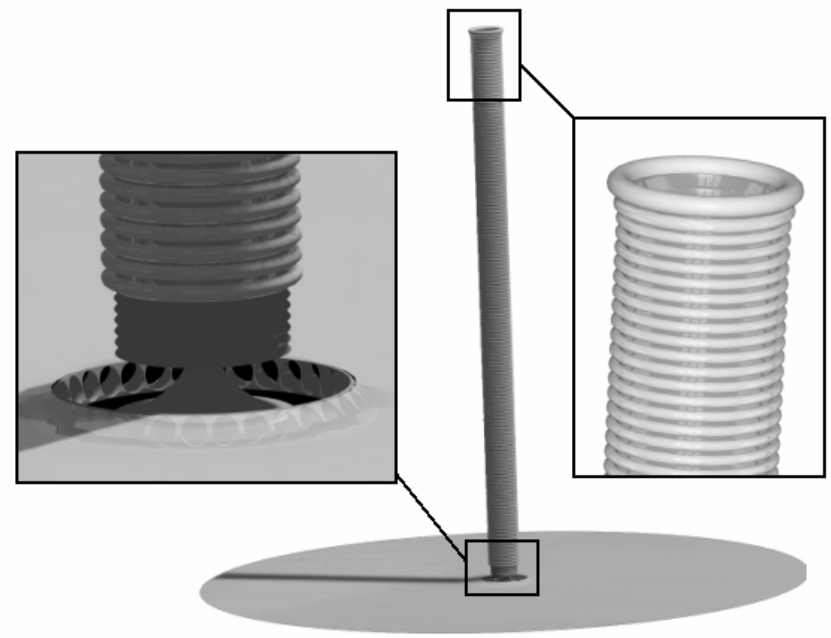


Figure 16.3: Layout of the STPS with base joint/turbines and chimney detail

**Layout of the collector**

The total collector radius is set to 1600 m, when measured from the centre of the chimney. The height of the collector will range from 2 m at the outer section, where the air will be taken in, to 16 m when approaching the turbines. A steel frame, consisting of square cross-sectional bars placed vertically and horizontal T-profiles, will support the glass surface. The horizontal T-profiles are needed to keep the glass plates in place. These profiles will be equipped with rubber fittings to seal the collector. The area under the collector will be used to store energy by means of water spread over the entire surface. The depth will increase stepwise from 0.5 up to 3 m with decreasing collector radius, equally divided across the collector radius.

**Layout of the turbines**

Power will be provided through a set of axial turbines and generators. In total 32 turbines and generators will be installed that will be able to generate a power output of 200MW. They will be placed vertically at ground level (axes are horizontally placed with respect to the ground) in a circular layout as illustrated in figure 16.4. In the centre the flow

deflector is placed, as well as the foundation of the base joint. The aim is to redirect the horizontal flow 90 degrees upwards and to minimize frictional losses. The swept area of all the turbines together is equal to the required cross sectional area at the bottom of the chimney. This area was equal to the area covered by a circle with a radius of 62 m. To minimize kinetic losses, the chimney would need to diverge to an exit radius of 70 m, but to lower the cost a straight chimney channel is chosen. To reach the same effect as the diverging chimney, the channel after the turbines diverges to the required area covered by the bottom of the chimney with a radius of 70 m.

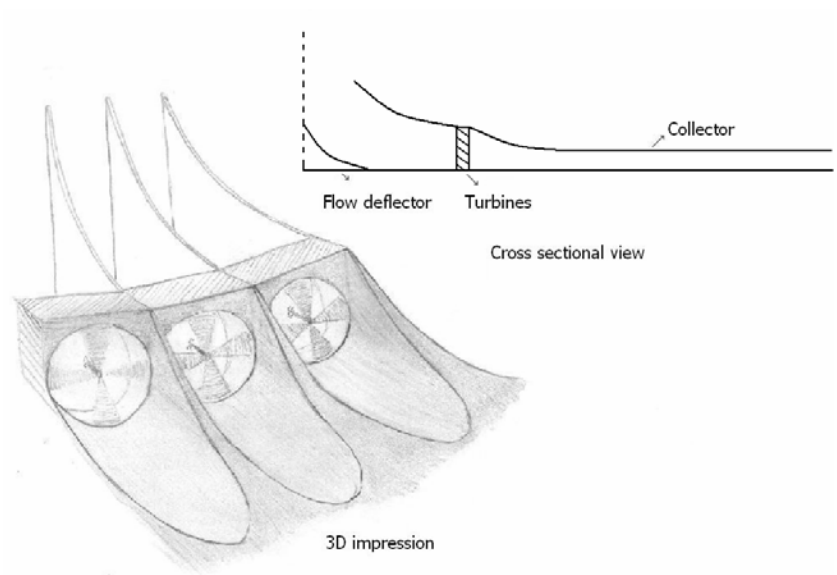



Figure 16.4: Sketch of the turbine section

**Layout of the chimney**

The floating chimney is one of the most challenging parts of the project. The structural height of the chimney is 3000 m and the average operating height is 2800 m (due to wind). Figure 16.5 shows the main parts of the chimney, which are supporting rings (to provide structural stiffness), tubular shaped fabric (to guide the flow) and lifting rings (donut-shaped, to lift the chimney). The chimney is subjected to severe wind forces and other weather influences, however the chimney is designed to remain erected during its entire lifespan of 30 years. Repair and maintenance from the chimney will hardly be possible since it is a very difficult and time-consuming task

to take the entire structure down. The bottom of the chimney is connected to the base joint through the tubular shaped fabric, comparable to the connection to the supporting rings. The lifting rings can be connected to the supporting rings with ropes.

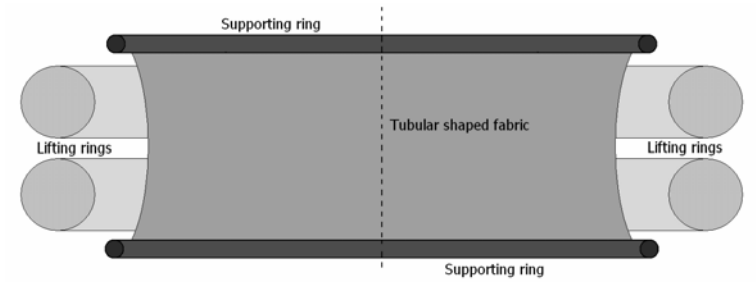



Figure 16.5: Cross sectional view of a chimney section

**Layout of the base joint**

The base joint is the connection between the floating chimney and the collector (figure 16.6). This is a complex component in the STPS design since all parts of the design come together in this point. The base joint has to allow the chimney to deflect over 44 degrees in all directions and has to transfer the loads on the chimney to the base foundation. Therefore a base ring made out of trusses is mounted on a cardan joint. Underneath this ring an accordion shaped fabric will be used to account for the bending of the chimney

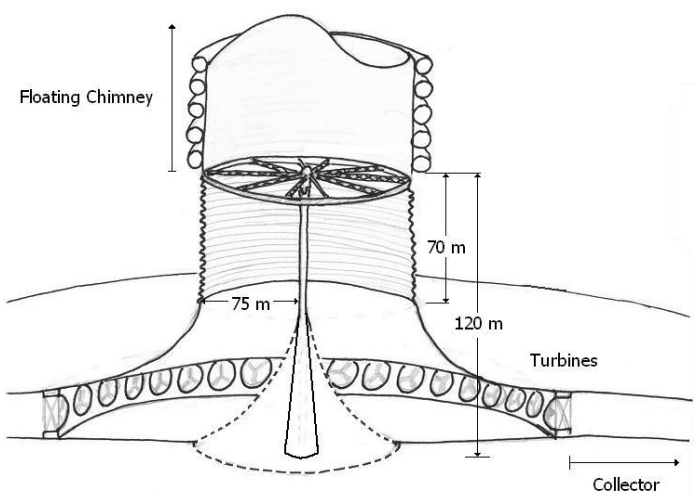



Figure 16.6: Sketch of the base joint section

**Materials**

Many different materials will be used to construct the various parts of the STPS. For the collector glass is needed, as well as steel and water. The chimney fabric will be constructed out of an aramid fibre; the supporting rings will be made of carbon/epoxy and the lifting rings out of engineering plastic, which are filled with hydrogen. For the base joint concrete and steel is needed as well as glass/epoxy for the inner supporting rings and nylon for the harmonic shaped part. An impression of the quantities of the materials that is needed: one and half times the amount of steel used to build the Eiffel Tower and enough hydrogen to fill 37 Hindenburg zeppelins.

**Costs**

The costs of the different components are summarized in table 16.1. Additional costs for the labour and transport are included in the separate component costs.

| Component description | Costs (M€ |
|---|---|
| Collector costs | 82 |
| Turbine section costs | 161 |
| Chimney costs | 212 |
| Storage costs | 16 |
| Base joint costs | 10 |
| Construction costs | 49 |
| Total costs | 530 |

Table 16.1: Component costs

It should be noted that a going rate of 0.1 €/kWh is accounted for. This results in a break-even point of 13 years and a production price of 0.03 € /kWh. Thus the financial requirements are met.

## 16.6 Conclusions and recommendations

**Conclusions**

At the end of the final design phase the following conclusions on the feasibility of a solar turbine power station with floating chimney can be drawn. The STPS with floating chimney proves to be capable of

delivering energy at a competitive price. Table 16.2 shows the compliance of the design with the set of requirements.

| No. | Requirement | Met? |
|---|---|---|
| 1 | 200 MW @ 800 W/m2, no heat storage | √ |
| 2 | Energy price below 0,05 €/kWh | √ |
| 3 | The break-even point within 20 years | √ |
| 4 | Lifetime of STPS at least 30 years | √ |
| 5 | Minimize fluctuations | √ |

Table 16.2: Compliance matrix

All requirements from the compliance matrix are met, this indicates that the STPS is competitive on the global energy market and therefore the final conclusion can be drawn:

The STPS is an economically viable and sustainable power source.

**Recommendations**

The solar turbine power station design described in this summary is not yet ready to be built. The experience from the project however helps identifying the next steps necessary to eventually come to a design that can be built.

In order to give a good overview of the main topics that should be investigated first, the recommendations will be stated per component:

Collector

- Drainage of rain
- Construction of the storage

Turbine section

- Outsource to specialists

Base joint section

- Influences on the chimney flow
- Optimization of the truss structure
- Dynamic loads and fatigue

Floating chimney

- Effect of temperature differences on the material properties
- Dynamic loads and fatigue analysis
- Wind modelling
- Testing of the permeability of the lifting rings
- The availability of the materials
- Risk analysis of the hydrogen gas contained in the lifting rings
- On-site construction and erection of the chimney

# 17. TWINFINITY

*Students:* J. Bronsvoort, S.A. Hahn, K.J. Brouwers, R.E. Klomp, M.A. Engelsma, C. Liem, B.M. Geurts, E. Soltani, D.M. den Haan, R. Toppinga

*Poject Tutors:* prof.dr.ir. Th. Van Holten, dr. M.D. Bos-Pavel

*Coaches:* H.A.P. Cremer Mtd, ir. A. Broker, T.J. Ahmed MEng

## 17.1 Introduction

The American Helicopter Society (AHS), established in 1944, is the world's premier professional vertical flight society. It has been a major force in the advancement of the global rotorcraft industry, marked by rapid technical developments, expanding military capabilities and commercial applications.

In 1980 the AHS set up a competition, called after Igor Sikorsky. A US $20.000 prize is awarded to the first team to build a Human Powered Helicopter (HPH) complying with the competition requirements. Since then, numerous teams from all over the world have made attempts to win this prize but still no one has been able to succeed.

In fact, only two HPHs have actually flown. First, on December the 10th in 1989, a team from California Polytechnic State University flew with its DaVinci III for only 7.1 seconds. The second attempt was done at Nihon University in Japan under supervision of Professor Akira Naito. This HPH, the Yuri I, hovered for 19.46 seconds in 1994 officially and later on an unofficial record of 24 seconds was set at a human powered flight conference in Seattle. Unfortunately, neither

HPH came close to meeting the Igor Sikorsky competition requirements of a one-minute flight while reaching an altitude of three meters momentarily.

As a result it is an extremely challenging project to design a concept that will meet the competition requirements. In a period of more than two decades numerous fruitless attempts have been performed. Perhaps Twinfinity will succeed this mission.

## 17.2 Mission objective

The Project Objective Statement is formulated as follows:

*Design a human powered rotary craft complying with the American Helicopter Society requirements in order to be the first to win the Igor Sikorsky Human Powered Helicopter Competition, with 10 people within a 10-week project schedule.*

After the HPH has been built, the following mission scenario needs to be performed. First, a professional cyclist for the record attempt needs to be contacted. Second, an intensive training will have to be done by this cyclist to learn how to hover with the HPH while controlling it by means of Weight Shift. Subsequently, the AHS needs to be contacted to arrange official observation during the attempt.

The disassembled HPH has to be transported in a truck to the flight location, RAI Amsterdam. There, the HPH has to be assembled and perform the flight. Finally, after the flight the HPH needs to be disassembled to transport it back by truck.

## 17.3 Design requirements and constraints

In order to design a successful concept a list of requirements is presented for the mission. The requirements are subdivided into the following groups:

- Constraints
- Performance requirements
- Functional requirements

An overview of the most important requirements is given below.

**Constraints**

- The vehicle must have a rotary wing configuration
- The helicopter must be human powered
- No parts of the vehicle may be jettisoned
- At least one crew member is non-rotating
- An identified reference point on the non-rotating part of the machine will stay within the confines of a 10-meter square
- The vehicle must be heavier than air
- The mission must be performed safely
- The design should be feasible for production
- The design process should be carried out by ten persons within ten weeks
- The design should be sustainable with respect to materials, production and maintenance

**Performance requirements**

- The vehicle must be able to vertically take-off and land
- The vehicle must be able to carry one pilot with a maximum mass of 65 kg
- The vehicle must hover for at least one minute
- The vehicle must achieve an altitude of at least three meters momentarily
- Minimum efficiency of drive system of 95%
- Minimum power-to-weight ratio of 0.6 W / N

**Functional requirements**

- The disassembled vehicle must fit within a truck having dimensions of length×width×height = 10m×2m×2m
- All parts of the vehicle must have easy access for maintainability, replacement and repair

## 17.4 Concept study

Before developing one final design, numerous different concepts were generated and evaluated. A first distinction was made through a first trade-off process, after which three concepts remained for more thorough analysis. These concepts are briefly described below. Each concept uses pairs of counter-rotating rotors as torque compensation.

