Development of a Supersonic Research Rocket with a Hybrid Propellant Rocket Engine

Stefan May, Georg Poppe*, Michael Pöppelmann*, Hans Philipp Sültrop* and Peter Vörsmann***
** ExperimentalRaumfahrt-InteressenGemeinschaft e.V.*
Hermann-Blenk-Straße 23, 38108 Braunschweig, Germany
*** TU Braunschweig, Institute of Aerospace Systems*
Hermann-Blenk-Straße 23, 38108 Braunschweig, Germany

Abstract
As participant in the STERN program of the German Aerospace Center (DLR), the ExperimentalRaumfahrt-InteressenGemeinschaft e.V. (ERIG) is developing a research rocket within the Leonis project. The paper presents a preliminary concept of the hybrid rocket engine Helios and the prospective rocket Regulus. This design is based on the former achievements of the ERIG (telemetry system, sensor systems, microprocessor programming, structural design, launching of amateur rockets), which are also presented. The latest developments and newest test results of the hybrid rocket engine HYDRA-3X are described. Furthermore, initial results of the self-developed flight simulation program ExRaS for the current Regulus and Helios data are carried out and presented.

Abbreviations

CAD	-	Computer aided design
CFRP	-	Carbon fiber reinforced polymer
DLR	-	German Aerospace Center
DOF	-	Degrees of freedom
ERIG	-	ExperimentalRaumfahrt-InteressenGemeinschaft e.V.
ExRaS	-	**Ex**perimental-**Ra**umfahrt-**S**imulation
FPGA	-	Field Programmable Gate Array
GFRP	-	Glass fiber reinforced polymer
GOX	-	Gaseous oxygen
GPS	-	Global Positioning System
GSM	-	Global System for Mobile
HTPB	-	Hydroxyl-terminated polybutadiene
HYDRA	-	**HY**brid**D**emonstrations-**R**aketen**A**ntrieb
PE	-	Polyethylene
PMMA	-	Polymethyl methacrylate
STERN	-	**ST**udentische **E**xperimental-**R**akete**N**
TIC	-	Truncated ideal contour

1. Introduction

The ExperimentalRaumfahrt-InteressenGemeinschaft e.V. (ERIG) is a registered student association at the TU Braunschweig, founded in 1999. At the first time, some small single-stage amateur rockets propelled by solid fuel motors were designed. These rockets were only equipped with a simple recovery system and measurement electronics. In 2001, the hybrid rocket engine program of the ERIG was started and the HYDRA-1 (**HY**brid**D**emonstrations-**R**aketen**A**ntrieb) was designed and tested. This first step in the development process was an

engine, operated with PE and PMMA as solid fuel and GOX (gaseous oxygen) as oxidizer. This small lab engine was used as proof of concept and finished in the same year. After that, the design of the HYDRA-2 was started. With this engine, initial measurements were carried out and data sets to design bigger hybrid engines were obtained. HTPB (Hydroxyl-terminated polybutadiene) and nitrous oxide were finally chosen as a further fuel combination, because they are not toxic or carcinogenic, comparatively easy to get and simple to handle. This engine has achieved a thrust of 40 N for a burning duration up to 10 s. In the year 2004, the development of the HYDRA-3 was started. This engine was designed for a total impulse of 5 000 N s and new construction materials for the nozzle (graphite) and the inner heat shielding (phenol composite materials) were used. The HYDRA-3 was able to reach a thrust of 750 N up to 1000 N and it was the base for the current hybrid rocket engine, the HYDRA-3X, which is described in chapter two.
In the year 2012, the German Aerospace Center (DLR) Space Administration has started the STERN (**ST**udentische-**E**xperimental**R**akete**N**) program. The intention is the education of more young students in the development of launcher systems in Germany. The mission patch of the STERN program is shown in Figure 1. For more general information, see reference [1].

Figure 1: Mission patch for the STERN program of the DLR [1]

The ERIG and the Institute of Aerospace Systems of the TU Braunschweig started the participation in the STERN program with the Leonis project in July 2012. For this project, the ERIG will build the research rocket Regulus, which is based on the current biggest rocket of the ERIG, the Mephisto. A new hybrid rocket engine called Helios will be developed to achieve the objectives of the project. The self-designed objectives of the ERIG are clearly more difficult than the objectives of the DLR. Both are summarized in Table 1.

Table 1: Summarization of the ERIG and the DLR objectives for the STERN program

	DLR objectives	**ERIG objectives**
Max. altitude	3 000 m	> 11 000 m
Max. speed	Ma=1	Ma>1.5
Rocket systems	Telemetry payload	Telemetry payload
		Scientific payload (2 kg)

2. Former achievements

During the past decade, the ERIG has collected many achievements in the design of on-board computers and structural components of research rockets. Furthermore, the ERIG has already gained experience in launching research rockets in the size of the presented Mephisto (see Figure 2) and in the design of telemetry during a launch campaign of research balloons in 2011.

2.1 Structural Design

The Mephisto is the most powerful research rocket of the ERIG, constructed in 2002. It is able to reach an altitude of 2 300 m with a total mass of 9 kg and length of 1.9 m. This rocket is a good example for the structural design, developed by the ERIG. A CAD model of the research rocket is depicted in Figure 2. The Mephisto has a modular structural design and is made up of CFRP (carbon fiber reinforced polymer) tubes and connection rings consisting of aluminum. The connection rings can also be used to integrate other components to the structure such as different recovery systems, telemetry modules or payloads. The nose, the fins and the boat tail are made up of GFRP (glass fiber reinforced polymer) and have been produced in self-made forms. The top of the Mephisto has space for scientific payloads. The bottom of the rocket contains the parachute, the on-board computer and the solid fuel motor.

