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THE DESIGN SYNTHESIS EXERCISE: PROJECT EDUCATION AT THE FACULTY OF AEROSPACE ENGINEERING, DELFT UNIVERSITY OF TECHNOLOGY

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ABSTRACT

The Design/Synthesis Exercise (DSE) is the capstone project for the Bachelor of Science program at TU Delft, Faculty of Aerospace Engineering. This paper highlights its conceptual foundations, as well as the project management and systems engineering aspects involved throughout the 10-week full-time exercise. Two DSE projects – one aircraft-related, one spacecraft-related – are presented to give insight into typical design processes and associated outcomes observed in DSE projects.

1. Introduction

The Design/Synthesis Exercise (DSE) is the concluding project of the BSc program at the Faculty of Aerospace Engineering (FAE), Delft University of Technology (DUT), and is considered to be the final thesis of the bachelor students. It was initiated by the faculty in 1997, and has been organised as a three-month, full-time group design project. In the first year, four groups of ten students participated, and the number of groups has gradually grown over the years, from 15 in 2002 to about 30 from 2017 onwards. The exercise is organised twice a year, i.e., in the Fall and Spring semester. The main learning objectives for the exercise are to improve the design skills of students by developing skills in teamwork, communication, project management and systems engineering, and sustainable development, by applying the knowledge and skills they acquired throughout the BSc. In Figure 1 the setup of the BSc curriculum is shown, and how the DSE fits into this.

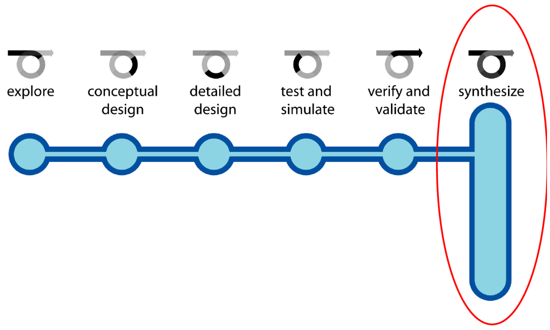

Figure 1 – Layout of the BSc curriculum (FAE, DUT).

Before the initiation of the DSE there was already an existing design exercise. Participation was limited to students graduating in a design specialisation. Design assignments were limited to aircraft designs only. In the late 1990s the curriculum was reformed and the DSE became the thesis project of the Bachelor degree program. It thus became compulsory for all students. From then on, also space-related design projects and designs focussing on wind energy became available to the students.

The DSE is an exercise that involves quite a number of people. The organisation is headed by a six-person organising committee. They coordinate the whole exercise. All student design groups are chaired and coached by a team of three staff members. From these three, one is the so-called principal tutor. He or she comes up with the design assignment for the team, and is further supported by two coaches. By definition, both principal tutor and coaches have to come from different fields of expertise. This guarantees a multidisciplinary coaching team. Furthermore, the organisation is supported by a team of teaching assistants, who take care of practical logistics and help the student design teams with assessing their performance in project management and systems engineering, of course under supervision of members of the organising committee.

At the end of the exercise students are given the opportunity to present their work for a larger audience in a one-day symposium. The audience consists of their fellow students, staff members and an international jury. The students can also invite their parents to attend. The international jury judges the presentations and determines who wins the DSE challenge trophy, but the jury grading does not count towards the final grade of the exercise itself. Furthermore, all design teams write a chapter for a book that is published after the DSE.

The principal tutor leads the design project and, as mentioned, he or she typically is also the one who comes up with the design assignment. However, external parties (companies, research institutions) and even students themselves can also come up with ideas for this. Every design assignment has to be written down in a uniform template, and are then passed on to an external quality assessment committee. They review the assignments on content, but also on the level of difficulty. In that way, there is a consistent, uniform level for all assignments, despite the broad range of design topics. Examples of past topics are:

- High-altitude VTOL rescue
- Thin haul transport and air taxi
- Water bomber UAVs
- Aircraft maintenance drone
- Returning to Saturn to characterise the icy moons and rings
- Demonstrator for airbreathing electrostatic propulsion, Earth observation satellite
- A personal air mobility vehicle as maritime pilot shuttle
- A stratospheric balloon as operational and test platform for Earth observation.
- Development of a secondary rotor wind turbine
- Low-cost system for stratospheric aerosol injection