**Tandem**

The Tandem consists of two counter-rotating rotors connected by a truss structure. The rotors are slightly interleaved, which is beneficial for the performance. The pilot is positioned above the rotors to take maximum use of the ground effect. Due to the separation of the rotors the pitching stability of the vehicle is increased in ground effect. Main cause for concern was the stability in rolling direction since the moment arm of the lift in lateral direction is smaller compared to the one in longitudinal direction.

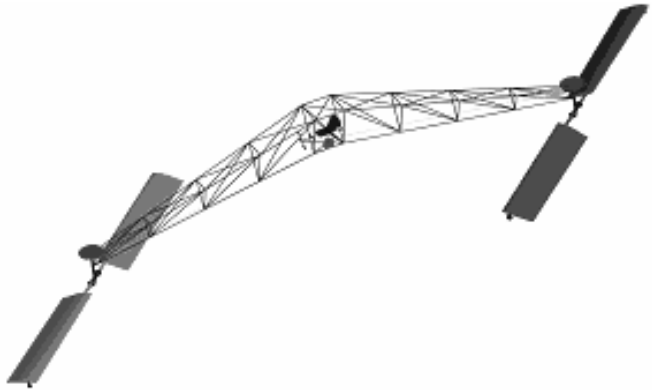


Figure 17.1: Tandem Concept

**Compact**

The Compact consists of a truss structure with four fully interleaving rotors. Due to the large overlap, no performance benefits are obtained. However, it does result in a more compact and therefore lighter design. The pilot is again positioned above the rotors. The Compact has good rotational stability due to the presence of the four rotors. However, the created 'air cushion effect' causes the vehicle to drift

away laterally and makes it very difficult to control the HPH in an effective manner.

Figure 17.2: Compact Concept

**ARTVY**

The ARTVY is similar to the Compact, except for the fact that the rotors are no longer interleaved. Instead, an auto-rotating thrust-vectoring rotor is included in the middle. This small rotor is driven by the upwash of the other rotors and hence no torque is created. The generated lift can be used to control the vehicle, by tilting the auto-rotor in the desired direction. Therefore, in theory, this concept has good stability and control characteristics. However, the high weight of the vehicle proved to be fatal.

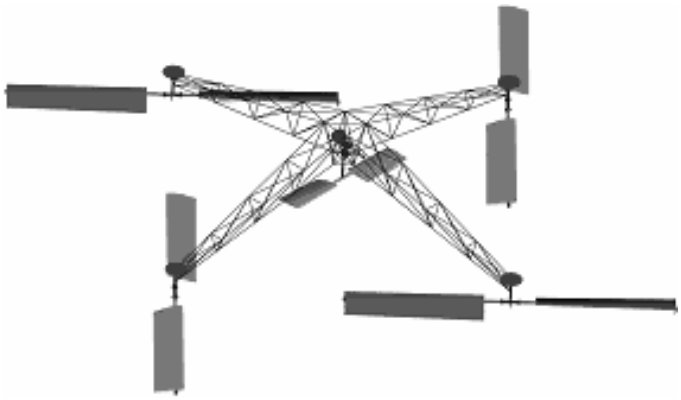


Figure 17.3: ARTVY Concept

**Second trade-off**

An elaborate trade-off between these concepts was performed, in which both quantitative and qualitative analyses were executed. A summary of the trade-off is given in table 17.1.

| | Mass | Power Required | Stability | Transmission Efficiency | Aerodynamic Characteristics |
|---|---|---|---|---|---|
| Weight Factor | 35% | 25% | 20% | 10% | 10% |
| Tandem | Low | Low | Possible rolling motion | High | Good |
| Compact | Moderate | Moderate | Stable | Moderate | Low |
| ARTVY | High | High | Stable | Moderate | Moderate |

Table 17.1: Trade-off Summary of the Final Concepts

The final selected concept was the Tandem. This design scored best on each trade-off driver, except for stability. However, it was considered that these problems could be overcome by the addition of an appropriate control system. The decisive factors in the selection were the low weight of the Tandem and the accompanying low required power.

## 17.5 Final design

The development of the final design was done in three groups. Each group focused on one of the following disciplines: Aerodynamics & Performance, Structure & Materials and Stability & Control. A short description of the design is given below.

**Aerodynamics and performance**

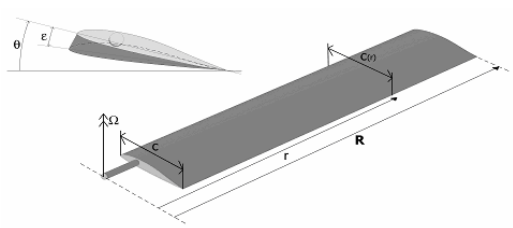
The aerodynamic and performance analysis was mainly focused on designing the optimal rotor geometry. The tandem configuration consists of four identical rotor blades. The rotor is optimised for an altitude of three meters in order to take maximum usage of the ground

effect at this specific altitude. This design methodology greatly enhances the chance of achieving the difficult requirement of momentarily reaching three meters altitude.

The ground effect is a crucial factor in the design of the HPH. Success or failure of the mission depends on it. In the ground effect, the same amount of thrust can be generated with a reduced amount of required power. This is of vital importance, since the amount of power a human can deliver is limited. The ground effect increases the closer you get to the ground. The performance analysis has been performed with three variants of the Blade Element Method, in which the ground effect has been implemented on element level. All variants produced similar results. The most accurate method has been used to optimise the rotor.

The Eppler E220 has been selected as the most suitable airfoil for the HPH. This profile has favourable aerodynamic characteristics (high $c_l/c_d$ and low cd0, for good hover performance) and a very low pitching moment coefficient cm (to relieve structural loading).

The optimisation procedure compromised an elaborate iterative process. The goal of this process was to achieve a high power loading, i.e. an acceptable amount of thrust, generated with a low power required. Parameters, that were optimised to this cause, are the rotor radius R, rotor chord c, wing planform c(r), linear twist • in combination with a collective pitch • (clockwise angles are taken positive) and a rotor angular velocity • (at 3 meters altitude). The resulting rotor geometry can be found in figure 17.4. A cut out of 0.1R has been implemented to provide space for the rotor clamping and to limit the amount of twisting needed.




| Parameter | Value |
|---|---|
| $R$ | 9.0 m |
| $c$ | 1.03 m |
| $c(r)$ | constant [-] |
| $\varepsilon$ | -7 deg |
| $\theta$ | 15 deg |
| $\Omega$ | 16.4 RPM |

Figure 17.4: Rotor Geometry

With this geometry and using a power output of 840 W at three meters altitude, a thrust of 1015 N can be generated. This value, equal to 103.5

kg, was set as a limit for the weight of the HPH. However, the amount of power required for hovering decreases with decreasing altitude, due to the ground effect. This is illustrated in figure 17.5. As a result, just 550 W is needed for close hovering above the ground. A professional cyclist can easily sustain the above mentioned power outputs for the desired amount of time.

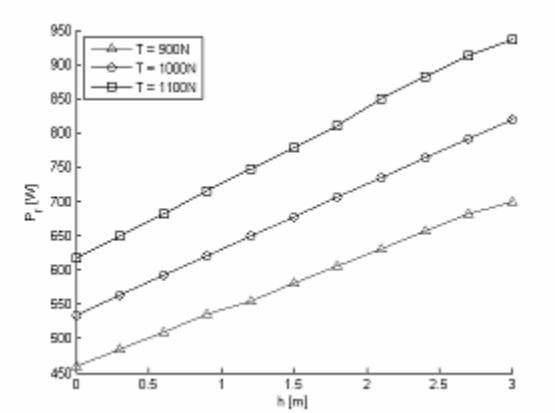



Figure 17.5: Required Power to Hover as a Function of Height above the Ground

**Structures and materials**

The structure of the Twinfinity can be subdivided in five sections: the rotor blades, the truss structure, the pilot support structure, the ground support and the transmission. Each component of Twinfinity's structure, except the transmission, is designed by means of Finite Element Analysis (FEA). Every structure segment will be explained briefly in the following sections.

All the structure elements, including the rotor blades, are designed and optimised with use of a FEA-tool in Matlab. The rotor blades can be split into two parts: the rotor tube and the airfoil. The rotor tube can be seen as the spinal cord of the rotor blade. This part is designed to cope with all the loads acting on the rotor blade. It is manufactured out of carbon fibre by means of filament winding. This manufacturing method is chosen because of different loads the tube has to carry. Furthermore, the airfoil segment is constructed out of ribs, foil and spars for the leading and trailing edges. Balsa wood is used for the ribs and spars. For the skin of the rotor blade a plastic foil, called Oracover, is applied. The final rotor structure can be seen in figure 17.6.

Figure 17.6: Rotor Blade Structure

The Twinfinity concept is a tandem configuration, whereby trusses are carefully designed to support the rotors and to handle the induced loads in a sufficient manner. Between the two trusses, a pilot support is located. Just like the rotor tube, the base material for the truss and pilot support is carbon fibre. For these elements only normal forces are considered. Consequently, simple off-the-shelf carbon fibre tubes are used. All the tubes have the same wall thicknesses. Only the diameter of the tubes is optimised to carry the maximum buckling loads.

Before the launch and after the landing, Twinfinity has to be able to stand safely on the ground. Therefore, the aluminium rotor shafts are lengthened, to give the rotor blades enough room to rotate freely. To support the aircraft in a sufficient way while standing on the ground, two people with supporting bars are needed to prevent it from falling over. Before flight, the rotor blade tips can hit the ground. Therefore little wheels are adapted to the blade tips, to slide the blades smoothly over the ground during start-up phase.

To transfer generated human power to the rotors in a satisfying manner, losses have to be minimised as much as possible. To achieve this, without adding much weight, stiff and lightweight materials have to be used. The applied sprockets and chains are standard aluminium-alloy bicycle parts. These components are widely used and evolved to a very efficient system. The applied cables to drive the rotors need to be very stiff to decrease elongation due to tensile forces (shown in figure 17.7). The ideal material for this application is Dyneema.

**Stability and control**

Stability and Control is a major part in the design of the HPH. Stability is the natural characteristic movement of a vehicle upon a disturbance.

The stability of the Twinfinity was analysed by formulating the equations of motions. With these equations the stability derivatives are determined, which are needed for the state space model. A six-degree of freedom model is developed for the analysis of the three translational and three rotational motions of the HPH. The directions corresponding to the rotational motions are found to be stable. However, the translational motions are not stable and drift can occur in these directions.

The roll and pitch stability are checked by carrying out an analytical analysis. In the analysis performed for the concept selection, the tandem configuration was expected to be unstable in roll motion. For this motion a two-degree of freedom model is made from which the eigenvalues are determined. These values show a large negative real part, which indicates that the roll motion is highly damped. This means that in roll motion the Twinfinity stabilises itself very fast. This high stability is due to the fact that the centre of gravity is placed above the rotors. Investigation on pitch motion showed a stable behaviour as well. It may also be expected that ground effect will have a positive influence on the pitch stability; therefore the pitch stability can further improve.

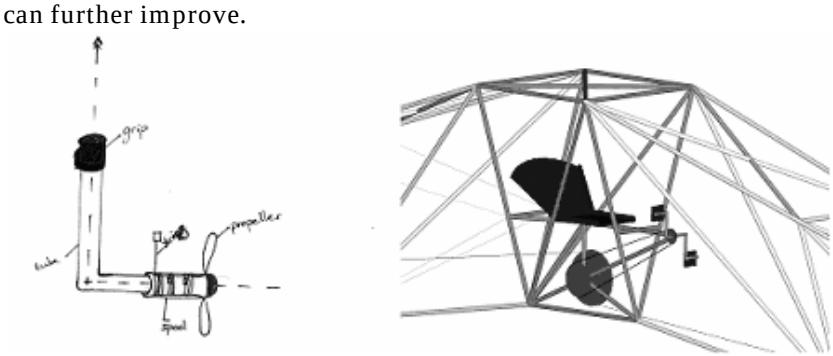



Figure 17.7: Propeller Spool System (left) and Pilot Seating (right)

Although the Twinfinity is stable in rotational motion, it needs control for the translational motions. This is done by means of the propeller spool system as shown in figure 17.7. By pulling the chord a propeller is driven and it can be steered with the grip to compensate for drift. Control in pitch is not applied, since it is assumed that the helicopter is stable in this direction, especially in ground effect. Control by means of weight shift is applied to roll motion. The weight shift is a result of

the movement of the torso of the pilot. The width of the back of the chair is adjusted to these movements as shown in figure 17.7.
By using a Matlab Simulink model, the reaction of the helicopter to the weight shift moment around the longitudinal axis is simulated. From the results obtained, it can be concluded that this control system is effective and Twinfinity's motion will damp itself out in time. In case of weight shift, accurate responses from the pilot are required to counteract disturbances. However during intensive cycling, the pilot might overcompensate in control and create unwanted oscillation. Therefore good training and testing is required in order to let the pilot control the Twinfinity.

Finally, control in vertical direction is done by varying the RPM of the rotor blades, since the collective pitch angle is set to a fixed value.

## 17.6 3-View drawing

The final design of the concept is displayed in a 3-view drawing in figure 17.8.

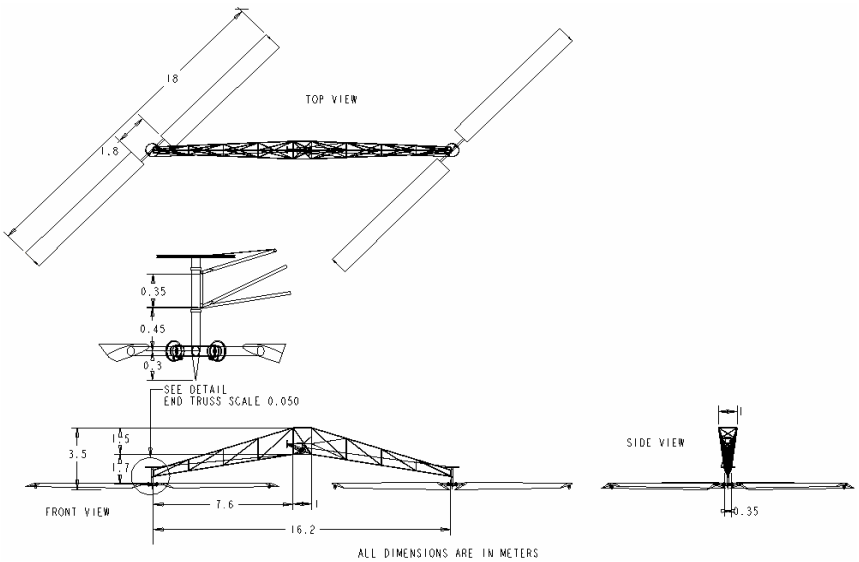



Figure 17.8: 3-View Drawing of Twinfinity

## 17.7 Conclusions and recommendations

The final design of the human powered helicopter resulted in a concept, which fulfils all the requirements formulated by the AHS competition. The power required to hover and to achieve a maximum of three meters altitude could easily be achieved by a professional athlete. In first instance, stability seemed to be problematic for a tandem configuration, especially in roll direction. Fortunately further stability investigation proved the contrary. Just like stability, control of the rotorcraft appeared also a bit difficult. Nevertheless, application of simple weight shift proved to be sufficient. Energy losses could be disastrous in case of an HPH. Therefore a very efficient transmission system has been designed. By using off-the-shelf bicycle sprockets in combination with stiff and light wire material like Dyneema, the total efficiency of the transmission system can get as far as 97.3% in case of Twinfinity. A minor point of the concept is the final mass. Although the calculated total mass (98 kg) was below the determined specification mass, the final mass including contingency exceeds this value with about four kilograms. Due to time constraints, it was not possible to investigate the optimisation opportunities any further.