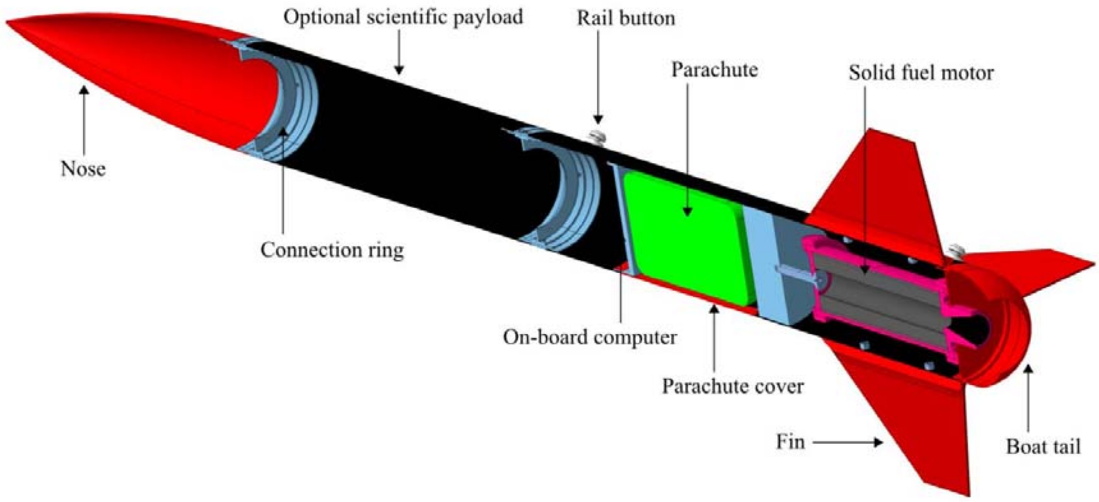

Figure 2: Sectional view of the research rocket Mephisto

A critical part of a research rocket is the recovery system. So far, the Mephisto is using a recovery system with a drogue and a main parachute, which are ejectable through a flap on the rocket body. Controlled by the on-board computer, a servo motor opens the flap. This recovery system has many disadvantages. The servo, which opens the parachute cover, can jam easily. Furthermore, the probability that the parachute is pulled out by aerodynamic force, depends strongly on the flight attitude, and the hole in the CFRP-tube through the parachute cover is a high structural weakness. Due to this disadvantages and a complete failure of the system in the past, a new recovery system located in the rocket nose was developed, but it is not completely implemented in the Mephisto at the moment. However, the functionality of the new separation system is underlined by ground separation tests. A complete implementation is intended in the third quarter of 2013.

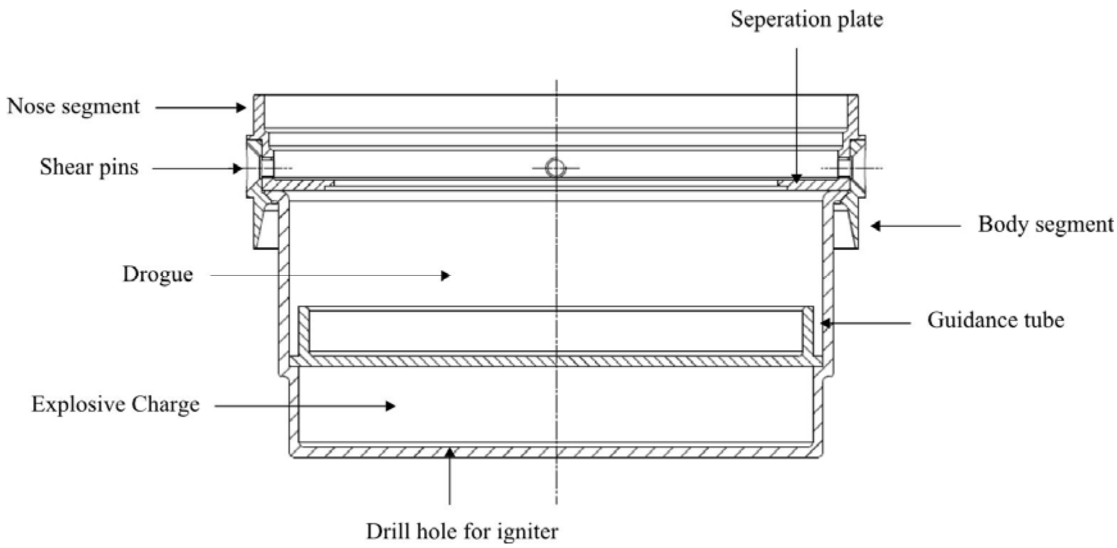

Figure 3: Sectional view of the separation system for the new recovery system

One of the main components of the presently developed recovery system is the separation mechanism, depicted in Figure 3. After detecting the apogee of the rocket flight parabola, the on-board computer ignites a small explosive charge. The pressure created by the explosion cuts the shear pins, the nose separates from the rest of the rocket and the drogue parachute opens. After that, the drogue pulls its box out of the body tube in order to clear the way for the main parachute. This separation mechanism is integrated into the connection ring. The design is optimized to prevent jamming and to protect the drogue and main parachute from the hot explosion gases. In order to prevent drift and strong structural stress, the main parachute opens after the drogue, about 250 m over ground. It is released by the on-board computer, which triggers two redundant Tender Descenders. Tender Descenders are main parachute release devices used in amateur rocketry and very reliable.