- Adaptive Regional Airliner
- eVTOL emergency aircraft

Once all assignments have passed quality control, the principal tutors can present their project to the students. This takes place in a half-day session where all principal tutors are given the opportunity to introduce their design project with a five-minute pitch. After that session all students are required to express their interest in the projects by ranking them. With the help of a smart algorithm the preferences of the students are matched with the available projects. In this way students can be assigned to a design project that is high on their preference list (normally students are assigned to projects in the top 25% of their list).

After the students have been notified to which design team they are assigned, the work can start. The kick-off forms the start of an intense ten-week period for all staff and students involved.

2. Project Management and System Engineering

The DSE is aimed at a synthesis of knowledge and skills of the aerospace BSc Curriculum after (nominally) 2.5 years), and is centred around the design of an aerospace-related product, i.e., an aircraft, spacecraft, or wind turbine. The outcome of the exercise is a conceptual design, on paper. Prototypes are not required. The designs are based on system and mission requirements that could be provided by an external customer from, for instance, industry or a research institute. The design is much more than to simply conceptualise, draw or dimension; it is to come up with a solution for a problem/assignment in a structured way: the analysis of the problem, the definition (and review) of the requirements, the conception of more than one solution, the trade-off based on pre-defined criteria, and finally, the detailed design of the chosen concept. In each phase of the exercise, the process followed is similar to an industrial design process.

After the kick-off of the project, the team of ten students has to organise themselves, and take on two roles, one from an organisational point of view (e.g., project manager, system engineer, quality-control manager, sustainability manager) and one from a technical perspective covering the required technical fields (e.g., for a satellite design, astrodynamics, structures, stability and control, power, thermal control, communication, etc.). The group also establishes so-called project rules, in terms of daily and weekly meetings, communication means, document templates, and so on. This team organisation is documented in a Project Plan, to be handed in after one week.

In the second week, the team is preparing for the Baseline Review in the beginning of week 3, by reviewing the User Requirements provided. These requirements are analysed critically to understand where they come from, to identify potential killer requirements, and to have insight in the driving requirements. In case killer requirements have been identified, the group can "negotiate" with the customer (or tutor) to alleviate those such that they become feasible, and to avoid trying to come up with an impossible design. From the set of User Requirements, the group then derives a (generic) Functional Flow Diagram and Functional Breakdown Structure, which give insight in the functions of the design solution and its operations. These will enable the team to formulate Mission and System Requirements, and, if possible, create a list with sub-system requirements, even though at this stage it will be hard – not to say impossible – to come up with dedicated numbers. A thorough Market Analysis supports this phase, and should confirm the justification of the project and possibly also lead to additional requirements, for instance, if a small design change can open up additional market segments. A similar reasoning applies to the Sustainability Analysis, but in this case, it might lead to constraints in the design process, or will even eliminate potential design options. The last step in this phase is to create the so-called Design-Options Tree that covers all feasible (and infeasible!) solutions to the design problem. At the Baseline Review the results of this phase is presented to the customer, culminating in a subset of three to five (feasible) top-level concepts that enters the trade-off phase.

During this phase, each concept is evaluated for a number of criteria and traded off, and the results are presented at the Midterm Review. Typical trade-off criteria are performance related, e.g., flight range, or power consumption and total mass, but also more obscure criteria are typically considered, such as risk, reliability, complexity of the design, and technology-readiness level. A sensitivity analysis, not only on the used trade methods, but also on the trade criteria and their respective weights shall guarantee that the outcome of this process is robust, and the most viable concept will enter the detailed-design phase. An important aspect not overlooked is verification and validation (V&V) of the tools developed that are used for the calculations. Anticipating further tool development, a V&V plan with detailed procedures needs to be provided to guarantee a consistent use of verified tools.