The Twinfinity concept can be further elaborated in the future. By constructing a scale model, more information can be found in the field of aerodynamics and performance, especially on the airfoil performance in ground effect. Besides, further investigation has to be done on the human power output. According to the calculations, the Twinfinity has sufficient stability and control. Still, some research needs to be done on translational movements. These motions, except vertical direction, are very difficult to control. To make fully use of the generated power, more research has to be performed on the pilot-machine interface. Regarding structures, much can be optimised in the choice of material. Optimisation of fibre direction in case of filament winding has to be contemplated as well. Ultimately the chance of winning the AHS-prize is very difficult. Anyhow, if the duration of the project is lengthened to a certain extent, Twinfinity could become reality.

# 18. VERTUGO, DESIGN OF A HUMAN POWERED HELICOPTER

*Students:* N. Bastiaensen, N.P. Brinkerink, T.J.A. Dolle, E. de Jager, S. De Lucia, G. Nati, A.M. Oyen, H.L.M. Van Raemdonck, A.H. Verdaasdonk, L. Zwang

*Project tutor*: ir. J.A. Melkert

*Coaches*: dr. R.M. Barrett (Kansas University), dr.ir. S. Koussios, R.A. Humble MEng

## 18.1 Introduction

In 1980, the American Helicopter Society started the Igor I. Sikorsky competition. It is a challenge to build a heavier than air rotary wing aircraft, solely powered by a human being. The competition will be won if a one minute flight is performed, reaching an instantaneous altitude of at least three meters. The helicopter is not allowed to leave a 10x10 meter area and must have at least one crew member, who is not rotating.

Although many attempts have been made by other universities, of whom the most successful one was the University of Nihon, Japan, no one has been able to claim the prize of the Igor I. Sikorsky competition.

In the context of the Design Synthesis Exercise, the project team has done a feasibility study and designed a Human Powered Helicopter to win the Igor I. Sikorsky competition.
VerTUgo is the result of the effort of ten students during a period of ten weeks, in which concepts have been developed and evaluated. The

concept that showed the best characteristics in the evaluation was worked out in more detail. If VerTUgo will be developed further, and in the future even built, this design may be next in line of successful and prize winning DSE projects.

## 18.2 Conceptual designs

Five concepts have been created. The first concept is a single rotor configuration. Within this configuration, there are two design options: a helicopter with a tail rotor and a helicopter with tip propellers. The configuration with tip propellers is the most efficient of the two design options. A similar design has been developed by a team from the Polytechnic University of California.

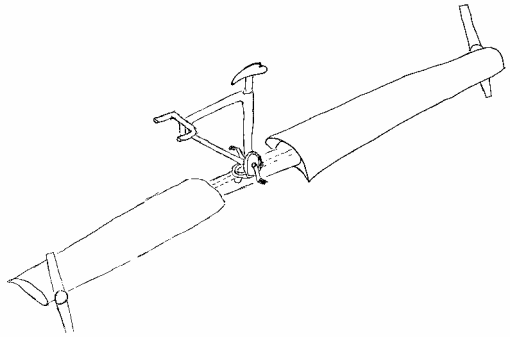


Figure 18.1: Concept 1

The second concept is a two rotor configuration. The advantage of this configuration is that since the two rotors counter-rotate, there is no residual torque, which is a prerequisite for a successful design. There are two design options: co-axial rotors or bi-axial rotors. A choice has been made for bi-axial rotors, because in case of co-axial rotors, the airflow of the lower rotor will be disturbed by the wake of the upper rotor. Moreover, unequal bending of the lower and upper rotors can cause a collision. An example of such an event is the attempt by the Thunderbird team of the University of British Columbia.
A choice has therefore been made to use a bi-axial configuration.

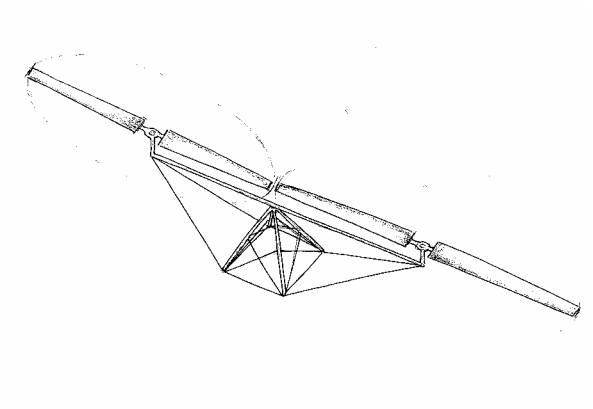


Figure 18.2: Concept 2

The third concept is a three rotor configuration. Because this configuration has an odd number of rotors, one rotor needs to be larger than the others, or needs to have a higher rotational speed. The structure consists of three beams, which are joined at the top and connected by wires.

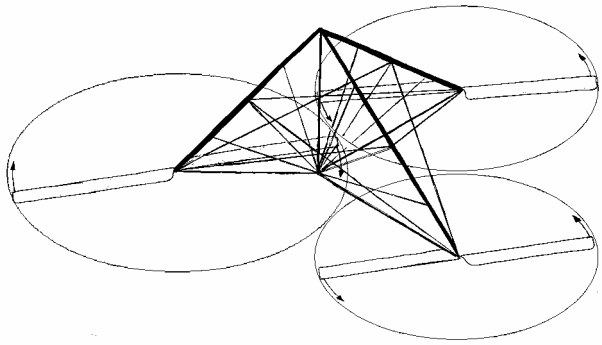


Figure 18.3: Concept 3

The fourth concept has, as can be expected, four rotors. The structure is similar to the structure of the three rotor concept. The University of Nihon, Japan, which broke the duration record with a flight of 19,46 seconds at an altitude of 20cm, also used four rotors.

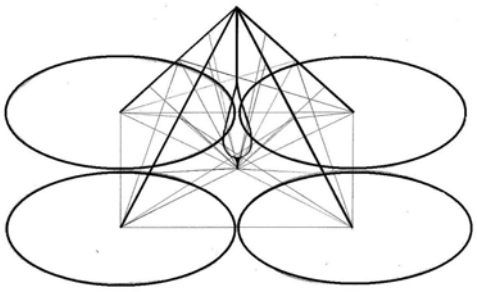


Figure 18.4: concept 4

The fifth concept uses solar energy to heat up the air inside the structure to create buoyancy. Although this configuration was very innovative and promising, unfortunately it turned out that the use of hot air to create buoyancy is against the rules of the competition. For this reason this concept is not taken into account during the trade-off.

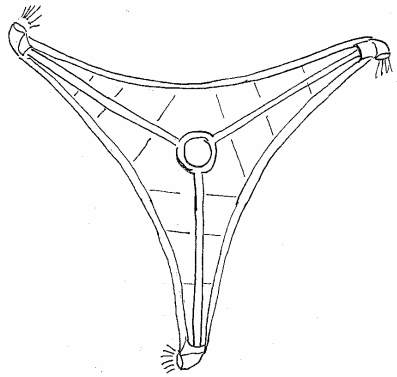


Figure 18.5: Concept 5

## 18.3 Trade-off

After evaluation of all concepts, plusses or minuses are assigned to different areas of performance. This trade-off is presented in table 18.1.

| | Aerodynamics | | | Structures | | | Manufacturing | | Performance | |
|---|---|---|---|---|---|---|---|---|---|---|
| Categories | Aerodynamics | Stability | Control | Weight | Reliability | Aero Elasticity | Manufacturing | Costs | Transmission | Pilot position |
| Weight | 0.28 | 0.04 | 0.08 | 0.21 | 0.06 | 0.03 | 0.1 | 0.1 | 0.07 | 0.03 |
| 1 | + | 0 | 0 | 0 | + | - | - | + | - | + |
| 2 | + | 0 | - | + | + | 0 | + | 0 | 0 | - |
| 3 | - | 0 | - | + | + | + | - | - | - | - |
| 4 | - | + | + | ++ | ++ | ++ | 0 | 0 | - | - |

Table 18.1: Trade-off

The grades are multiplied with their weights and the scores are added. This gave the following result:

| | | |
|---|---|---|
| Concept 1: | 0.27 | points |
| Concept 2: | 0.48 | points |
| Concept 3: | -0.30 | points |
| Concept 4: | 0.24 | points |

Concept 2 earns the best grade by far. This means that according to the trade-off, the final design should be a derivative of concept two.

## 18.4 Final design

The design of VerTUgo has a two rotor, bi-axial configuration with a rotor diameter of 20 meters. A connection beam (nr.1 in figure 18.6) connects the two rotors (nr.3 in figure 18.6) and the pilot cabin (nr.2 in figure 18.6). The cabin is positioned underneath this connection beam to lower the centre of gravity, because this is needed for static stability. The pilot is seated in a recumbent position to minimize the height of the cabin and thus the total helicopter. This optimizes the ground effect. By a cycling motion the pilot transfers his power to the helicopter.

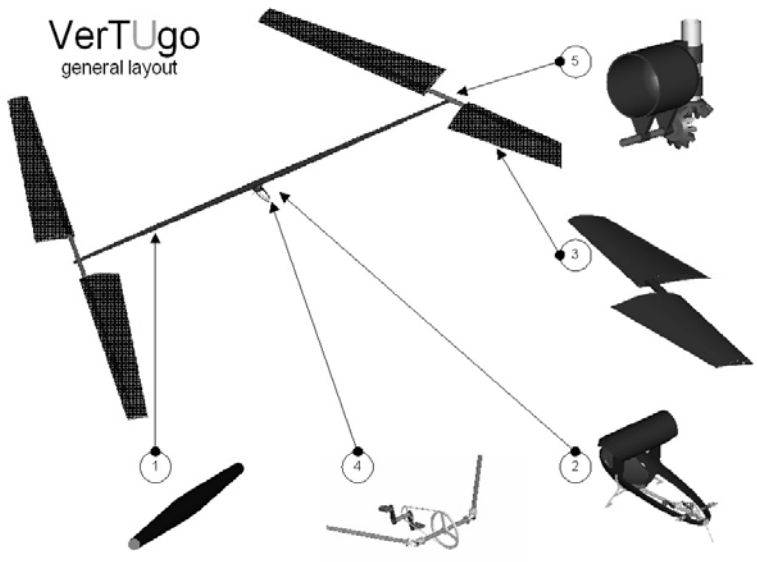



Figure 18.6: VerTUgo - General Layout

The connection beam is made of an inflatable structure supported by two carbon fibre compression elements and with fibres wound around from one end to the other. The upper compression element is loaded in compression when lift is produced, whereas the lower compression element takes up the compression load when the rotors are at rest. The introduction of this beam to the design gives VerTUgo a distinct weight advantage with respect to other structural designs. The 21-meter long connection beam will have a total weight of just 3.6 kg. If a composite structure had been used, it would weigh about 6 kg.

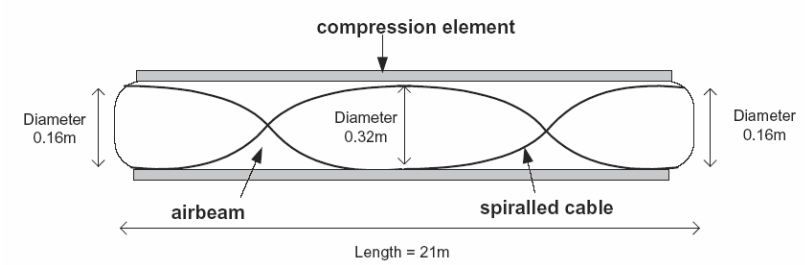



Figure 18.7: Impression of the Connection Beam

The caps (nr. 5 in figure 18.6) will be fixed to the compression elements at both ends of the connection beam. These caps will be a connecting

element between the connection beam and the rotors, as well as a support for the transmission system.

The rotors are of a spar-ribs design. The same structure used for the connection beam will replace a traditional spar to save weight even more. The ribs, which are made out of Styrofoam, will be glued onto the compression element of the spar. The whole structure will be covered by a Mylar skin.

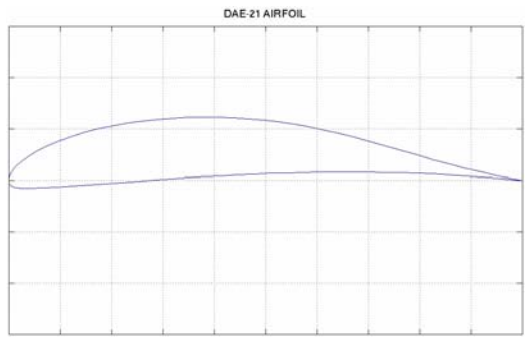



Figure 18.8: The Daedalus-21 Airfoil

To find the right airfoil, more than a hundred airfoils were analyzed and compared on $c_l/c_d$, $c_l/\alpha$ and $c_{l,max}$. The airfoil most suitable for VerTUgo proved to be the Daedalus-21 airfoil shown in figure 18.8. To optimize the performance of the rotor blades, a taper of 25% and a twist are applied. The twist is a non-linear twist, which starts at 20° at the root of the rotor blades and ends at 9° at the tip of the rotor blades.

| Airfoil | Angular Velocity [rpm] | Radius [m] | Lift [N] | $P_{ind}$ [W] | $P_{prof}$ [W] | Torque per rotor [Nm] | Chord at root [m] | Chord at tip [m] |
|---|---|---|---|---|---|---|---|---|
| DAE-21 | 9.55 | 10 | 863 | 483 | 70 | 276 | 1.84 | 0.51 |

Table18.2: The Rotor Blade Properties

The cabin (see figure 18.9) consists of several components, which are all made out of carbon fibre. To manufacture the cabin three different processes are use. Filament winding for the cylindrical part of the

frame and the nose-seat support bar, Hand Lay-up for the seat and the landing gear and Vacuum Infusion is used to produce the integral structure of the frame.