2.2 Electronics design

Several electronic devices were developed within the ERIG. The flight computer Waldemar was used for the Mephisto. The electronics consists of a micro controller, the memory, an accelerometer, a pressure sensor and a power supply unit. The launch of the rocket is detected by means of the acceleration sensor. During the flight, acceleration and air pressure (and therefore altitude) are sampled and stored in the on-board memory. The apogee is detected via the flight altitude and the acceleration sensor. When the rocket reaches the apogee, the electronics triggers a servo motor to open the flap for the drogue parachute. After that, below a defined altitude, another servo motor releases the main parachute. In case of a sensor failure, the recovery system is activated by a backup timer.
Another less comprehensive electronic device is used for the research rocket Phoenix. This rocket was primarily constructed for educational purposes and is used in a lab course at the TU Braunschweig. The on-board computer detects acceleration and altitude like the Waldemar, but it is only capable of triggering a single stage recovery system via a small explosive charge. Moreover, this electronic device is not capable of storing flight data.

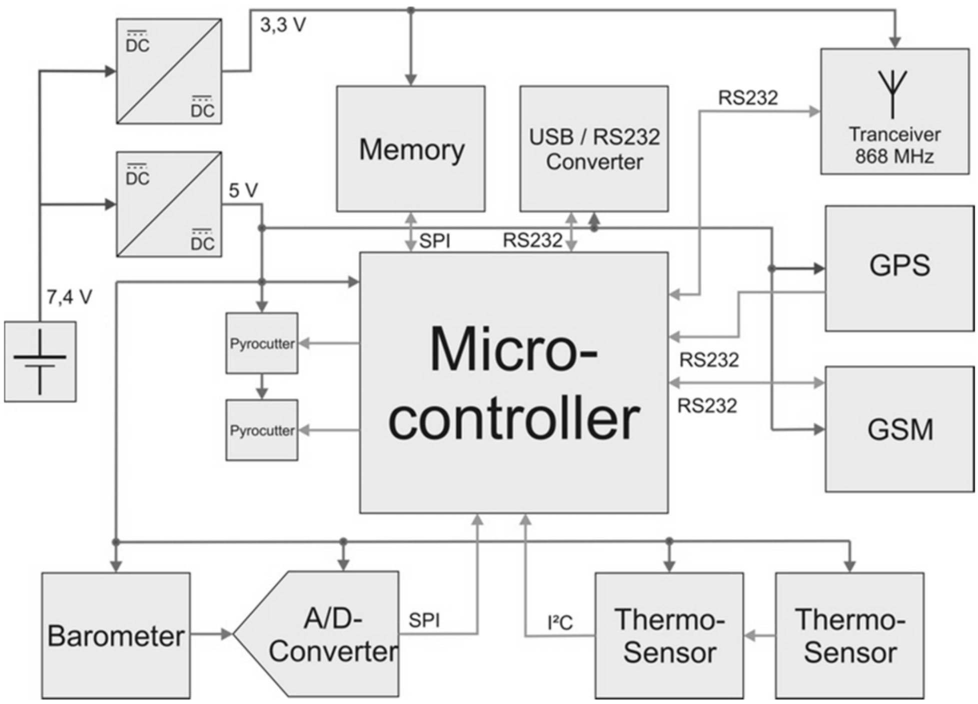

Figure 4: Architecture of the on-board computer of the payload box used during the launch campaign of research balloons

For a launch campaign of research balloons in 2011, the ERIG has developed an on-board computer (see Figure 4), which is capable of measuring position and velocity by means of a GPS receiver. Furthermore, altitude can be determined using a pressure sensor. In addition, several temperature sensors can be connected to the on-board computer. All peripheral devices are connected to an 8-bit RISC micro controller. The acquired data is stored on the on-board memory and is transmitted via an XBEE-Pro telemetry device to the ground station. The data link has an effective maximum range of 60 km. Moreover, the device is equipped with a GSM modem. In case of a bad data link or a too great distance to ground station, the on-board computer transmits the landing position of the payload box via SMS. To drop scientific probes, the electronics can actuate two pyro cutters. Pyro cutters are standard equipment in parachuting to cut robes, and therefore they function very reliably.

2.3 Launch of research rockets

During the last decade, the ERIG has collected much experience in launching research rockets with solid fuel motors and has developed a very well-functioning start procedure. In order to ensure a safe launch, this procedure includes all important steps which have to be done before, during and after the launch. For the launch of research rockets, a launch pad was constructed. To connect with the launch rail, the rocket is guided by rail buttons in order to reach a sufficient velocity for aerodynamic stabilization.
In order to handle solid fuel rocket motors in Germany, it is necessary to hold a special governmental permit (§ 27 SprengG). Several ERIG members are holding this permit and furthermore, the ERIG is authorized to instruct others to receive this governmental permit.

2.4. Hybrid rocket engine development

The ERIG has developed a hybrid rocket engine called HYDRA. The current version HYDRA-3X, which is intended as flight version, can currently produce an average thrust of 850 N for 10 s burning duration. ERIG's aim is to reach a total impulse of 12 000 N s by a maximum thrust of 1 300 N, which will be achieved in the next test campaign by the use of a new injector. The engine uses HTPB with metal additives as fuel and nitrous oxide as oxidizer. In Figure 5, a sectional view of the engine is presented.