Finally, in the second half of the project a detailed design of the winning concept is made, considering all interfaces between the respective sub-systems. An N^2-chart will aid the systems engineer to account for all these mechanical, electrical, and other interfaces to enforce a proper functioning of the design, composed out of sub-systems that are designed in detail by the different team members. At a higher design level, Risk Maps (before and after mitigation) are prepared, and aspects of sustainability, Reliability, Availability, Maintainability, and Safety (RAMS) are enforced on the top-level design and flown down into the sub-systems. Each sub-system is given budgets for mass, power, volume, etc., which are iterated until converged in the design within the margins appropriate for the level of detail in this phase. To conclude, an 'as detailed as possible' cost analysis will be made, separated into design (hardware, software, and manpower), development (including testing), and operations. The Operations and Logistics plan will provide input to this process. The outcome is presented at the Final Review, which marks the end of the design phase in the DSE. To prepare for the concluding symposium, the groups can prepare detailed Catia renders of their design, and sometimes even print 3D samples of (sub-)systems or even a scaled model of their final design.

3. Example design projects

3.1. Low-cost Narrow-body Aircraft (RELOAD)

In 2010, Airbus announced the replacement of its A320 aircraft family by the A320 new engine option (neo), a partial redesign of the A320 featuring new engines and a range of more subtle design changes. The anticipated effect was, amongst others, a decrease of 15% in fuel consumption and an 8% lower operating cost. The A320neo was chosen over the alternative: design of a full-blown successor to the A320, known internally as the A30X. In a similar fashion, Boeing opted to develop the Boeing 737MAX as the fourth generation of the 737 series, replacing the current 737 Next Generation (737NG) and promising a 4% lower fuel burn when compared to the A320neo. A 'clean-sheet' design for a new single-aisle Boeing aircraft (codenamed the Y1) was postponed to at least 2030.

These replacement decisions are characterised by incrementalism: relatively small advances beyond state of the art coupled with reduced business risks (i.e., required investments on part of manufacturers and operators). What if one of the major aircraft manufacturers had chosen to hit for the fence by developing a fully new single-aisle aircraft? Given typical lifecycle costs and their distribution, would it be feasible to develop a competitive narrow-body aircraft in terms of performance, while achieving a substantial impact on lifecycle costs by bringing significant reductions in direct operating costs?

In trying to address these questions, the objective of one of 2016's DSE projects was to design a narrow-body aircraft with a 30% reduction in direct operating cost compared to (then-)current competitors (A320ceo family, B737NG), for market introduction by 2030. The aircraft had to offer similar performance as its contemporary competitors, while improving life cycle cost and sustainability characteristics (particularly through the reduction of CO_2 and NO_x emissions). Several high-level requirements and constraints were defined as part of the assignment, but these were free to be developed into more depth by the team and challenged where relevant. As part of the initial phase of the project, an extended requirement analysis was performed to derive and define a consistent set of requirements to system level, with some subsystem-level requirements already being taken into account. The analysis covered design regulations, development constraints and a list of stakeholders' requirements with subsequent derived technical requirements and constraints, uncovered in part through functional and market analysis. Given its key role in the project objective, direct operating cost (DOC) was determined not to exceed $3,125 per flight hour, which is in line with the 30% DOC reduction target specified. In addition, other top-level requirements and constraints such as seating capacity (175 passengers), range (6,500 km at maximum payload), cruise speed and altitude (0.75 Mach; 11 km), technical dispatch reliability (99.7%), gaseous emissions, lateral, fly-over and approach noise levels were defined. The team put in additional effort to uncover medium-level, low-level and stakeholder requirements, with decreasing importance levels and/or quantification of requirements.

Following on the functional, market and requirement analyses, a large set of design options was generated to fulfil the mission. After elimination of infeasible and less likely concepts, four concepts were determined to be the most viable:

1. A conventional, low-risk design, very similar to current narrow-body, single aisle aircraft, with cumulative improvements including a geared turbofan engine, winglets and morphing flaps and slats;
2. A blended wing body, using biofuel, having split winglets, a twin tail with rear roof-mounted engines;
3. A three lifting surfaces concept involving a canard, a main cantilever wing and a T-tail, allowing for a very high lift to drag ratio to be achieved. The design is equipped with spiroids, morphing flaps and slats and a boundary layer ingestion turbofan engine;
4. A braced wing concept, with an extra wing strut allowing for high wing aspect ratios, increasing efficiency. The concept utilises geared turbofan engines using biofuel and making use of boundary-layer ingestion.