Figure 18.9: The Cabin

The propulsion system has been designed with a cycling mechanism. A drive shaft is designed between the pilot cabin and the rotor connections with two purposes. The first being power transmission from the pilot to the rotors. The second function of the drive shaft is structural support. The shaft is subjected to a tensile force with the use of tapered bearings. Four small angles in the drive shaft are made by using universal joints, two large angles by bevel gears. In total, the efficiencies of all parts of the transmission system add up to around 90%.

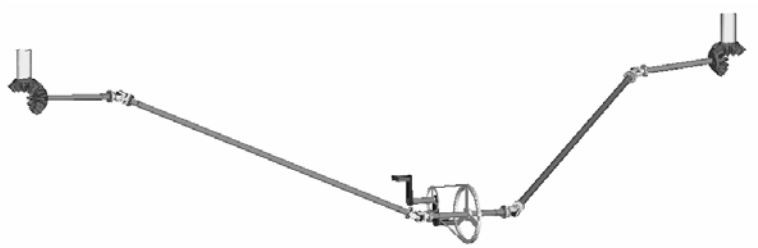


Figure 18.10: The Transmission system

## 18.5 Performance of VerTUgo

To predict the performance of VerTUgo, a simulation program has been written in Matlab. The input of this program consists of the power variation delivered by the pilot. From theory on movement sciences, combined with test results, it is estimated that for a one minute cycling effort, the average power output of a well-trained 60 kg athlete will be around 600 W. It is also concluded that a peak power early in the run is favourable. The reason for this is that momentum gained in this stage is useful in the entire run, whereas momentum gained at the end of the run will be "lost" once the run is over. With this information, the power variation has been estimated as presented in figure 18.11.

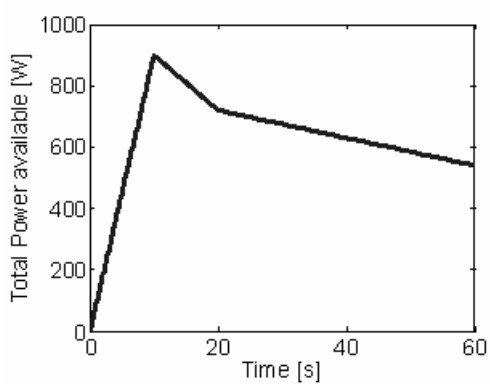



Figure 18.11: Estimated power output of the pilot

The simulation program uses the power delivered to determine the vertical velocity. Taking into account the variation of induced velocity as well as the changing ground effect, the result of the simulation is the variation of height during the flight. In figure 18.12, this result is presented.

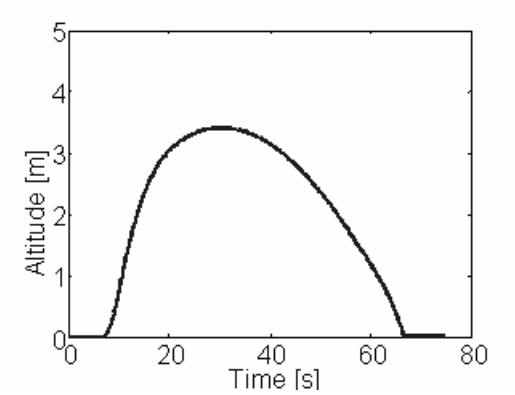



Figure 18.12: Simulation of the Height

The results of the simulation program confirm VerTUgo's potential to win the Igor I. Sikorsky prize. The flight time is sixty seconds, and an instantaneous height in excess of three meters is achieved.

## 18.6 Costs

In case VerTUgo will be produced, the costs have been estimated to be around € 22,400. To cover the costs, sponsors will have to be attracted. Sponsors may be motivated to provide knowledge, materials or finances. Since the human powered helicopter challenge has attracted much attention in the past, and a successful design will certainly be an eye catcher, VerTUgo can be an attractive project to sponsor.

## 18.7 Conclusion

The conclusion of the project team is that the human powered helicopter project is feasible, and that the VerTUgo design is the best approach to successfully fly a human powered helicopter.

Go VerTUgo!

# 19. DESIGN OF AN EMERGENCY ESCAPE POD

*Students:* E.S. van Dijk, N. van Dorland, M.C. van Hoek, J.N. Hooplot, M. Kamphorst, A.M. Ouwehand, R.H. Sneep, R.S.L. Stals, W.T. Tulfer, M. van de Ven

*Project tutor*: prof.dr. A. Rothwell

*Coaches*: dr. A. Podgaets, ir. E.J. Schut, ir. G. Larocca

## 19.1 Introduction

High-rise buildings are very efficient for working and living with respect to the use of ground space. As ground space becomes increasingly rare and thus more valuable, the amount of high-rise increases, especially in the Far East. No problem, one would say… until disaster strikes.
Imagine that for some reason (a bomb, a plane crash or just an accident) a huge fire is started somewhere in the building. Everybody wants to leave at once, but the elevators are shut down for safety. People take the stairs, but these are partly blocked by this fire, which leads to inevitable congestion. Waiting for a rescue operation, which will probably come too late, or jumping (it has happened!) is not attractive either.

Several alternative solutions to this problem do exist. Existing systems as well as those under development operate very close to the building, which means a fire would still endanger evacuees. Furthermore 'flying' systems lead to the problem that they endanger the police, doctors and fire fighters on the ground.

For this reason another type of system should be designed. Before this can be done, its objectives should be clear. As described, it should rescue people from a high-rise building in case of an emergency. An 'emergency' is a direct threat to people's lives (for example a fire spreading or danger of collapse). The system has to bring people from the danger zone directly to a safe place; therefore it has to be airborne. It has to rescue the people from the 25th floor and higher.

This leads to the following Mission Need Statement:

*Enable people to safely escape from an elevated position in a high-rise building in case of an emergency, using a sustainable airborne device*

With this Mission Need Statement several top-level requirements have been derived together with our customer. They provide a more detailed understanding of the required performance of the system:

- The total evacuation process should be completed within one hour.
- Because of falling debris, the system must bring people to at least 260 meters away from the building.
- The system should be able to work in wind speeds up to 90 km/h.
- The total system cost should remain within 5% of the total building cost. This means the maximum cost of the system is US$ 1100 per occupant.
- No professionally trained personnel should be required to operate the system.

After generation of various different concepts, a trade-off can be made using these requirements as a tool. In the following section an evacuation with the chosen system will be described, and finally a technical description will be presented.

## 19.2 Concept study

During brainstorming sessions, the Mission Need Statement was used as a basis to devise concepts. This led to eight competing systems:

- Parachute system: the occupants enter a multiple person device, which is then launched. A ballistic phase follows, and a parachute deploys. A crumple zone absorbs the landing impact.
- Cable system: a UAV (Unmanned Air Vehicle) carries a cable down to a predetermined landing area. When the UAV has landed, this cable will be tensioned. Then a slide can be deployed along the cable and people can slide down.
- Balloon system: balloons are inflated while people enter the cabin of the device. They float away calmly and are kept in the air by a trained "pilot" who can let gas in and out to determine the rate of descent/ascent. The balloon lands outside crowded regions.
- Rotor blade system: a system with an autogyro rotor. The device is launched into the air after boarding. In flight the autogyro is controlled by a trained pilot and descends with an acceptable rate.
- Inflatable backpack system: evacuees get a backpack and go to a slide, from which they are 'launched' individually. Once in the air the backpack is inflated and becomes a lift-creating structure. It adjusts its orientation by its aerodynamic shape such that it slowly descends and floats away from the building.
- Paraglider system: a multiple-person pod is launched using a guide rail system in the building. After launch, multiple sails deploy and the system lands using an autopilot.
- Glider system: a multi-person fixed-wing rigid glider. It is propelled by a launch mechanism to give it initial velocity for its flight. After launch, the glider flies to a safe location and lands horizontally with a parachute to reduce velocity.
- Inflatable wing system: a multiple-person pod. Its wings consist of an inflatable structure, which is deployed after launch. When fully deployed, the inflatable wing glider flies to a designated landing area guided by an autopilot.

On the basis of the specified requirements and possible threats, which determine the feasibility of the concepts, three of the eight concepts were chosen. These concepts were respectively the Inflatable backpack system, the Paraglider system and the Inflatable wing system. Subsequently the three concepts have been evaluated further in

different aspects. These subjects are logistics & performance, aerodynamics, control & stability and structures & materials.
After the analysis of the three concepts, a final trade-off has been made in order to select the winning concept. In table 19.1 an overview of the main trade-off data is given for each of the three chosen concepts.

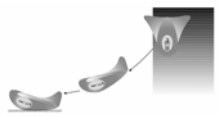
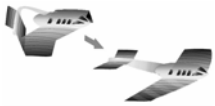
| | Inflatable backpack | Paraglider | Inflatable wing |
|---|---|---|---|
| Number of persons | 1 person | 20 persons | 20 persons |
| Cost | $1800 | $1750 | $1600 |
| Flight speed | 34 km/h | 80 km/h | 50 km/h |
| Mass | 38 kg | 750 kg | 750 kg |
| Sketches |  |  |  |

Table 19.1: Main parameters of the three best concepts

In this trade-off process, requirements satisfaction, technical risk and commercial feasibility were taken into account. This led to the paraglider as the winning concept, having the best overall performance on each of the subjects. The paraglider concept is therefore chosen for further investigation in this project.
A description of the system can now be given. This is done first by describing what would happen in case of an evacuation. Then a more detailed technical description will be given.

## 19.3 Description of an evacuation procedure

In case of an emergency, an alarm bell sounds in (a part of) the building. People start moving to special emergency floors, guided by evacuation plans. One of every nine floors is designed as an

emergency floor. Here the pods, in which the people will escape, are stored. The layout of an emergency floor is shown in figure 19.1.

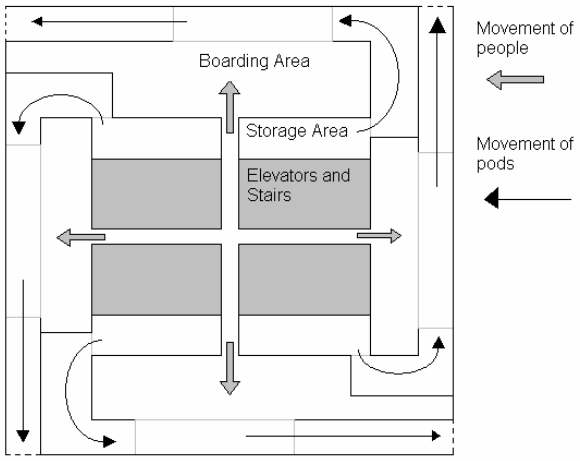



Figure 19.1: Lay-out of an emergency floor

As can be seen, there is a maximum of four directions in which pods can be launched. Depending on wind conditions, this number might have to be reduced. There are 10 trained safety managers per system (and 10 backup). Their job is to take the pods out of the storage area and prepare them for launch. The pods are stored uninflated to be able to store enough of them on a floor. Therefore the safety managers must inflate the pods with air-filled tanks. This process is shown in the first three steps of figure 19.2.

After the first stage of inflation, thirty people board the pod (five next to each other) and strap their four-point seatbelts. The safety managers check the seatbelts and zip a transparent door (to make people feel safe). Next, airbags that absorb the impact during landing are inflated. These airbags contain overpressure valves that allow air to escape when the pressure inside reaches a certain value. Because a horizontal impact with objects like buildings and other pods is also possible, a front and rear airbag are coupled to this bottom airbag and work on the same principle. Finally, a simple press on a button by a safety manager launches the pod.

On each side of the floor three pods are prepared at the same time, taking about three minutes per pod. Every minute a pod is launched;

with a total of 80 pods per floor and four launch areas in use per emergency floor in the ideal case, this means launching would only take twenty minutes.

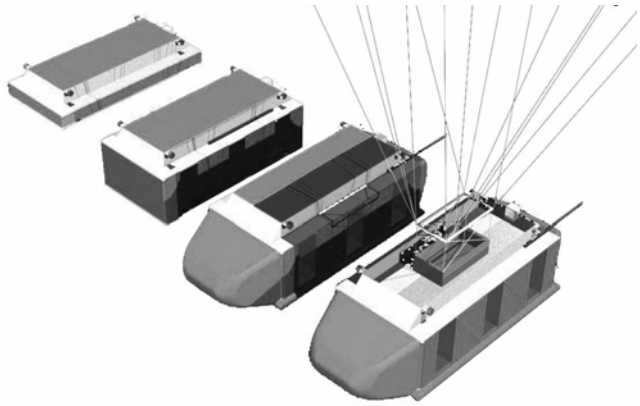


Figure 19.2: Inflation and deployment stages of a pod

When the pod has been launched, three sails are deployed to make the pod fly (the fourth step in figure 19.2). To do this quickly the sails are, just like the cabin, partly inflatable. Inflation is initiated by an autopilot and requires small air tanks on top of the cabin. Three sails are positioned above each other to reduce the velocity of the pod and the span of each sail. The pod in flight is shown in figure 19.3.

After deployment of the sails, the pod has to land on a safe spot, which could be a river, lake, a park or just a street. This location is pre-programmed in the autopilot, which steers actuators on top of the cabin. These actuators pull the bridle (cables) leading to the control surfaces on the rear side of the sails to steer the pod in the right direction.

Figure 19.3: The pod in flight

On the rear of the cabin a retractable beam can be seen. At the end of this beam, which is deployed together with the sails, an altimeter is attached to make the autopilot initiate a flare on time. This flare reduces the vertical and horizontal speed of the pod before touchdown.

After touchdown the friction with the ground and the drag of the sails make the pod stop, after which the occupants can zip the door open and leave the cabin. Firemen can deflate the pods on the street and tow them away to make space for other incoming pods. The exact after-landing logistics plan has to be determined per building and city. In case of landing on water the occupants will have to wait for further rescue inside the cabin.