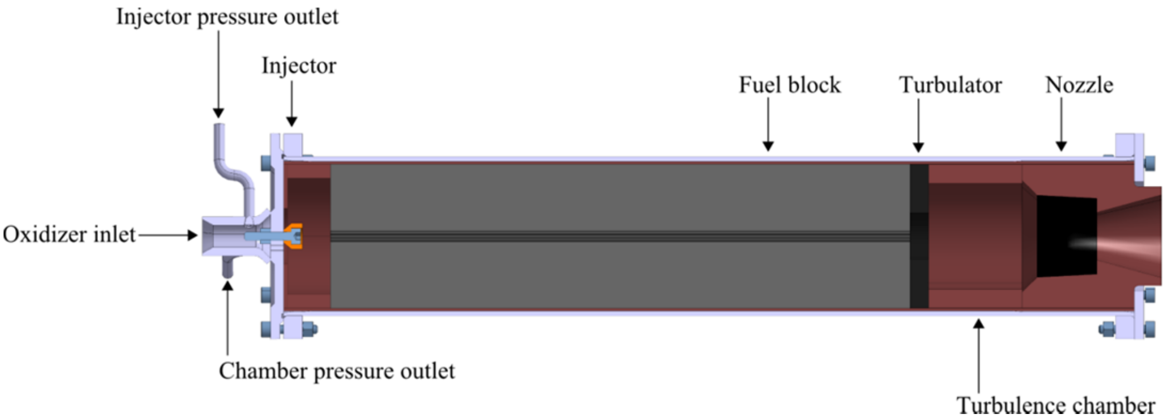

Figure 5: Sectional view of the HYDRA-3X

The oxidizer is injected into the combustion chamber through a shower-type injector. The oxidizer mass flow, which runs through the inner injection ring, collides with a conus. This is attached to the middle of the injector. The result is a better decomposition of the oxidizer droplets and therefore a more effective combustion in the top part of the engine. The main part of the combustion takes place inside the fuel block. Its geometry is a star-shaped form, which leads to a larger combustion area. The HTPB is mixed with fine aluminum powder to raise the combustion temperature and the efficiency of the engine. After passing the fuel block, the combustion gases have to pass the turbulator. The turbulator is a plate made up of a phenol paper composite with a restriction in the middle, which causes a higher mixing grade of the combustion gases through induced turbulence. Also, this measure leads to higher engine efficiency. Behind the turbulence chamber, the gases are accelerated in the nozzle. The nozzle consists mainly of phenol cotton composite, but the throat inlay is made up of graphite. Therefore, the nozzle can withstand one test with a burning duration of about 10 s.
The oxidizer is provided by a tank made up of carbon fiber. During the tests, the tank is pressurized to 50 bar to keep the nitrous oxide in its liquid phase and to maintain the mass flow to the engine. The pressurization is done by a 200 bar nitrogen gas bottle with a pressure regulator between the bottle and the tank. The resulting mass flow of the oxidizer to the chamber is measured by a Coriolis sensor. Furthermore, the pressure is measured at the tank, directly in front of the injector and inside the combustion chamber. The thrust of the engine is measured by a force sensor. Moreover, the weight of the tank is measured for the complete test duration.

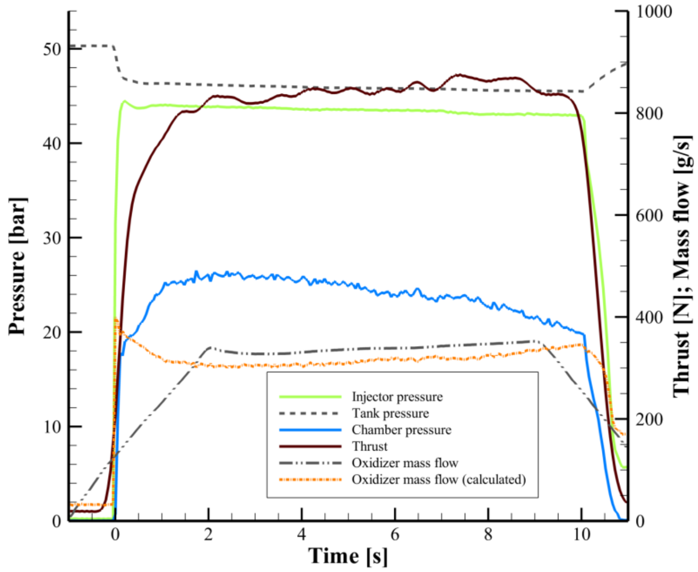

Figure 6: Diagram of measurements during the test run of the HYDRA-3X, which was conducted in October 2012

In October 2012, the latest test of the HYDRA-3X was completed. The most important measurements are presented in Figure 6. The diagram shows the progress of the pressure measurements vs. the time inside the tank, in front of the injector, and inside the chamber. Furthermore, the measurements of the oxidizer mass flow and the engine thrust are shown. When the test starts, the injector pressure and the chamber pressure are rising to their expected values, while the tank pressure is falling slightly. After the start, the thrust of the engine is increasing up to 850 N. It can be noticed that the mass flow seems to increase only slowly, which is caused by a high down time of the sensor. Therefore, the mass flow measurements of the Coriolis sensor are only suitable as estimation. To make up for it, a calculated graph of the mass flow was added to the diagram. The values were derived from the total oxidizer mass measured by the Coriolis sensor and the injector pressure. After 10 s, was the planned duration, the test ends. Subsequently, the engine is extinguished with gaseous nitrogen which is not shown in the diagram. Figure 7 shows a photo of the test run.