The performance and design characteristics of these four concepts were analysed on several criteria, some of them being maximum take-off weight, aerodynamic performance, design and operational complexity, and cost. The main outcome of the trade-off process, which involved sensitivity analysis on the criteria weights and trade method, was that concept 2 outperformed the other concepts in terms of weight, performance and operational costs. However, due to the technical risk profile of this design, a choice was made to combine some of the technical characteristics of concepts 2 and 3 to come up with a final concept. In particular, due to the placement of emergency exit doors only the last part of the fuselage was blended into the wing. For stability reasons, a canard was included into the design. The resulting design was re-evaluated, came out best in a revised trade-off and was selected for detailed design in the second half of the DSE. It was named RELOAD (REliable LOw-cost Aircraft Design) and has been depicted in Figure 2.

The final conceptual design of RELOAD included design and analysis on aerodynamics, structures, propulsion, stability & control, and various aircraft subsystems, while performing iterations on system and subsystem levels to integrate and converge the design. For all primary design disciplines, fairly intricate design modules were custom-built to support the design process. Together with a top-level design integration module, developed on the back of a set of N^2 charts, this allowed for traceable and verified design and management of design parameters over time, while speeding up the design-process iterations.

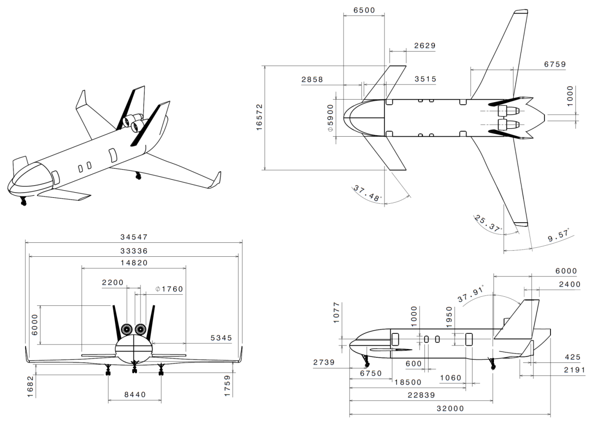

Figure 2 – RELOAD conceptual design.

The end result was a canard aircraft with a rear placed wing and two ultra-high bypass turbofans placed between two vertical stabilisers. The wings include morphing flaps, while having a contour, which is based on transonic airfoils and ending up with two blended winglets. In terms of the aircraft's structural design, a mix of safe-life, fail-safe and damage-tolerant design philosophies has been applied, while focusing on a limited set of primary load cases for fuselage and wing structures. For the control and avionics, augmented stability has been implemented to have an all-moving canard. Commands from the cockpit to the flight controls would be sent using fly-by-wireless technology, while the actuation would be performed electrically and hydraulically only. RELOAD's flight deck design introduced the possibility of a single pilot operations system. That, in turn, would allow for a reduction in crew costs. Noise mitigation was primarily performed by positioning the powerplant system on top of the fuselage to meet the noise reduction requirements.

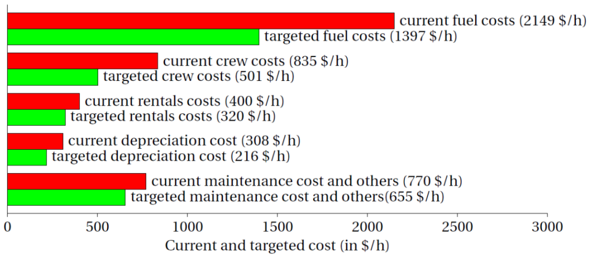

Figure 3 – RELOAD direct operating cost evaluation.

Referring back to the project objective, a primary requirement for the design was to meet the stated direct operating cost (DOC) reduction. Based on a detailed understanding of current-generation narrow-body DOC contributors, a comparison was made between these values and the anticipated RELOAD (operational) cost performance. This comparison is given in Figure 3, summing up to successfully meet the DOC requirement, with the associated competitive positioning of RELOAD in terms of cost-range and passenger payload-range being illustrated in Figure 4.