## 19.4 Technical specification

**Aerodynamics**

The sail configuration of the pod is three sails above each other. The number of sails is optimized for low flight and landing speed and a sufficiently small sail span. For the shape of the sails, the principle of a membrane airfoil is used. The aerodynamic performance of a single and a double membrane airfoil are comparable. Since a double membrane airfoil not only needs internal pressure in the spar and the

ribs, but also in between the two pieces of cloth, a single membrane sail wing is chosen. The front view of the sails has an arc-shape with an anhedral angle of 30 degrees. As planform a rectangular geometry has been chosen because a rectangular configuration without taper is cheapest to produce. This planform has a drag coefficient that is only 0.7% higher than the drag coefficient of an elliptical planform of the same size.

The cabin has been modelled as a beam for aerodynamic calculations. The most important characteristic determined for the cabin from an aerodynamic point of view is the drag it generates as function of its speed, since it influences the distance the pod is able to cover during flight.

**Control**

To enable the pod to follow the desired flight path and land at a predefined location, a control system is needed. The use of pilot is not an option for cost reasons, since a lot of training would be required. To follow the desired flight path an autopilot system has been chosen to accomplish this. To control the pod, both symmetric and asymmetric control is needed, which is provided by two flaperons on each sail. If the flare manoeuvre just before landing were to be controlled by the flaperons only, a relatively powerful primary control would be needed. Instead, the front constraint of the bridle lines is cut, effectively lengthening the lines. A schematic drawing of the two control methods is shown in figure 19.4.

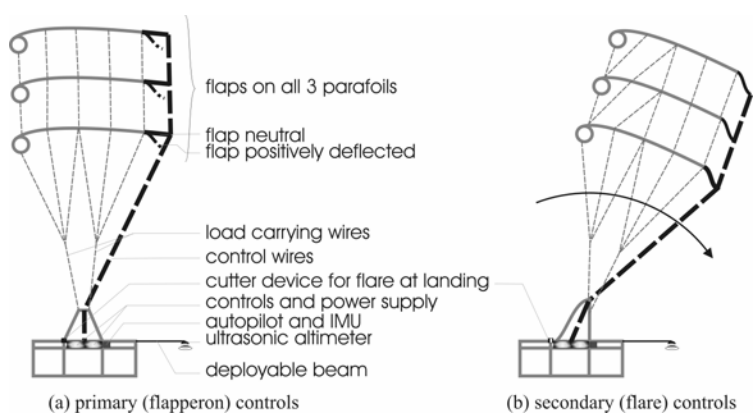



Figure 19.4: Schematic control drawings

**Structure**

The structure of the pod consists of three main parts, respectively a solid roof, an inflatable core and a solid floor. The launch load is imposed on the roof, which is made of an aluminium sandwich plate. Connected to this plate are a box containing the folded sail (before inflation), an autopilot, actuators to give steering input to the sail and a device to attach the cabin to a launch rail. The section between the roof and bottom plates consists of inflatable cells and eight diagonal cables. These cables are placed such that they can carry the launch and landing loads together with the inflatable part of the structure. The solid floor is also an aluminium sandwich plate that provides stiffness and protects the inflatable parts from damage by high heels and other sharp objects. Furthermore, a rigid floor gives the occupants a safe feeling. For the dimensions of the cabin and sail see figure 19.5.

The loads taken into account for calculations on the sail structure are the aerodynamic loads, the control loads, and the weight of the cabin together with the payload. The sail construction consists of multiple sails with inflatable front spar and 11 ribs each. The inflation system is a simple gas bottle with a valve for each sail. Bridle lines connect the sails to each other and to the cabin.

The materials chosen for the various structural elements are:

- Aluminium sandwich plate for the roof and floor, because of its stiffness and weight
- Kevlar for the cabin, because the inflatable part of the cabin needs to be strong and reliable
- Steel for the cabin cables, because of its high strength and low cost
- Dyneema SK60 is chosen as the material for the bridle lines
- Ripstop Nylon Chikara for the sail fabric and the inflatable front spar and ribs

**Flight performance**

On the basis of the equations of motion for the emergency escape pod, a simulation program was written which evaluated these equations many times per second. This program is used to calculate:

- the distance the system covers before it lands
- the horizontal and vertical speed at which it lands
- the time required to evacuate the building

These data are given in table 19.2.

**Costs**

The total cost for a system in a detail design stage are normally defined as the total cost of purchase and ownership. The cost analysis discussed for this preliminary design project concentrates mainly on the purchase cost of the system. The total purchase cost for one escape pod can be divided in the following items:

- Recurring costs
- On-board system costs
- Launcher costs
- Construction costs

In table 19.2 the estimated total cost per user are given.

| Dimensions | | Weights | |
|---|---|---|---|
| Wing span | 10 m | Operating Empty Weight | 4.7 kN |
| Height | 24.3 m | Payload Weight (30 pers) | 23.5 kN |
| Length | 8.7 m | Maximum Take Off Weight | 28.2 kN |
| Chord length | 5.5 m | | |
| Performance | | Logistics | |
| Launch speed | 60 km/h | Amount of emergency floors | 1 per 9 floors |
| Landing speed | 61 km/h | Number of pods per floor | 80 |
| Average glide angle | 18.4o | Total evacuation time | 20 min |
| Distance covered from 25th floor | 260 m | Cost per user | $1400 |

Table 19.2: Overview of the characteristics of the emergency escape pod

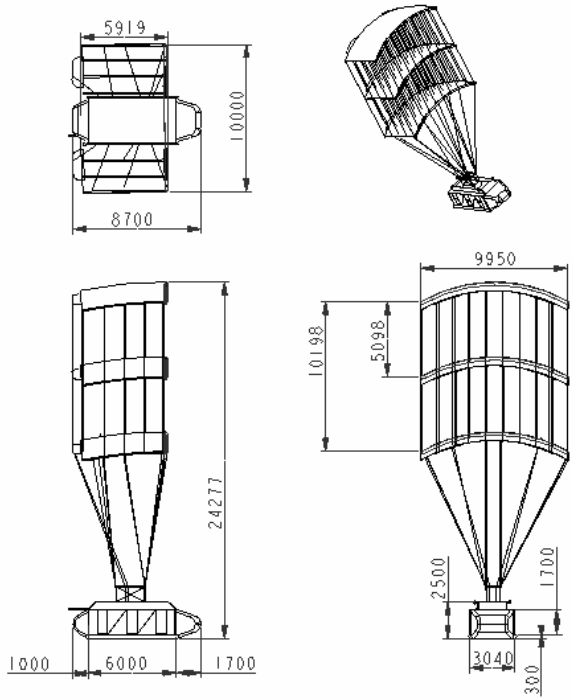



Figure 19.5: Configuration of the Emergency Escape Pod

## 19.5 Conclusions and recommendations

If an airborne system is to be found to provide a solution to building entrapment in case of an emergency, a triple-sailed paraglider is the best option. The system as described provides enough capacity and has a flight velocity, which is within safety boundaries. The system is called SAFE, which stands for Sustainable Autonomous Flying Evacuator.

The question is, whether this airborne solution will ever be implemented. As a system like this makes buildings more expensive, for a real estate developer it might be much more attractive to use the same amount of money to strengthen his building design and add extra reinforced stairs and elevators.

Nevertheless in the future, as building size increases, stairs and elevators could lose their monopoly. For buildings higher than a

kilometre, the traditional solution of stairs is technologically far behind the state of the art of building. To compensate for this, and to increase the evacuation possibilities for high-rise buildings, an airborne solution is a necessary supplement. And if events such as the attacks on the World Trade Centre in New York are likely to be repeated, an airborne device is the only solution to rescue the occupants from the building.

The topics that have to researched in order to prove the feasibility of this emergency escape system are:

- Multiple sail aerodynamics and stability
- Automatic sail inflation
- Influence of wind and turbulence around a large building (on fire)
- Fully autonomous autopilot
- Cabin design optimization for crash impact and weight
- Emergency floor lay-out
- Emergency floor and landing logistics
- Psychological aspects
- Economic and legislative aspects

All in all it can be concluded that a feasible system has been designed, but much more investigation needs to be done which is only worth its cost for extremely high buildings.

# 20. DESIGN OF A FLEXIBLE AUTONOMOUS UNMANNED AERIAL VEHICLE

*Students:* T. van den Berg, C. Feddes, M.A.M. Hoogerwerf, P.M.A de Jong, H. Joore, T.W.A. van Mil, A. Oonk, G. Ouahadi, E. Rath, E.J. Terink and M. Westerlaken

*Project tutor:* ir. P.C. Roling

*Coaches:* ir. B. Bijnens, ir. P. Joosten

## 20.1 Introduction

Since the Kyoto-agreement in 1997 more regulations on greenhouse gas emissions have been created worldwide. Also in the Netherlands discussions on emission registration and reporting for all industry rise. However, all these regulations are in need of inexpensive but adequate measuring techniques and accurate emission models in order to learn how to effectively fight for the quality of our atmosphere. Although more and more masts are being equipped with air quality sensors, providing data about the whole of the Netherlands requires a more mobile and flexible measuring solution.

Due to the difficulty of performing many simultaneous measurements in order to catch the complete picture, it is very hard to provide adequate objective data for many places in the Netherlands. A swarm of aerial vehicles — small enough to be deployed without hazard and large enough to carry accurate gas sensors — would be a highly interesting scientific instrument and a first step towards a better understanding of the influence of industry, but also farming and

woods, on the quality of the air. Unmanned Aerial Vehicles (UAVs) have the advantage of being relatively inexpensive. Many recent UAV programs have shown the feasibility of such a cheap and reliable aerial vehicle.

Although the goal of the project, based on the reasoning given above, was to design a UAV capable to perform $CO_2$ concentration measurements, it was decided to design a flexible aerial platform that is also able to carry a $CO_2$ sensor. Other possible payloads are $NO_x$ and $CH_4$ sensors and (infrared) cameras. This increases the market for the UAV considerably.

## 20.2 Design specification or list of requirements

The design requirements for the UAV platform are:

| | |
|---|---|
| Endurance: | 2 hours |
| Flight area: | 5 x 5 x 0.5 km |
| Wind condition: | 4 Bft. on ground level |
| MTOW: | 5 kg |
| Payload mass: | 0.5 kg |
| Safety: | The aircraft should not cause severe injury in 99% of the cases when impact on a human body occurs |
| Availability: | Sufficiently robust to withstand one year of occasional operation, 10 hours of flight per month, safely |
| Other: | Able to fly in bad visibility or above reflecting surfaces |
| Cost: | A budget of € 10,000 can be made available |

## 20.3 Conceptual design

For the design of a UAV many configurations can be applied. Initially, the configurations were divided into six main categories:

conventional, multiple fuselages, blended wing body, airship, helicopter and the auto-gyro concept. After the first trade-off, the conventional and blended wing body configurations turned out to be the most suitable for the assignment. Within these two categories, three concepts are created and further investigated. These concepts are displayed in figure 20.1.

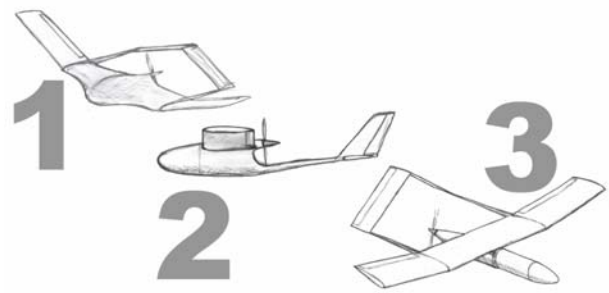



Figure 20.1: The blended wing body, conventional and modular fuselage concept

**Concept 1: blended wing body**

The blended wing is considered to be the best low drag configuration. When long endurance is considered, drag should be as low as possible. The difficulty of a blended wing is its highly unstable behaviour. To meet stability demands during system failure and to keep control systems simple a tail is added to this configuration, resulting in a blended wing with a tail. To provide sufficient volume for the payload and all other internal systems the centre part of the wing is made relatively thick.

The centre of gravity must be located in front of the aerodynamic centre for static stability. To achieve this, wing sweep must be applied to the wing for this concept. Unfortunately this will result in a more complex wing. To protect the vulnerable wing tips and increase stability, dihedral is applied at the wing section behind the tail support. To simplify the wing design as much as possible, sweep shall only be applied to these tips.

**Concept 2: conventional**

The conventional concept consists of a fuselage on which a push propeller is mounted. The single tail boom is fixed below the push propeller. This results in a simple layout of the aircraft by using a

single boom in combination with a push propeller. In this case the wing can best be mounted on top of the fuselage such that it can be straight and without sweep. Like for concept 1, applying positive dihedral to the wing tips can protect these vulnerable parts during the landing. Again for simplicity a conventional tail configuration is chosen.

**Concept 3: modular fuselage**
The philosophy behind this concept is to obtain an aerial platform with high payload flexibility. The fuselage is composed out of components that are easily interchangeable, which is important to be flexible in case of exotic dimensions of a new payload. For this modular concept, simple redesign of only a small part of the fuselage is possible and this new module can simply be connected to the UAV.

In this modular concept systems within the fuselage can easily be changed and shifted to obtain an acceptable centre of gravity position. The push propeller is placed at the end of the modular fuselage. The tail is mounted on two tail booms that are connected to the wing. The tail configuration chosen is the inverted V-tail. Because the tail is mounted on two booms, ground clearance is not an issue and it can be concluded that this is the most suitable tail configuration.

The wing is similar to that of concept 2, without sweep and mounted on the fuselage. The main difference is that in this case the wing supports the tail. Like concept 1, dihedral is applied at the wing section behind the tail support to protect the vulnerable wing tips and to increase stability.

## 20.4 Trade-off

The general layout of the UAV is chosen by use of a trade-off analysis on the 3 concepts discussed above. The most important criteria for the concept used for the trade-off where aerodynamic efficiency, ease of design, ease of use, payload flexibility and producability.
Especially the ease of design and producability criteria favour the last concept, but also on payload flexibility concept 3 gains most points.

Concept 3 is selected for the detailed design phase and is given the name SensAir.

## 20.5 Detailed design

The next section discusses the detailed design of concept 3, the concept that was found to be the best option after the trade-off was performed.

**Payload**

The most important part of the UAV is of course its payload. Since the UAV is designed to be flexible for several payload types and sizes, it is important to understand the effect on endurance when the payload is decreased.

The UAV is designed for a flight of 120 minutes carrying a payload of 0.5 kg at a cruise speed of 15 m/s. The range of the UAV during the flight at cruise speed is 108 km.