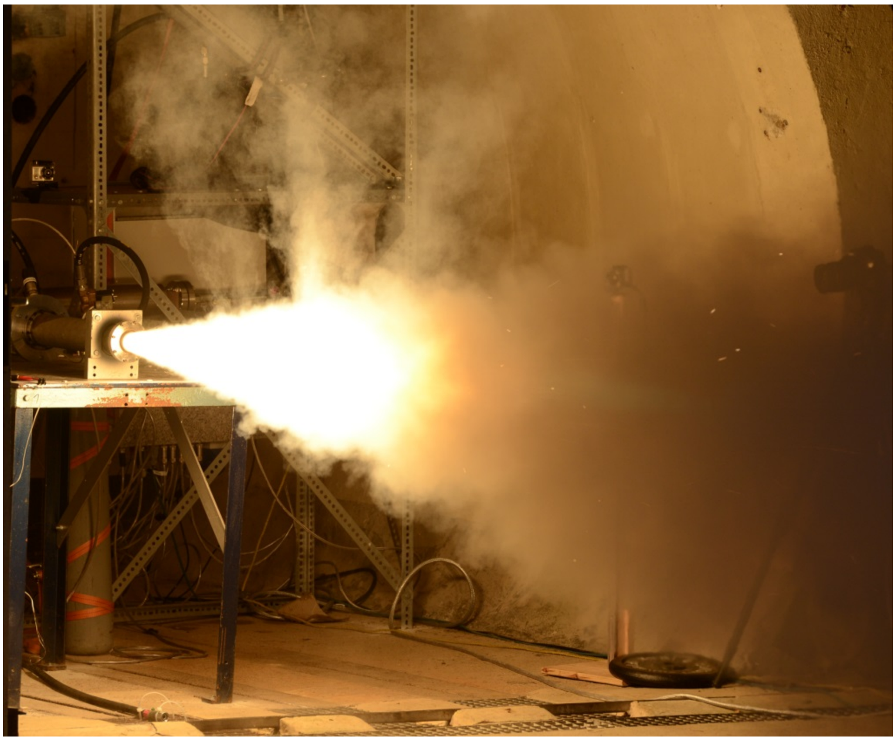

Figure 7: Test run photo of the HYDRA-3X

3. Concept for the Leonis project

Based on the former achievements of the ERIG described in chapter two, the concept for the Leonis project was developed. In addition to a new engine and rocket design, a new engine test bench and a new launch pad are needed. The success of this project is a big challenge for the ERIG students, but also a great chance to learn more about engine and rocket design.

3.1. Pre-design of the Regulus

The Regulus rocket is pre-designed and the conceptual study is shown in Figure 8. Like the Mephisto, the Regulus will consist of several segments built up of CFRP adjunctive by connecting rings. At the current design phase, aluminum or CFRP are discussed as construction materials.
For many systems, like the recovery system and the on-board computer, the experience gained from the Mephisto and the balloon project will used. The recovery system will be a scaled-up version of the new Mephisto recovery systems, also consisting of a drogue and a main parachute. Furthermore, the on-board computer will be enhanced with acceleration and motion sensors, a GPS and a telemetry module. The oxidizer and the pressurization tank will be made using CFRP winding. For launching, a remote controlled pyrotechnically opened main valve will be used, which was developed for the ground tests of the HYDRA-3X. The Regulus will use a scaled-up version of this valve.