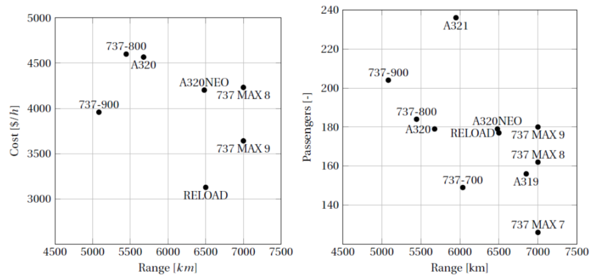

Figure 4 – RELOAD competitive positioning.

3.2. Saturn Ring Observer

Ever since the discovery of the rings, Saturn has been a celestial body of intense study, both with Earth-based telescopes and from closer by with spacecraft. Space exploration of Saturn began with the Pioneer 11 flyby on September 1, 1979, followed by the Voyagers 1 and 2 in 1980 and 1981, respectively. They showed that the rings consist of a multitude of ringlets, gaps, and small shepherd moons. It was also confirmed that the bright B ring is marked by strange ephemeral "spokes." The gaps and ringlets are the result of gravitational interactions with Saturn's many moons; the spokes, on the other hand, remain mysterious. The most detailed observations of Saturn, its rings and moons has been done by the Cassini spacecraft, which reached Saturn in July 2004. Its mission came to a spectacular end on September 15, 2017, when it dove into Saturn's atmosphere after having executed a number of risky passes through the gaps between Saturn and its inner rings.

Despite all observations, still many questions about the rings remain. This is primarily due to the fact that the ring particles are very small (ranging from 1 cm to around 10 m), and the observing spacecraft have never been flying too close to the rings to avoid any hazard to the spacecraft. Therefore, a dedicated mission that will fly close to the rings - actually be in a "hover orbit" just above them - could fill in (some of) the blanks. Primary focus would be on the mechanisms of formation and evolution of planetary ring systems, as they are poorly understood.

The objective of one of 2017's DSE projects was a mission design to investigate the composition and particle dynamics of Saturn's rings, to obtain close-up observations of centimetre-scale ring particle interactions to better understand these processes. As the particle processes are expected to be very dynamic and time varying, a global observation period of many months would be required, with a number of close-proximity excursions to study local effects in greater detail.

Constraints to the mission design were a maximum budget of €1.5 billion with a launch date in 2025. In-situ measurement duration in proximity of the rings should be 1 year, whereas the minimum close proximity hover duration should be 1 month. Finally, a clear end-of-life strategy had to be included in the mission design, and the use of radioisotope propulsion systems and/or thermal generators was to be avoided. The latter constraint turned out to be an impossibility for this deep-space mission and was successfully renegotiated by the team.

After reviewing the requirements, the team started with a detailed market analysis to fully understand the scientific objectives. Besides a study of relevant literature, the science case was also discussed with planetary scientists. A list with objectives was created, ranging from a study of individual ring particles and ring dynamics, to the interaction of the rings with the Saturnian atmosphere as well as its (many) moons. Mission success is based on grouping the science objectives in five categories, the most important being an *essential primary objective* and the least important being a *low-yield secondary objective*. Complete mission success dictates that all primary science objectives are to be met and the results transmitted back to Earth. Partial mission success is achieved when all essential and at least half of the non-essential science are completed.

After defining the common functions that the space system has to perform, many design options were generated that could fulfil the mission, and organised in a Design Options Tree. After elimination of infeasible and less likely concepts, three concepts were determined to be the most feasible: a single orbiter, a single orbiter with six CubeSats, and dual satellites.

1. The single orbiter concept will carry the complete instrument package to achieve the science goals, and perform both the global observations and the in-situ measurements by hovering over the rings. Even though it minimises the total number of interfaces, it has a complex sequence of operations.
2. Main characteristics of the second concept is to send six CubeSats to the rings to take samples of ring particles, while at the same time the orbiter will hover over the rings to take high-resolution measurements.
3. In the third concept, one orbiter will hover over the rings, while the other remains at a safer distance and relays the data of both spacecraft back to Earth. The latter will remain in orbit after the hovering spacecraft ends it mission.