The modular design enables the UAV to carry different payloads. The range of the UAV is extended slightly for payloads lighter than 0.5 kg and the standard amount of batteries (1.6 kg). This is displayed in the payload-range diagram in figure 20.2. The Operational Empty Weight (OEW) consists of the weight of the complete UAV without payload and batteries. Without any payload and the standard amount of batteries the range becomes 121 km, which corresponds to a flight of 135 minutes.

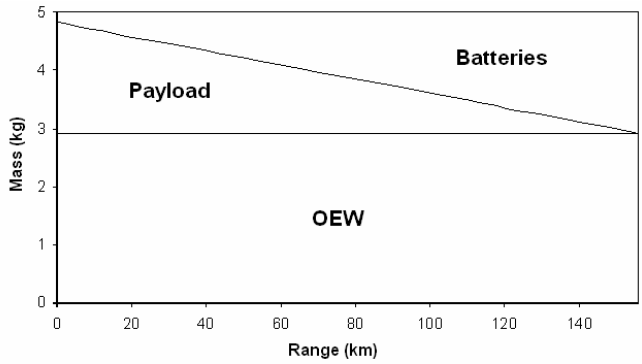



Figure 20.2: Payload-range diagram

The UAV is able to carry different payloads, because of its modular design. Of course it can carry a $CO_2$ sensor, which it was initially designed for. Examples of other payloads include (infrared) cameras and sensors for other gasses like $NO_x$ or $CH_4$.

**Construction layout**

To store the internal systems efficiently, a square shaped fuselage turned out to be more efficient then an aerodynamic round fuselage. A compromise resulted in a square fuselage shape with rounded edges. The walls of the fuselage are made of 1 mm thick Glass Fibre Reinforced Plastic (GFRP) for structural integrity. To absorb the impact loads from for example the landing additional stiffeners are incorporated to prevent the fuselage wall from buckling.

Inside the fuselage, foam will be placed at certain locations to absorb (impact) shocks and damp the vibrations of moving components such as the motor. Especially the payload should be well protected from possible damage.

An aerodynamically shaped nose module improves performance and is constructed of foam, which will disintegrate during frontal collisions to provide safety. An air intake in the nose module is used for the cooling of subsystems such as electronic components and the motor, but also for performing the atmospheric measurements.

The aft section of the modular fuselage houses the motor and the push propeller. Figure 20.3 displays the nose module, motor compartment and all internal systems of the fuselage that will be discussed next.

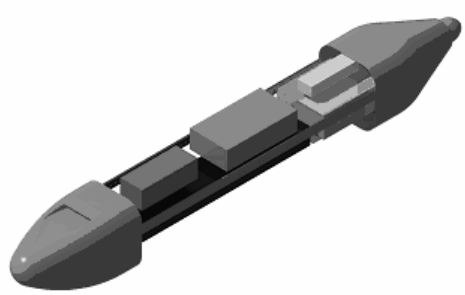


Figure 20.3: The fuselage section

The wing is placed on top of the fuselage via a rail to ensure a flexible centre of gravity position. An appropriate wing profile is the SD8040 with a thickness of 12%. For simplicity no dihedral and twist are applied. However, a taper ratio is applied to minimise the lift-induced drag. For the UAV to have a mass of 5 kg a wing area of 0.72 m2 and the wingspan of 2.24 m are needed.
Flaps have to be present on the UAV to decrease the minimum speed to 7.9 m/s and thus decrease the landing distance. The flaps are combined with the ailerons resulting in the use of two flaperons that are installed on the wing.

The tail is of the inverted V-tail type and is mounted to the wing by two tail booms to give a very rigid and light construction. Figure 20.4 displays the general layout of the SensAir UAV.

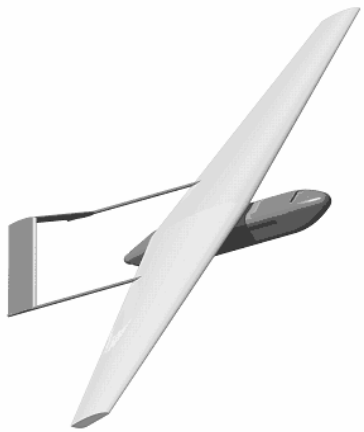


Figure 20.4: The SensAir UAV

**Control and communication architecture**
Since the UAV performs its missions autonomously the aircraft must be equipped with an autopilot. To reduce constraints on the autopilot the aircraft is designed such that the UAV is entirely stable by itself.
Before take-off an individual flight plan is uploaded from the ground station to the onboard mission planner of each UAV. The flight plan consists of chronologically predefined waypoints, which together encapsulate the entire mission. Once airborne, the autopilot flies to the first waypoint before proceeding to the next waypoint.
If desired, the operator can upload additional waypoints to each UAV individually during flight. Each UAV continuously sends its position

to the ground station. The ground station will also control the distance between the UAVs to avoid collisions in the air. If one or more UAVs are approaching each other the ground station temporarily overrules the onboard flight plans and uploads collision avoidance commands to the involved UAVs.

**Propulsion**

The exhaust gasses of a regular combustion engine will influence the measurements. Therefore the propulsion of the UAV is provided by a brushless electric motor rated at a maximum input power of 330 W.

The propeller is chosen to be of the folding propeller type. This increases safety since the blades will fold back when the motor is turned of. This way the blades cannot hit the ground during the landing. A very strong carbon fibre propeller is chosen.

**Batteries**

A lot of energy is needed on the SensAir UAV since it has an electric motor and must be able to fly for two hours. The motor gets this energy from one battery pack made of lithium polymer cells, because of the high energy density of these cells. Also a lot of other devices need energy, for example the avionics. Another battery pack of lithium polymer cells will be installed to satisfy this need.

**Emergency device**

To meet the safety requirement a parachute is installed on the UAV. The parachute is of a simple circular design, such that it is easy to build, and it is stored in the centre part of the wing. It is only activated in case an emergency situation occurs after which the UAV is unable to continue its mission due to for example loss of control or a power problem of the UAV. The parachute is activated by means of a small servo that runs on an auxiliary battery. Figure 20.5 displays the deployed parachute of the SensAir UAV.

Figure 20.5: The SensAir UAV with deployed emergency parachute

**Performance characteristics**

In order to avoid damage during flight a flight envelope must be determined in which it can operate. This flight envelope limits the speed V as well as the load factor n. The maximum allowable load factor is +/- 6 g for the onboard electronic equipment. This is derived from the critical load factor of +/- 10 g and taking into account a safety factor of 1.5.

The airspeeds corresponding to the positive and negative load factors are depicted in figure 20.6. Additionally the flight envelope in flaps down configuration is included in the figure as well.

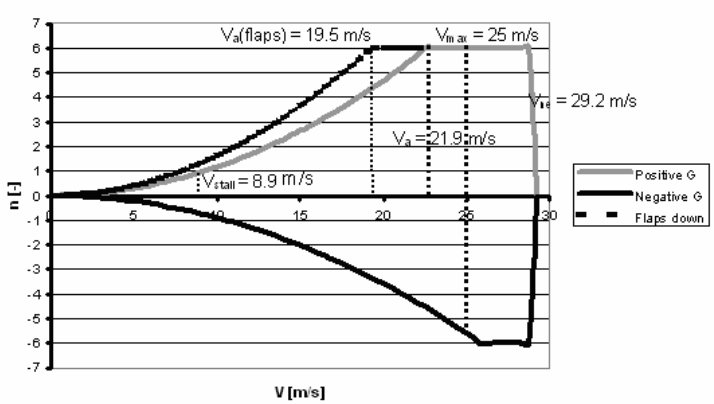



Figure 20.6: The flight envelope of the SensAir UAV: speed versus load factor

**Launch and landing**

The UAV has to be assisted during the launch because it has no landing gear. To avoid free movement of the UAV during the acceleration, a rail should be used. The rail provides guidance to the aircraft during the period when the control surfaces do not have sufficient control authority. Use of a rail also reduces the chance of human error and puts only minor constraints on the terrain.

To make sure the launch rail is not of excessive length the UAV has to be externally accelerated. This is done by a bungee that can easily be interchanged. Using this option the launch rail becomes 2 m long. Besides no real constraints are being placed on the take-off area.

For the landing the UAV uses its belly. This is not the most proper solution because of the shock loading on the instruments, but it is the easiest to implement. The UAV will fly to a predefined landing waypoint from which it will glide down to the landing field. During this approach the flaperons are fully extended and the motor is switched off such that the propeller folds back.

## 20.6 Conclusion

SensAir is a complete system for performing aerial missions for payloads up to 0.5 kg. It can operate a single UAV or operate multiple UAVs in a swarm. Its strength lies in its modular design. It allows different payloads for different missions without extensive adjustments.

Measuring $CO_2$ concentrations to enforce the Kyoto protocol is possible using this system. Expanding the sensors to also measure other greenhouse gasses can easily be done because of the modular design. Figure 20.7 represents a complete swarm of UAVs that can be deployed in the future to take various measurements and to make our world a better one.

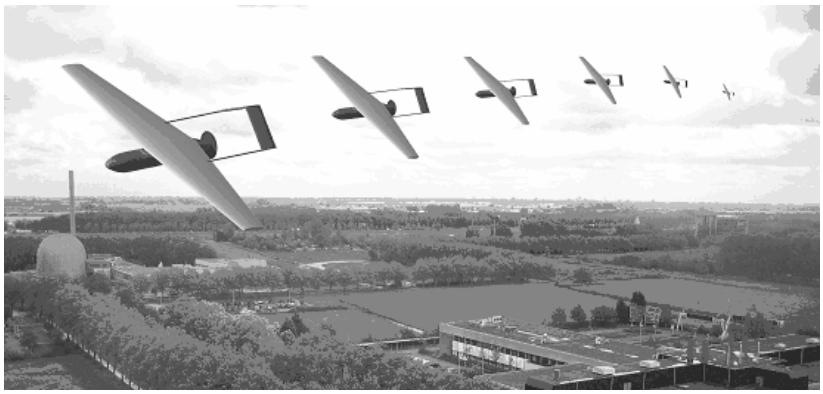


Figure 20.7: A swarm of UAVs taking measurements above Delft

# 21. THE FUTURE OF HIGH SPEED COMMERCIAL AIR TRAVEL

*Students:* S. Amusa, N.L.Bradshaw, L. Bruin, P.A.L. Dhaeze, K. van Drimmelen, A. van der Eijk, J.P.N. Flores, Th. Mathot, J.C. Raterink, O. de Swart

*Project tutor*: prof.dr.ir. S. van der Zwaag

*Coaches*: ir. J.T.P.J. Berends, ir. F.F.J. Schrijer

## 21.1 Introduction

Time is scarce in modern society. People are trying to gain time by stretching the boundary of technology to the extreme. Since the industrial revolution, the concept of "time is money" has been an important aspect in the way of life, especially in western society. Modern world requires time to be used efficiently. That is why many activities, which were time consuming in the past, have been cut down to a minimum by changing their mode of operation. This effect can also be seen in our travelling habits. Faster means of transport are being introduced, for example high-speed trains. This trend has not yet manifested itself in civil air transport systems. When Concorde went out of service in 2003, the speed at which people could travel long distances reduced dramatically. The main passengers group for the Concorde were the business passengers for whom time is money. This can be seen in the growth of the business jet market, which has been booming in the recent years. It shows that business travellers are willing to spend vast amounts of money to save time.

## 21.2 Mission statement

*Given the constraints of time (ten weeks), resources (ten persons), and skills (BSc. level students), investigate and develop perspectives, strategies and concepts for different classes of commercial air transports flying faster than the speed of sound. Assess the feasibility, viability and sustainability, using proven and state-of-the-art technology as well as expected technological progress in relevant areas.*

## 21.3 Company "Beyond Mach"

There is a demand from the market for faster means of civil air travel. The established manufacturers do not for see in this need. They are bounded by the sonic boundary, which they are not willing to cross due to a multitude of reasons. The most prominent reason is that current manufacturers have an extensive experience with subsonic aircraft and the development of successful supersonic aircraft will not increase their market share; they will be competing with their own products. Therefore the virtual aircraft manufacturer "Beyond mach" is introduced which aims to build high-speed air transport systems.

## 21.4 Market study

A detailed analysis of the market has been done in order to find out what the customer requirements are and if the product can be profitable from an operational point of view. The market outlook of numerous aircraft manufacturers, including Boeing and Airbus, predict that the volume of passengers carried by the airlines worldwide will continue to grow by 5% a year. A part of this growing market will be reserved for supersonic flight.

It can be stated that short range will not be economically feasible, because the distance is too short to win a large amount of time to compete against subsonic aircraft. It is predicted that the North

Atlantic, Europe-Far East and North and Mid Pacific flight routes will form the largest market for medium range flight routes.

## 21.5 Design requirements

For a starting aircraft company it is hard to gather start capital. Therefore Beyond Mach will produce a small supersonic aircraft first. With the profit of this first aircraft, a larger and more technically advanced aircraft can be produced. Finally the company will define the future standards by producing highly advanced aircraft. Therefore the requirements shown in table 21.1 are set for the short term, long term and future projects of the Beyond Mach company:

| Project | Short | Long | Future |
|---|---|---|---|
| Speed (Mach) | 1 – 2 | 2 – 3,5 | 3,5 and above |
| Passengers | 10 – 50 | 200 and more | To be determined |
| Range (nm) | 3000-5000 | 3000-5000 | 5000 and above |

Table 21.1 Requirements for short term, long term and future projects

Constraints: the aircraft need to comply with safety, noise and emission regulations.

## 21.6 Available technologies

Supersonic flight challenges technology. Thorough research is done on the technologies available for supersonic flight. The technology is divided in three areas: aerodynamics (sonic boom reduction as well as drag reduction), propulsion and materials. The following most important options are found:

Aerodynamics:

- Pelican nose
- Quiet Spike
- Formation flying

- Flying out of the atmosphere
- Canard configuration
- Area rule
- Morphing wing
- Delta wing
- Lifting body (wave rider)
- Swept trapezoidal wing

Propulsion:

- Turbojet
- Turbofan
- Pulse detonation engine
- Ramjet
- Rocket
- Hybrid engines (two or more types of engines combined into one single engine)

Materials:

- Metals
- (Non-) Ferrous alloys
- Polymers
- Ceramics
- Composites
- Fibre metal laminates
- Carbon nano tubes

## 21.7 Concept development and selection

From the given requirements for range, speed and passenger capacity concepts are generated for each of the three projects. For the first two projects, short term and long term, the same approach is used. For the third project a slightly different approach is used to generate concepts, because of their flight characteristics.