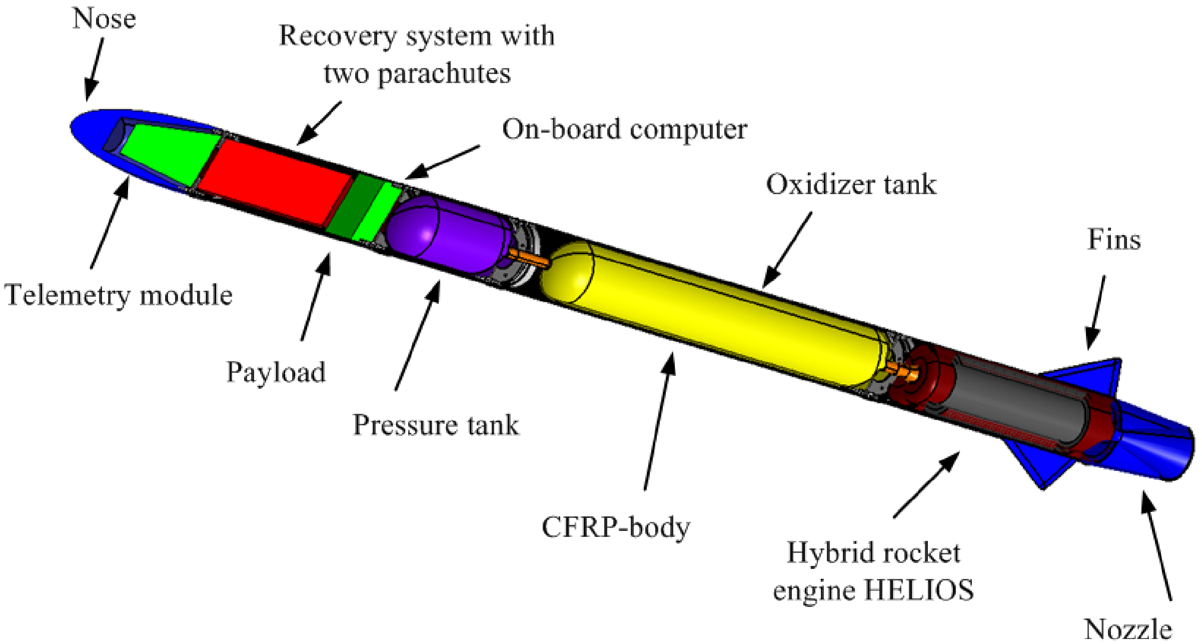

Figure 8: Sectional view of the pre-designed research rocket Regulus

Currently, the hybrid rocket engine Helios is in the construction design phase. The design calculations are based on the extensive experience of the ERIG in the field of hybrid rocket design and testing especially with the HYDRA-3X. The fuel combination has not changed and will consist of HTPB with metal additives as solid fuel and nitrous oxide as liquid oxidizer. Helios is designed for a thrust of about 5000 N and total impulse of nearly 75 000 Ns with 15 s burning duration. For expansion of the combustion gases, a TIC (truncated ideal contour) nozzle with a graphite or wolfram inlay will be used. The current design data of the Regulus and Helios compared with the data of the Mephisto and HYDRA-3X are summarized in Table 2.

Table 2: Pre-design parameters of the Regulus rocket and the Helios hybrid rocket engine

	Regulus	Mephisto		Helios	HYDRA-3X
Max. altitude	>11 000 m	2 300 m	Max. thrust	5 000 N	850 N (1300 N)
Max. speed	>Ma=1.5	Ma=0.8	Burning duration	15 s	10 s
Length	5.0 - 6.0 m	1.9 m	Total impulse	75 000 N s	12 000 N s
Weight	80 – 85 kg	9 kg	Solid Fuel	HTPB + Al	HTPB + Al
Scientific Payload	2 kg	300 g	Liquid oxidizer	Nitrous oxide	Nitrous oxide
Outer diameter	180 mm	120 mm	Fuel geometry	Telescope	Star

3.2 New launch pad

Currently, a new launch pad for research hybrid rockets is being developed. This launch pad is especially designed for the Regulus, but also for the Mephisto, which is supposed to test new components as development platform. The main technological challenges are the design of a fueling station and the development of a control system for the fueling and launch process without risks for personal safety. Furthermore, in a student research paper alternatives to rail buttons will be discussed, because they create high parasite drag in supersonic flight. In order to reduce the engineering and construction period, the structural design is based on commercially standard aluminum trussing and aluminum profiles.

3.3 New test bench

For the new Helios engine, a new test bench has been constructed and will be mounted at the DLR test facility in Trauen, Germany. The test bench is designed to withstand a thrust up to 10 000 N and includes various ways to install sensors. Also, a new combined measurement and controlling system is used, which is based on a FPGA (Field Programmable Gate Array) and a real-time controller. The system can be easily programmed with LabVIEW, which gives also beginners the opportunity to understand the software and the safety structure of a common measurement and controlling system. While the FPGA is used to ensure safety as well as to record and save the measurements, the real-time controller takes the part of controlling and communication. Even when the connection to the control station inside the monitoring bunker is lost, the system will ensure safety and record the measurements. The measurements are recorded with a nominal sampling rate of 1 kHz in addition to one port with a sampling rate of 100 kHz. While the ports with the lower sampling rate are used for thrust and temperature measurements, the high frequency port is used for the chamber pressure sensor. Hence the system can detect specific combustion chamber oscillations, which sometimes occurred in the past. To measure temperatures, thermocouples are used, which are amplified inside the measurement system. Therefore, the thrust is gained from four force sensors, which are connected in a shunt circuit to amplify the signal.

4. Flight Simulation

For the pre-design and examination in the development of a research rocket, the determination of the performance, the aerodynamics and the flight stability is very important. For this reason, the ERIG develops its own flight simulation ExRaS (**Ex**perimental-**Ra**umfahrt-**S**imulation) based on MATLAB/Simulink. This simulation is able to check the given aims of the STERN program as well as the further aims of the ERIG (see Table **1**). Most current open source or proprietary software is designed for simulating model rockets. Special developments and complex systems are usually not capable of being integrated. The ability to take these into consideration is one of the advantages of an own flight simulation. Thus, the primary application field of ExRaS is the development and construction of research rockets. In addition, the program source code is simple to modify and also easy to understand for ERIG students.

