MULTI-DISCIPLINARY VEHICLE DESIGN BASED ON THE TOOLS ASTOS AND ESPSS

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ABSTRACT

One key aspect of today's design tasks is the fluent workflow from early MBSE tasks to gradually refined discipline simulations. The need for highly sophisticated models and tools to perform the required concept validations at least of mission critical aspects drives the question, how such workflow can be executed with lowest possible effort and without neglecting critical elements of the causal verification chain.

This paper presents an approach that first groups the depth of modelling according to interdisciplinary dependencies. Then it introduces the capabilities of the ASTOS software to model gradually the different levels of complexity and to interact with external tools making use of FMI and other technologies. Finally, it addresses the need for digitalization of the workflow to reduce the effort and cost of multi-disciplinary design tasks.

The approach is grouped into two major steps. First, the design optimization part, which allows to adjust design parameters of multiple disciplines under consideration of the mission performance and complex orbital dynamics. Second, the analysis part, which requires such costly computations that a complete optimization makes only sense under very special conditions.

The multidisciplinary optimization approach makes use of scalable approximation models of the discipline models, which are calibrated after several optimization steps. At the end of the design process the discipline models are used for an accurate validation of the mission concept.

Several application cases will be presented to demonstrate the efficiency of the workflow. In more detail the design of a hybrid rocket engine is presented using ESPSS. First, ESPSS is directly linked with ASTOS. Further it is used to tune an approximation model which is linked to a design optimization of ASTOS.

1. INTRODUCTION

Together with the commercialization of access to space many new players entered the space market. Just the microlauncher market counts more than 100 potential concepts. With the commercialization also the demand for efficient design tools has increased. The associated return-of-invest oriented working approach asks for turn-key solutions, which are at least partly decoupled from the classical ABCD phase approach.

The key user requirements are reduction of design loops, reduction of expert knowledge required for using the tool, and maximizing of the productivity.

Multi-disciplinary design optimization (MDO) tools cover those needs. This is especially true for launch vehicle configurations with vertical take-off, as all critical disciplines can be considered in an all-at-once (AAO) optimization approach without losing relevant accuracy. Such an AAO approach uses one central tool for optimization, e.g. the ASTOS software, which links expert tools for the complex disciplines. If such expert tools require too much computational time, approximation methods are applied whose parameters are adjusted with help of expert tools.

A widely used MDO tool for launch vehicle design is ASTOS. It is dedicated to trajectory and vehicle design optimization and provides approximation models for subsystems which contribute with a relevant mass to the launch vehicle design. Moreover, it allows to define all the specifics of the to be designed launch vehicle and its mission objectives. The EcosimPro "European Space Propulsion System Simulation" library (ESPSS), developed by Empresarius Agrupados on behalf of ESA, is one of the expert tools, which can be linked with ASTOS. It can be used to model the propulsion systems of any launch and orbital vehicle using liquid or hybrid propulsion systems.

2. VEHICLE DESIGN APPROACHES

2.1. MBSE And Multidisciplinary Design

A model-based system engineering (MBSE) approach examines as many system aspects as possible. At early stages typically mass and power budgets are analyzed.

In contrast to orbital applications, it is characteristic to rocket ascent problems that both properties are highly linked. The rocket equation provides a relatively easy link between them and hence could be directly considered in a MBSE tool. However, the accuracy and especially the significance of such results is questionable as too many design criteria are not sufficiently covered.

Modelling of rocket ascent requires at a quite early design stage optimization capabilities and trajectory propagation. The process becomes more efficient, if the degrees of freedom are as open as possible, i.e. no predefined thrust levels and stage sizes. Combining the models for propulsion system, stage sizing and optimal control results in a multi-disciplinary design optimization approach. The more disciplines are covered the more accurate is the resulting design and the more system aspects of the MBSE model are covered.

2.2. Multidisciplinary Design Optimization

MDO in combination with All-At-One (AAO) optimization intends to define all degree of freedom as optimizable design parameter and combines this parameter optimization with the trajectory optimization.

In contrast to AAO, multilayer optimization (MLO) methods link different tools, which are typically running in a different timescale. MLO methods require clearly more preparation and execution time. Moreover, it is difficult to determine final convergence (see [1]).

Typically, AAO parameters are related to the engine performance and mass-flow, the required propellant for each stage and the resulting tank and stage size, the resulting geometric shape for the aerodynamics computation. The trajectory optimization provides the optimal time for staging and defines this way indirectly the stage size. Constraints on stage separation, stage impact points, station visibility and others impact in addition the required propellant and stage size.

A key aspect of an AAO approach is that the models of each discipline are using the same level of accuracy and, if possible, also similar CPU demand. This allows for a gradual refinement of the models from one working step to the next as described later in section 4.1.

An important aspect of AAO is the verification of an approximation method against an expert tool. The expert solution including its design margins should be part of the approximated solution.