With the use of the design option trees of the available technologies, straw man concepts are generated for the short term and long term project. From the straw man concepts, obvious losers are eliminated.

For the remaining concepts a trade-off is made. For the final chosen concept a material and propulsion system is chosen, again with the use of a trade-off. The chosen concepts are named after the company Beyond Mach and their respective cruise speeds, resulting in the BM160 for the short term and the BM240 for the long term projects. Below a first impression can be found for the BM160 and the BM240, their characteristics can be found in table 21.2.

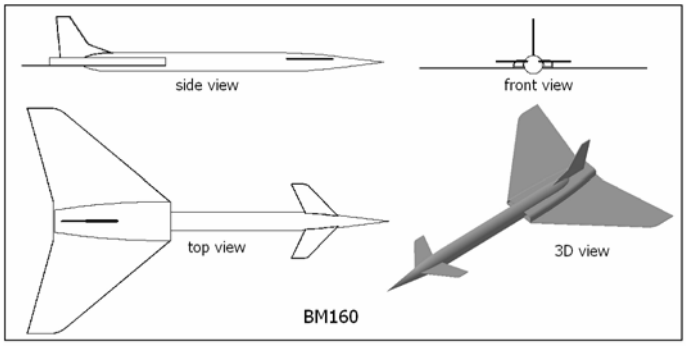



Figure 21.1: 3-view and 3D-view of the BM160

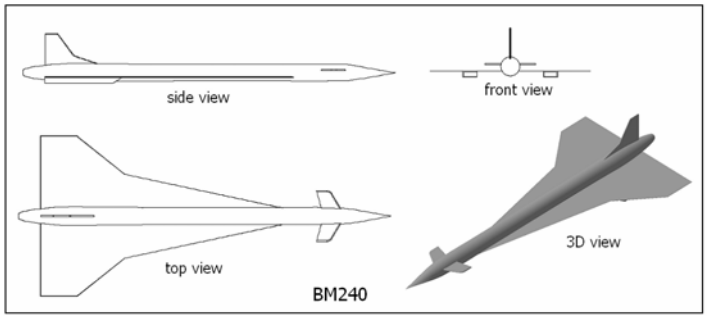



Figure 21.2: 3-view and 3D-view of the BM240

For the future projects first a flight path is chosen. From this, the best option for an engine is selected. Because the engine choice affects the start and landing phase, these are chosen next. At last some options for materials are researched. Promising options are carbon carbon composites and carbon nano tubes. The material(s) to be selected will depend on future developments. From both the trade-off and the company interest, two concepts are chosen. These chosen concepts are named after the company Beyond Mach and their respective dates of entry into service, resulting in the BMFuPro50 and the BMFuPro70.

Below a first impression can be found for the BMFuPro50 and the BMFuPro70, their characteristics can be found in table 21.2 as well.

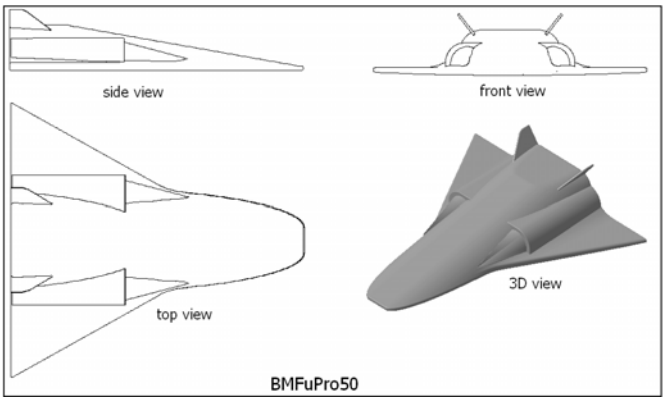



Figure 21.3: 3-view and 3D-view of the BMFuPro50

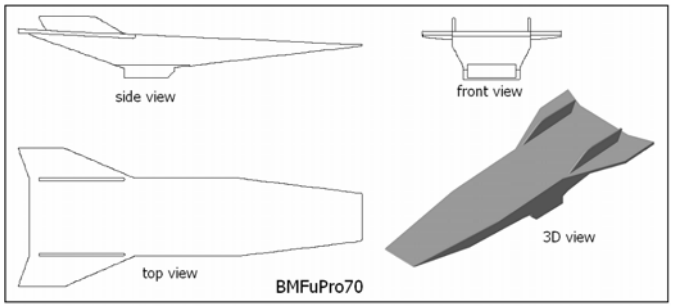



Figure 21.4: 3-view and 3D-view of the BMFuPro70

| Airplane | BM160 | BM240 | BMFuPro50 | BMFuPro70 |
|---|---|---|---|---|
| Range (nm) | 4.000 | 5.000 | 7.000 | 7.000 |
| Speed (Mach) | 1,6 | 2,4 | 3,9 | NA |
| Max. Pass. | 50 | 250 | TBD | TBD |
| Engine | Mid-tandem fan | Mid-tandem fan | Ramjet | Scramjet |
| Fuel | Kerosene | Kerosene | Hydrogen | Hydrogen |
| Material | PMC | PMC | TBD | TBD |
| Purchase price (US$ FY2004) | 150 | 230 | TBD | TBD |
| Entry into service | 2017 | 2027 | 2050 | 2070 |

TBD = To Be Determined NA = Not Applicable

Table 21.2: Characteristics of the Beyond Mach product family

## 21.8 Family of products

The strength of the company Beyond Mach is that it will produce a family of aircraft. The first aircraft it will produce is the BM160, which can be used either as a business jet or used as a passenger carrier operated by airlines. The BM160 will use existing technologies and is designed to be able to operate at small airports. Therefore the BM160 will entry into service as early as 2017. The follow up of the BM160, called the BM240, will be available in 2027. Although it is a more ambitious project (faster, larger, longer range etc.) development-time, -cost and -risk are reduced by using the knowledge and experience gained from the development and production of its predecessor. Furthermore can established contacts with customers and suppliers be used and development costs can partly be covered by the profit of the BM160.

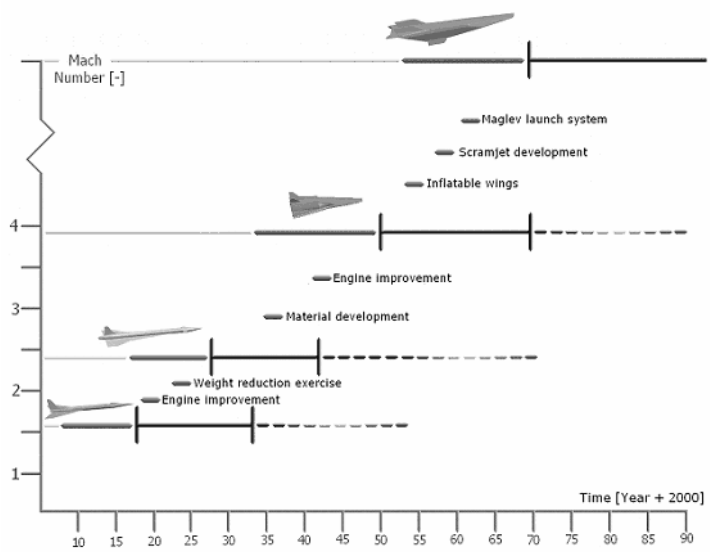



Figure 21.5: Beyond Mach product family timeline

As a company it is always good to look into the future and be one step ahead of the competition. Therefore the department of future projects researches what will be possible in the future. The BMFuPro50 will be the result of 30 years of supersonic flight. Using this experience it will be able to fly even faster (Mach 3,9) and travel over a longer distance (7000 nm). The BMFuPro50 will be the view of the company on

commercial air travel for 2050. With the BMFuPro70, Beyond Mach looks even 20 years further into the future. Development stages accompany the transitions between the aircraft. Figure 21.5 shows a picture of the timeline for the four products.

## 21.9 Detailed design

The BM160 is designed in more detail to determine its cabin layout, weight, wing loading and wing characteristics. The BM240 and BMFuPro-series are not further elaborated yet, because first the BM160 will be developed and evaluated.
It is based on current business aircraft, supersonic bombers, Concorde and several design studies. The results of detailed design are stated in table 21.3.

| Parameter | | Value | |
|---|---|---|---|
| Fuselage diameter | $D_f$ | 2.44 | [m] |
| Overall length | l | 48.14 | [m] |
| Overall height | h | 6.61 | [m] |
| Maximum takeoff weight | $W_{TO}$ | 1,007 | [kN] |
| Thrust/Weight ratio | T/W | 0.27 | |
| Wing loading | W/S | 3,200 | [N/m2] |
| Wing area | S | 314.8 | [m2] |
| Thickness | t/c | 0.045 | |
| LE sweep | $\Lambda_{LE}$ | 50 | [°] |
| Quarter chord sweep | $\Lambda_{0,25c}$ | 44.1 | [°] |
| Semi chord sweep | $\Lambda_{0,5c}$ | 36.8 | [°] |
| TE chord sweep | $\Lambda_{TE}$ | 16.8 | [°] |
| Taper ratio | $\lambda$ | 0.2 | |
| Cantilever ratio | | 25.0 | |
| Aspect ratio | A | 3.0 | |
| Wing span | b | 30.73 | [m] |
| Root chord | $c_r$ | 17.1 | [m] |
| Tip chord | $c_t$ | 3.41 | [m] |
| Ground noise level | | 54 | [dB] |

Table 21.3 Detailed design results for the BM160

## 21.10 Conclusion

Beyond Mach developed concepts, containing proven and state of the art technology as well as expected technology progress, for different classes of commercial air transport flying faster than the speed of sound. It also describes the team its perspective on the best strategy to develop and produce these concepts in a feasible, viable and sustainable way.

The virtual aircraft company Beyond Mach is introduced because the established manufacturers do not want to produce supersonic aircraft. Producing supersonic aircraft will not increase their market share; they will be competing with their own products. Introducing a new company seemed to be the only solution to a feasible and viable future for high-speed commercial air travel.
The four aircraft of Beyond Mach will form a family in which technology, experience, financial means and contacts with customers of the previous project can and will be used on the next, more ambitious projects. This approach is used to reduce development-time, -cost and -risk, increase sales, improve collaboration with suppliers and reduce the amount of required outside money.

Beyond Mach will be the first to develop and build the next generation of commercial passenger aircraft that will fly faster than the speed of sound. Beyond Mach will in this way fulfil the fundamental need of the travelling human to reduce travel time, and take the leading role in this market!

# 22. INTERCEPTOR UAV 'HYPERION'


| | | |
|---|---|---|
| *Students:* | TU Delft:<br>J.L.G. Bonten, G. Gielen, B. Lubbers, G.J.J.M. Pauwels, J.G.R. Verbeke<br>Queen's University of Belfast:<br>D.E. Crummey, G.J. Davies, J.W.W.E. McCartan, S.M. McGuinness, O.P. O'Loan, G.M.T Winters | |
| *Project tutors:* | TU Delft: | ir P.C. Roling |
| | Queen's University of Belfast: | Dr. R. Cooper |
| *Coaches:* | TU Delft:<br>Ir J. Breukels, ir P. Joosten<br>Queen's University of Belfast:<br>Dr. E Benard, Dr. R. Curran, Dr. J. Early, Dr. M. Price | |


## 22.1 Introduction

Air travel is one of the safest ways to travel across the world. Nevertheless, a number of problems are still present, and in order to keep air travel safe there is an everlasting search to improve and maintain safety. One very current issue in aviation is the intercepting, escorting and observing of civil aircraft in distress, especially aircraft, which have lost communication or have problems with passengers or systems such as the landing gear.

Current practice in these situations is the scrambling of fighter aircraft. The international design synthesis exercise team consists of students from Queen's University of Belfast (QUB) and Delft University of Technology (TUD). The Aim of this team is:

*To produce a preliminary design of an Interceptor Unmanned Aerial Vehicle (IUAV) as a viable and more efficient alternative to this current solution. The Unmanned Aerial Vehicle should be able to intercept, communicate with and observe airliners, while being reusable, autonomous and remote controlled and cost approximately € 1 million.*

## 22.2 Requirements

The task put upon the design team is to produce a preliminary design of an IUAV. Therefore, a list of requirements has to be found to obtain all criteria the IUAV needs to comply to.
The most important requirements the IUAV needs to satisfy are set by the customer. These are divided in several categories:

Design requirements
- Unit production cost: ~1 million euros

Mission requirements
- Time to take off < 5 minutes
- Maximum flight range > 1800 km
- Maximum endurance > 3 hours
- Ceiling > FL420
- Maximum Cruise Speed > Mach 0.85
- Disabling a commercial airliner, possibly by sacrificing the UAV

Payload requirements
- Near 360 x 180 degree (multiple) camera view
- Autonomous and remote controlled flight
- High stability and recoverability for flying in close formation with aircraft
- On board transponder / Traffic detection and collision avoidance system.

Secondary requirements
- Operational concept for EU coverage, including estimations of interception times.
- Assessment of alternative uses for this vehicle (military operations, civil operation etc.)

Sustainability

- The UAV should be proven to have lower costs, lower environmental impact and be better suited for an interception mission than a fighter aircraft, as the F-16.

Although the customer requirements dictate in a large part the direction taken in the design process, these are not the only driving factors. In order to be able to perform the task of intercepting, observing and escorting airliners in a satisfactory manner, one must be able to partake in air traffic in a safe and sustainable way. It would indeed be a paradox to produce an aircraft with the task to benefit the safety of aviation, which itself is a danger to others on land and in the sky; hence the aircraft should also comply with all applicable airworthiness requirements and appropriate laws.

## 22.3 Concept study

After having obtained all requirements, concepts are developed and a trade-off is performed. In this exercise four conceptual designs have been developed and are displayed in Figure 22.1. These were:

1. The supersonic conventional concept
2. The delta wing with canard concept
3. The subsonic conventional concept
4. The blended wing body concept

**The supersonic conventional concept**
This concept is able to fly at supersonic speeds, thereby reducing the time needed to intercept an aircraft. The general layout resembles that of a conventional aircraft with a classic tail and the engine is located at the bottom of the fuselage, as is the air intake. It takes-off from a launch platform using a rocket and is recovered by parachute. Cameras are placed in the nose to ensure a 360x180 degree view to the front of the IUAV.