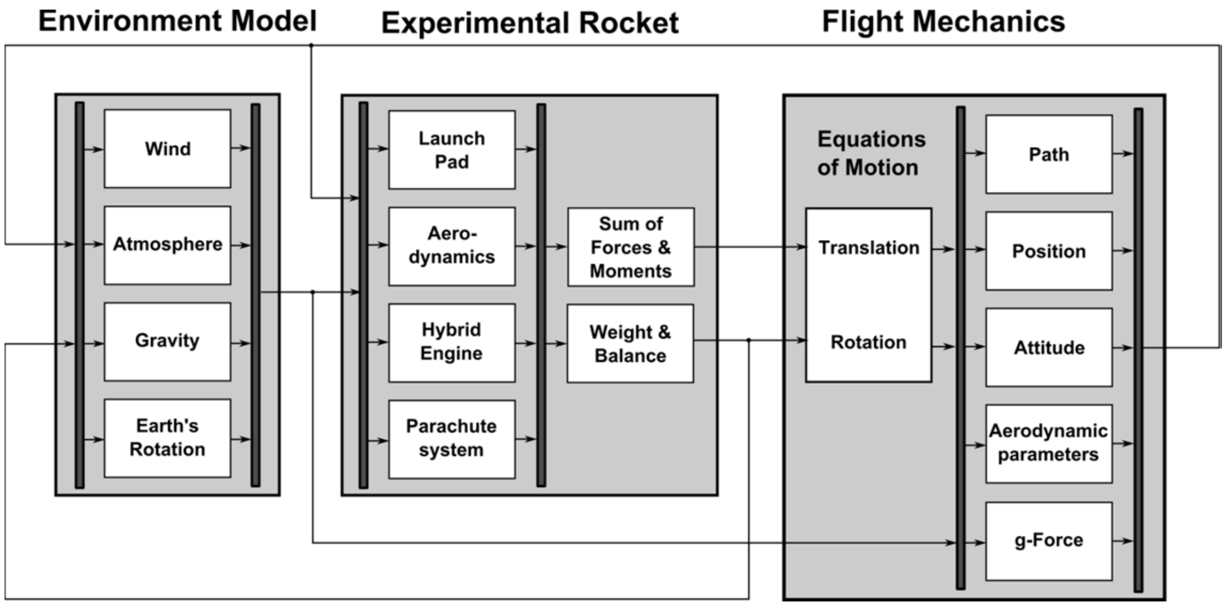

Figure 9: Architecture of the flight simulation ExRas

The main part of the simulation consists of the rocket specific modules, the flight mechanics and an environment model. This architecture of the simulation is shown in Figure 9. The flight mechanics are independent from the type of the flying object. The equations of motion are based on the nonlinear equations of momentum and angular momentum, described in [2]. Therefore, the full 6-DOF motion of the experimental rocket can be expressed by forces and moments which are generated in the rocket module and the environment model. The modules of the rocket are divided into the aerodynamics, a parachute system with a drogue and a main parachute, the launch pad, and the rocket engine. Furthermore, the mass and moments of inertia are calculated over time, as they depend not only on the geometry, but also on the burn-up of the hybrid engine. Currently, the aerodynamic coefficients are generated by the software AEROLAB, designed by Hans Olaf Toft [3]. The drag coefficient vs. Mach number for the powered and unpowered rocket Regulus calculated by AEROLAB is given in Figure 10. The peak at Ma=1 is caused by the drag effects in the transonic regime. In follow-up calculations, aerodynamic coefficients will be integrated into the simulation to design of an aerodynamic module, which is independent from external programs. The validation of this program will be done by measurements and computational fluid dynamics simulations.

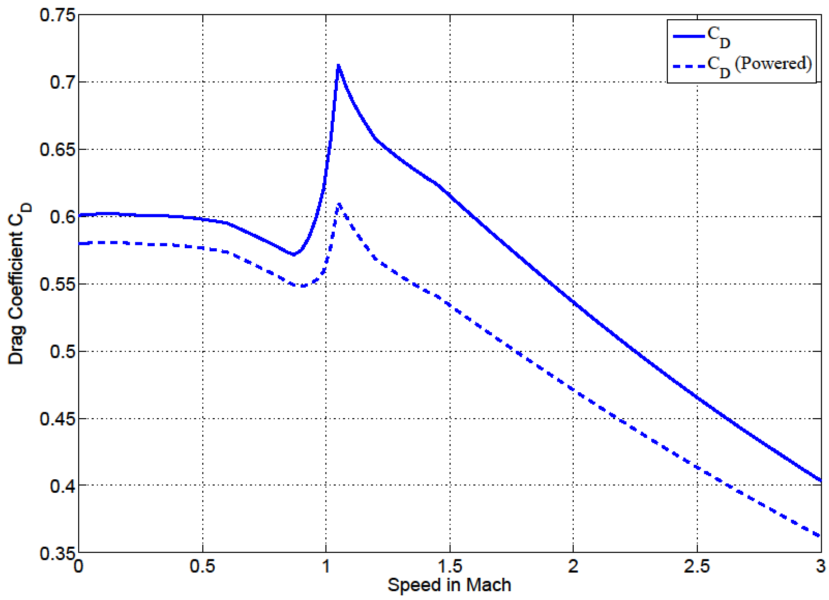

Figure 10: Drag coefficient vs. Mach number for the powered and unpowered rocket Regulus

The parachute simulation gives important results about the descent rate and the shock by the aerodynamic forces at the opening. In addition, the drift caused by wind and turbulence and the oscillation of the rocket connected to the parachute can be evaluated. The simulation of the launch pad is able to consider effects like the friction of the rail or a beginning oscillation of the angle of attack (short period) after leaving the rail.