The performance and characteristics of these three concepts were analysed on several criteria, some of them being (preliminary) cost, total mass, complexity of the design and operations, and scientific output. The main outcome of the trade-off process was that the total cost of concept #1 is €1.05 billion, it is characterised by medium risk, but has a low scientific yield. Concept #2 costs €1.45 billion, is high risk, and has a medium scientific yield. The third concept, i.e., the one with two satellites, costs €1.10 billion, is low risk, and has a high scientific yield. The latter concept came out the winner of the trade-off (including a sensitivity analysis on the criteria weights and the trade method), and selected for detailed design in the second half of the DSE. It was named SAURON, the Saturn AUtonomous Ring Observer Network, and has been depicted in Figure 5.

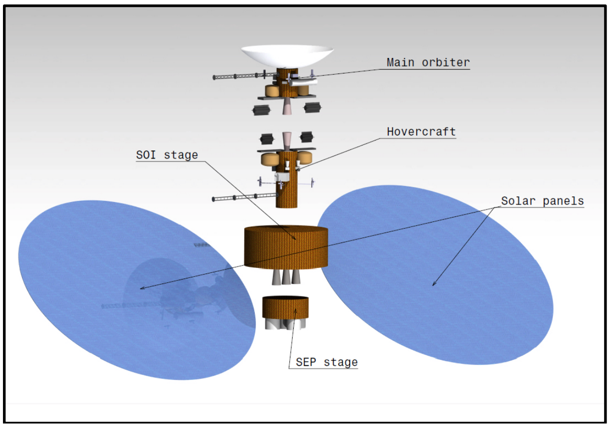

Figure 5 – System elements of SAURON.

SAURON will be launched with a Falcon Heavy on 12 June 2024. The two spacecraft will be attached to two kick stages, which take care of the transfer to Saturn and Saturn Orbit Insertion (SOI) and pump down of the orbit, respectively. Total launch mass of the system is 10,800 kg. The transfer kick stage is a solar electric stage that will propel the system during its 10.4-year inter-planetary trajectory until it no longer receives enough solar power. An initial gravity assist from Venus, followed by two Earth flybys, will lower the ΔV requirement for transfer and thus maximise the arrival mass. To test the payload, and to increase the "market value" of the mission, several measurements will be performed during the flybys. On 19 November 2034 SAURON will reach Saturn and dive between the G and F ring for Saturn Orbit Insertion, requiring a propulsive ΔV of 310 m/s that is executed by the high-thrust chemical SOI stage. This orbit is highly elliptical, with a periapsis of 155,069 km and a period of 100 days. After a periapsis raise manoeuvre of 150 m/s, SAURON is placed into an orbit encountering Titan. This moon is the first of several (also Enceladus, Dione, and Rhea) to be used for gravity assists to change the orbit to one with a periapsis at 142,000 km and the apoapsis at Enceladus' orbit. During this phase of 3.5 year a total of 350 m/s chemical propulsive ΔV is required to target the spacecraft towards the moons. A further 2,080-m/s burn is performed to lower the apoapsis, and it is during this orbit that the orbiter and hovercraft are separated. They will then separately perform a propulsive manoeuvre of 850 m/s to circularise into a 142,000 km orbit. The orbiter will remain outside the rings, whereas the hovercraft will start its hover mission (Figure 6). The orbiter and hovercraft have 400 m/s and 1,842 m/s propulsion budget to execute their respective manoeuvres.

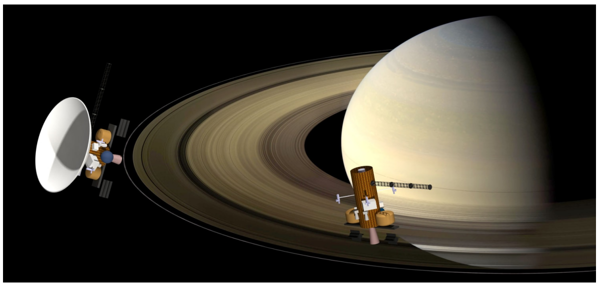

Figure 6 – Artist impression of SAURON's mission.