**The delta wing with canard concept**
This concept flies at supersonic speeds. It has a delta wing, making it more efficient in the transonic regions compared to a conventional

wing plan and reducing the wave drag in the supersonic regime. It has canards placed above and in front of the wing for stability and manoeuvring, making the IUAV highly manoeuvrable. The engine is at the back of the fuselage and the intake at the bottom of the IUAV. Take-off and landing are conventional using a landing gear.
One camera pod, having a 360x180 degree view, is located in the front and the other aft of the air intake, giving an 180x90 degree view to the back. Also, a forward-looking infrared camera (FLIR) is placed in the nose. This is fixed and will always give the pilot on the ground a forward view.

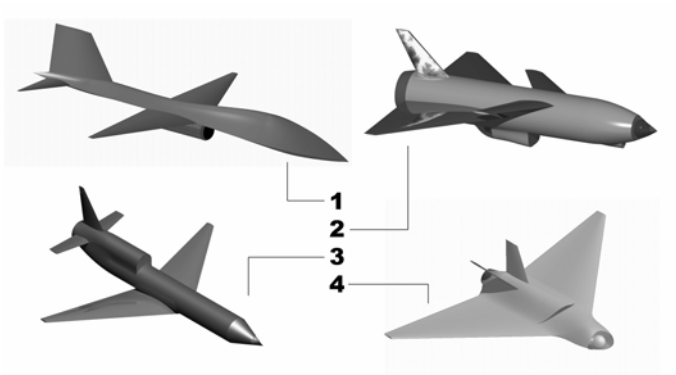



Figure 22.1: The four conceptual designs

**The subsonic conventional concept**
This concept flies at low transonic speeds (below Mach 1) and has a conventional layout with vertical and horizontal tail planes. The engine is located high up at the rear of the fuselage and has the intake on the top. Also, it has a landing gear, making conventional take-offs and landings possible.
There is one camera in the nose, giving the IUAV a 360x180 degree view, and one in the tail, enabling the operators to look aft of the vehicle. The strong point of this concept is it's ease of design and the proven technology used.

**The blended wing body concept**
This concept also flies at low transonic speeds. Its wing is located at the back and it has a V-tail. The wing and body are blended, making the IUAV aerodynamically more efficient. The engine is located in the rear of the fuselage and has its intake on top. It uses a rocket-assisted take-off and parachute recovery.

Both cameras are placed in the nose with one looking forward, giving a 360x180 degree forward view, and one looking down and back, giving it an aft view at an angle of about 10 degrees.

When the conceptual design phase is completed, a choice is made on which concept moves into the preliminary design. In order to make this decision, a trade-off study is performed. Each concept discussed above exhibits its own benefits and drawbacks. The trade-off has distinguished between the concepts and determined the final concept to be developed.

## 22.4 Supersonic dilemma

The supersonic dilemma has run across the entire project, the designs and through many decisions taken. Was the IUAV to cross the sound barrier or not? For the final design it is decided that Mach 1 would not be a design goal. This course is taken with care.
The mission of the IUAV is fast interception. Hence a supersonic plane has an advantage. However it can be seen in table 22.1 that the intercept distances for 15 or 30 minutes do not differ significantly. This can be explained by the fact that the time a supersonic design is able to fly above Mach 1 is limited due to, amongst others, the fact the IUAV must climb to the appropriate altitude and is hence not able to attain supersonic speeds directly.

| | Supersonic design | Subsonic design |
|---|---|---|
| 15 (min) intercept time | 140 km | 140 km |
| 30 (min) intercept time | 440 km | 390 km |

Table 22.1: Intercept distances for different intercept times

It is true that a supersonic design will be able to gain faster on an airliner, even one flying away from the IUAV. However, in order to assure an infallible and fast interception throughout Europe at least 2 or 3 IUAVs on different locations need to be scrambled to intercept a single target. This insures that at least one IUAV will always be able to

intercept the aircraft within the specified intercept time independent of the target's manoeuvres. Hence the need for supersonic speeds can be disregarded.

## 22.5 The Hyperion design

The trade-off resulted in a table showing each concept's strengths and weaknesses. The most optimum concept was the blended wing body. However, several strengths from other concepts were incorporated. The resulting concept is called the Hyperion. Hyperion is a Greek Titan and is considered the 'God of Observation' and is the brother of Theia the 'Goddess of Sight'. This was deemed an appropriate and dignified name for the IUAV, as observation is its main task. Here an overview of the final design is given

The Hyperion is a single-engine UAV with characteristics, which make it particularly suitable for the interception mission. It encompasses systems that allow the Hyperion to fly autonomously as well as remote controlled. Telemetry and all other data transfer between ground station and IUAV will be by UHF/Ku-band radio link. This link will provide enough bandwidth to accommodate the data that needs to be transferred. Cameras, placed in the front and rear of the IUAV, offer proper views of the intercepted aircraft in all flight interception scenarios, using interception regulations that follow from ICAO regulations. A landing gear is incorporated in the design, as it will increase the flexibility. Four views of the Hyperion can be seen in figure 22.2. The Hyperion will take-off in less time than a fighter aircraft, when scrambled. It will then accelerate to an optimal climb speed, after which an optimal climb is initiated in the direction of the aircraft to be intercepted. At cruising altitude the Hyperion will level out, accelerate to maximum cruise speed and intercept the aircraft. Once arrived at the aircraft it will perform its mission, observation or escort, and subsequently land by using the instrument landing system (ILS).

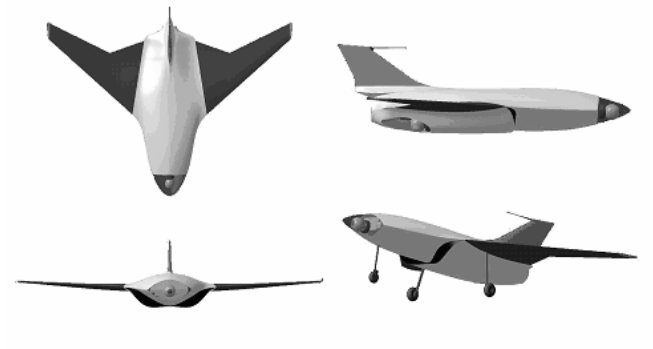


Figure 22.2: Four views of the Hyperion

## 22.6 Layout and systems

This paragraph will provide an insight in the design philosophy, and a clarification of some design decisions taken.

The Hyperion must be able to fly autonomously and be remote controlled. Therefore it has advanced avionic systems on board. These are mostly commercial of the shelf (COTS) products and are located in modules in the front of the fuselage. Fuel is located in the wings and in several tanks in the fuselage. The landing gear is also located in the fuselage (Figure 22.3).

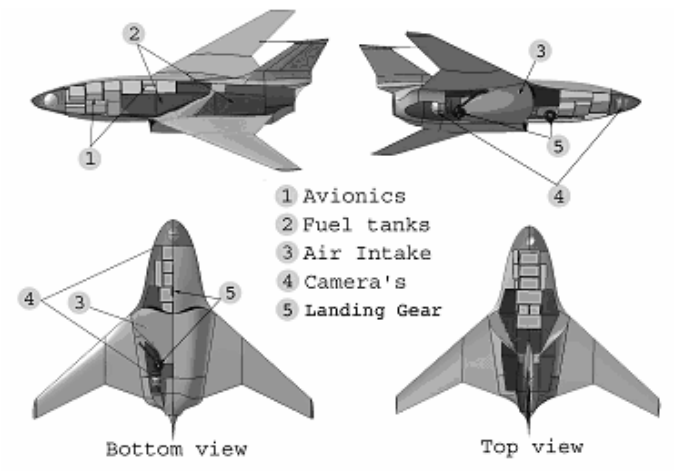



Figure 22.3: System layout of the Hyperion

**Take off and recovery method**

The advantage of a rocket assisted take-off (RATO) is the reduced time needed to take-off. However, as is shown in section 22.4, this will not necessarily mean a greater intercept distance. The advantage of a parachute recovery is the flexibility in putting the IUAV down. It can be done at any location, not only airfields. Also, in case of an emergency the IUAV can be landed immediately, without first flying to an airfield. Note however that RATO and parachute landing requires extra support equipment, such as a take-off and recovery vehicle, is needed and the operational costs would hence rise slightly. The Hyperion has a landing gear to decrease turn-around time and make the IUAV easier to operate, reducing extra support equipment. The Hyperion can refuel at any airfield and commence operation again while a parachute and RATO operated UAV needs service at designated stations before it is operational again, reducing speed and flexibility.

**Air intake**

Hyperion's air-intake is located between the fuselage and the bottom of each wing. This reduces drag and prevents airflow problems during high angles of attack. This inlet configuration also has a good efficiency in the speed regime that the UAV will operate in.

**Cameras**

The camera placement is selected in such a way as to have as much coverage as possible, while being positioned in the airframe as to produce as little drag as possible. The first observation pod is located in the Lexan nose giving a 180° x 360° view to the front. The second observation pod is located aft of the right air-intake. This makes it possible to observe the aircraft when flying in front of it during standard interception operations. The FLIR camera in the nose is fixed, always giving a controller on the ground a view in the direction of flight, even when the forward camera pod is directed away. The optical suit consists of two IAI Taman MiniPOPs and a ThermoVision EVS1000 FLIR-camera. The MiniPOP incorporates visible and infrared light cameras to enable operations in day- and night time.

**Laser-rangers**

Laser-rangers are installed in the camera gimbals to measure the distance between the Hyperion and the target aircraft with high

accuracy. This is needed for a safe escort and will allow the IUAV to fly close to the intercepted craft without sacrificing safety.

**Autonomy**

It is very important that the IUAV is able to fly autonomously. This greatly increases the flexibility and speed of the interception. The specific issues of a remotely and/or autonomously operated vehicle increase the need of specialized equipment over manned aircraft and conventional UAVs that operate under continuous monitoring of ground control. Therefore systems to improve situational awareness that are normally not present on UAVs are used in the Hyperion design. Also, special care is taken to ensure safe autonomous flight.

**Communication**

Data transmission of flight data and camera images is done via line-of-sight radio-link. The range of the Hyperion will be 360 km from the launch site, however another IUAV can act as a relay station, extending the range. Satellite communication is possible but omitted in this design, mainly due to cost limitations.

**Safety**

Sufficient flight control systems are present in the Hyperion, to ensure safe autonomous flight. However, for safety reasons the IUAV must be able to recover automatically in the event of a loss of the communication link. This has been considered and a proper procedure has been established for a safe recovery.

| Parameter | Value |
|---|---|
| Aspect ratio [-] | 4 |
| Wing area [m2] | 3.78 |
| Wingspan [m] | 3.89 |
| Mean wing chord [m] | 1.04 |
| Quarter chord sweep [°] | 40 |
| Taper ratio [-] | 0.16 |
| Thickness/chord ratio [-] | 0.1 |
| Fuselage length [m] | 2.65 |

Table 22.2: Parameter values of the Hyperion

After performing investigations into the aerodynamic and stability characteristics of the Hyperion, a final wing plan and control surface

sizing is found. Some parameter values become known (table 22.2). And Hyperion's planform is determined (figure 22.2).

## 22.7 Performance

The Hyperion complies with all requirements set upon it. Some performance characteristics are shown in Table 22.3.

| Parameter | Value |
|---|---|
| Maximum range [km] | 2,580 |
| Maximum endurance [hrs] | 3.5 |
| Ceiling [ft] | 50,000 |
| Maximum cruise speed [-] | Mach 0.9 |
| Unit production cost [€] | 1,325,000 |

Table 22.3: Performance of the Hyperion

## 22.8 Operational concepts

The IUAV should be able to disable an airliner. Yet, there are some legal boundaries that limit the use of this ability and therefore no offensive weaponry is carried. However, the Hyperion can use its laser-ranger to fly into a hostile airplane with great accuracy, sacrificing itself.

For the coverage of the European Union (EU) three scenarios were taken into account. The most economically and politically viable is the scenario where 23 ground stations are required (Figure 22.4). At each ground station at least 3 IUAVs are based, each with an interception range of 360km (within communications range).

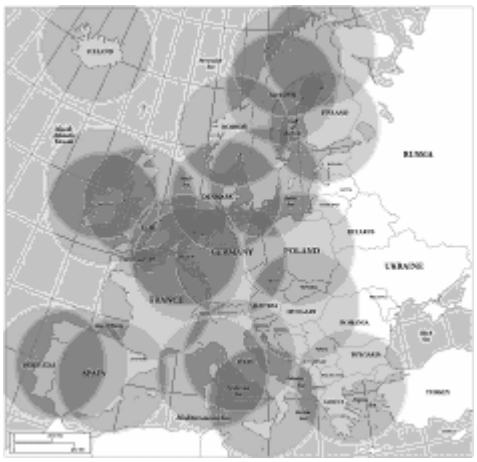



Figure 22.4: EU coverage concept

The Hyperion is designed to perform quick reaction alert (QRA) missions. However, it can also be used for other (para)military, public and commercial applications, such as search and rescue (SAR) or surveillance operations. In its SAR capability, the Hyperion is particularly apt in performing time-critical search assistance. Its quick reaction time and high speed allow for an unmatched time to target.
Surveillance applications can include detection and mapping of forest fires, performing border patrols, monitoring disaster or pollution areas or smuggling activities. It can also be used for combat reconnaissance and support, such as target designation or damage assessment.

## 22.9 Conclusions and recommendations

The Hyperwork's Hyperion is a viable solution for cheap and fast interception of airliners. The Hyperion is a single engine IUAV that is able to fly with a high degree of independence from direct operators. It has gimbals on board which carry cameras and laser-rangers. They are able to accurately observe the intercepted airliner, furthermore they can determine and maintain distance to an airliner. An UHF/Ku-band radio data link enables the data transfer of telemetry and video images between IUAV and ground station.

All requirements set upon the IUAV are met. With its cruise speed of Mach 0.9, its operational ceiling of 50,000ft (15.2 km), range of 2580 km

and its endurance of 3.5 hours, Hyperion exceeds the requirements. The Hyperion costs around € 1,325,000 for an approximation of 202 sold units. From the performance characteristics it is clear that the Hyperion design can be regarded as a good foundation for further detailed design.

Since the Hyperion is only designed in a preliminary stage, further research and design is necessary. Two of the research topics are the transportation of explosives through civil airspace and market research into search and rescue and disaster area assessment. This market research improves the economic viability of the Hyperion design

Furthermore, an increase in the use of composites such as composite wings would be beneficial. Composite wings decrease the structural weight and the risk of fatigue. The last recommendation is to further optimize and more accurately determine the aerodynamic characteristics of the Hyperion by performing wind tunnel tests and Computational Fluid Dynamics (CFD) calculations.