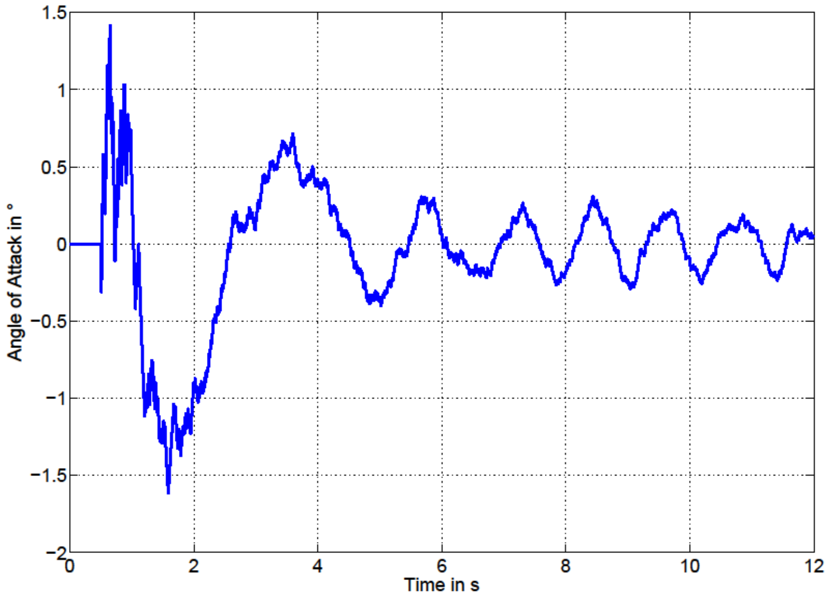

Figure 11: Short period of the research rocket Regulus after leaving the launch pad, caused by turbulence and a discrete gust at second one

The hybrid rocket engine simulation is based on a function that represents the thrust curve. The calculation of other parameters such as the deviation of mass or the motion of inertia is directly connected to this function. Finally, an environment model generates the necessary atmosphere conditions, the acceleration and direction of gravity, wind profiles and turbulence as well as discrete gusts. Also, fictitious forces are calculated to simulate the earth's rotation. A short period caused by a discrete gust, which started after one second, is plotted in Figure 11. The continuing oscillation is forced by turbulence.

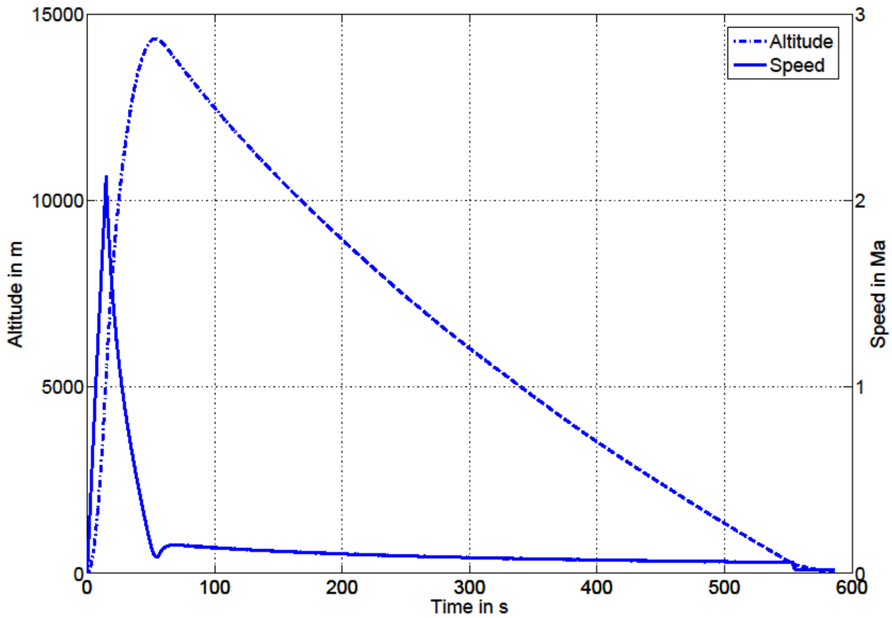

Figure 12: Time curve of the altitude and speed in Mach vs. Time for the research rocket Regulus

The simulation ExRaS is able to compile and save different files for the simulation, because for example the rocket's geometry, the parachutes or the engine to create some data sets which can be mixed together and compared afterwards.

In the following, the first results of the flight simulation are presented. Figure 12 shows the plot of the altitude and speed vs. time for the current level of development of the Regulus. At the beginning, the speed rises up to Ma=2.16 until the hybrid engine burns out after 15 s. Then, the speed decreases and reaches a local minimum altitude at the apogee nearly 14 350 m after about 53 s. Thereafter, the drogue parachute opens directly at the apogee and decreases the descending speed to around 20 m/s. Because the parachute does not open abruptly, but as a function of time depending on the current speed, the speed of the rocket increases a little bit. This is because the rocket falls back to the ground, while opening the drogue parachute. The main parachute opens at an altitude of 250 m.

By the maximum speed of Ma=2.16, the speed of the Regulus fulfills the requirements of a supersonic flight excellently. In conclusion, the first results indicate that the performance of the Regulus for the current level of development sufficiently exceeds the given aims.

5. Conclusion and look-out

The project Leonis as part of the STERN program is on a good course of success. The next period will see the completion and commissioning of the new test bench and first tests of the Helios hybrid rocket engine. Furthermore, the new recovery system will be tested by the Mephisto. Also the new launch pad will be used and tested.

References

[1] Lappöhn, K., D. Regenbrecht and D. Bergmann. 2013. A Rocket Programme for German Students. In: *5th European Conference for Aeronautics and Space Sciences.*
[2] Brockhaus, R., W. Alles and R. Luckner. 2011. Flugregelung. Springer-Verlag, Berlin Heidelberg.
[3] Toft, H. O. 2003. Aerolab. Online [Zugriff: 10.03.2013]. In: http://users.cybercity.dk/~dko7904/software.htm.