Detailed analysis of the User Requirements led to the conclusion that most science goals can be achieved with a wide-angle and a narrow-angle camera. Additional scientific measurements are performed using both an infrared and an ultraviolet spectrometer, a magnetometer, a plasma package, a dust analyser, and a radio science instrument. Each of these instruments is installed on the orbiter. In addition, the hovercraft is equipped with both types of cameras, an infrared spectrometer, a magnetometer, and a dust analyser. The preliminary selection of these instruments led to a mass and power budget of 50.2 (36.9) kg and 56.5 (41.3) W for the respective spacecraft.

The spacecraft structural design is based on a cylindrical shape, such that the driving (launch) load can be most easily withstood. The required thickness of the structure for the two kick stages is 4.2 mm, and for the orbiter and hovercraft 2.5 mm, and is to be made of aluminium-lithium alloy 8090. The height of each section is 1.213 m for the SEP stage, 2.17 m for the SOI stage, 2.94 m for the hovercraft and 1.79 m for the main orbiter. As the satellite must be able to handle temperature extremes at both Venus and Saturn, this was a challenge for the thermal control design, but the combination of louvres, heat pipes and radiators can keep the spacecraft's components within their operating ranges at both temperature extremes.

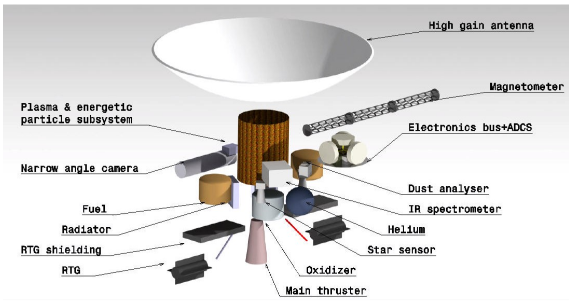

Figure 7 – Orbiter sub-system overview.

All subsystems are mounted to the structure, either internally or on the outside (Figure 7). Since a detailed description of the sub-system design is not possible due to page limitations, we will restrict ourselves to the main characteristics. The power subsystem is separated into two main elements, i.e., each spacecraft has two Radio-Thermal Generators (RTGs) using Curium-244 to provide power to all sub-systems for the duration of their lifetime. End-of-life design power is 170 W for the hovercraft and 270 W for the orbiter. The second main element consists of two large solar panels to provide a begin-of-life power (at 1 astronomical unit, au) of 37 kW to the Solar electric transfer stage. The second propulsion system, the high-thrust insertion stage, uses a combination of hydrazine and Nitrogen Tetroxide. Other components of the propulsion system include thrusters for attitude control, as well as for "hopping over" the rings. Part of the attitude orbit and control system, this design is based on the accuracy, stability and control requirements of the spacecraft. The pointing requirement of the narrow-angle camera drives these aspects of the sub-system design. To acquire the data required for state estimation, the sensor suite includes gyroscopes, star sensors, a Sun sensor, a lidar, and also the wide-angle camera provides navigation data. Finally, the telecommunications subsystem was designed with high reliability and fast downlinks in mind. Considering the 10-au distance from the orbiter to Earth, a high-gain antenna with a diameter of 3.7 meters and a Ka band gain of 59 dBi is needed to provide the necessary signal-to-noise ratio for a data rate of about 48 kbit/s.

With a total dry mass of 2,300 kg (3,000 kg budget), a total wet mass of 11,200 kg (11,900 kg budget), including a 12-17% contingency on all sub-systems, as well as extra propellants, and a (final) total cost of €1,460 million, this preliminary design has progressed to a believable and exciting proposal to become the next generation of Saturn observers.

4. Acknowledgements

For the two projects discussed in this paper, we have used the information provided by the design teams. Their work has been summarised in the following two references:

1. Melkert, J.A. (Editor), Delft Aerospace Design Projects 2016: Inspiring Designs in Aeronautics, Astronautics and Wind Energy, Uitgeversbedrijf Het Goede Boek, 2016.

2. Melkert, J.A. (Editor), Delft Aerospace Design Projects 2017: Challenging New Designs in Aeronautics, Astronautics and Wind Energy, Uitgeversbedrijf Het Goede Boek, 2017.

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