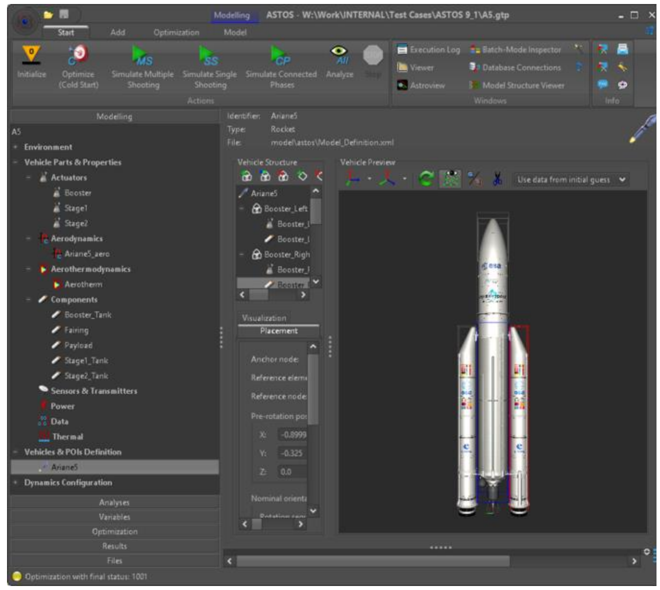

Fig. 1: ASTOS Vehicle Builder

2.3. Sensitivities

The design process should consider that for each design step only discipline models with comparable accuracy are utilized.

Considering uncertainties of 30% for aerodynamics, 20% for inert mass and 3% for Isp the following sensitivity against gross lift-off weight (GLOW) can be observed for a Ariane 5 type of vehicle: 8% to 14% due inert mass, 2% to 7% due to engine performance and up to 2% due to aerodynamics. It shall be pointed out that uncertainties in the first stage result in the largest sensitivity and that the aerodynamics of the super-/hypersonic regime have the biggest impact.

As consequence a clear focus must be put on the accuracy of the inert mass estimation during vehicle sizing.

3. ASTOS SOFTWARE

3.1. Overview

The development of the Analysis, Simulation and Trajectory Optimization Software for Space Applications (ASTOS) started in the late 1980-ties and has grown with the challenges of the past years. Its capabilities are especially useful for start-up companies looking into microlauncher design but fits also to any other space transportation application.

ASTOS offers the user to maintain the model definition from basic to detailed as described in section 4.1 and to setup this way a workflow and level of detail aligned with the specific project. Finally, it is possible to run avionics testbeds with ASTOS or to support operations. The graphical user interface of ASTOS is depicted in Fig. 1.

3.2. Multi-Body and Flexible-Body Dynamics

An expendable orbital launch vehicle is typically a slender body with a certain degree of flexibility exited by wind turbulences, distributed aerodynamic forces, attitude control forces, and sloshing of liquid propellant. Additional structural loads can occur from pressure oscillations in the motor, and separation shocks during lift-off and stage separation.

Rossi [2] presents, how ASTOS can model those aspects, which are of interest for GNC design and structural analysis. In addition, it can be used for the mechanical and collision analysis of multi-satellite separations (see Fig. 2).

3.3. System Concept Models

System concept models are addressing issues of detailed thermal analysis using a node model, power cycle analysis and data analysis. They can be typically combined with mission analysis topics like Solar radiation for heating and illumination on solar cells for power, station visibility and link budget.

Those models are of interest for space transportation flight which takes several hours or days, but typically not for short ascent flight to LEO or GTO.

3.4. GNC Design Capability

An interface to MathWorks/Simulink allows to model the dynamics, kinematics, environment and, if wished, subsystems inside ASTOS and to link the onboard algorithms for guidance, navigation and control (GNC) at its different development stages.

Moreover, ASTOS exports all required information to setup a linearized dynamic for the controller such as control modes, distributed aerodynamics, mode shapes and frequencies, or alternatively the state-space matrix of the linearized system computed by DCAP [3].

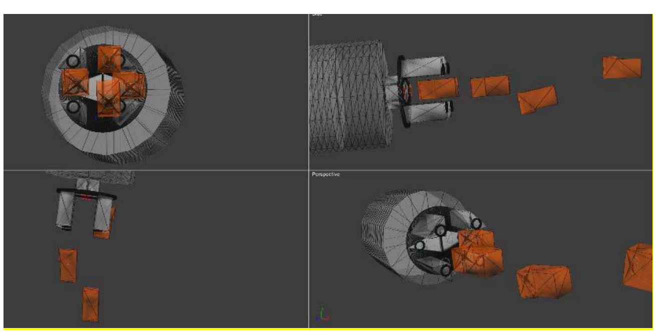

Fig. 2: Multi-satellite separation analysis [3]

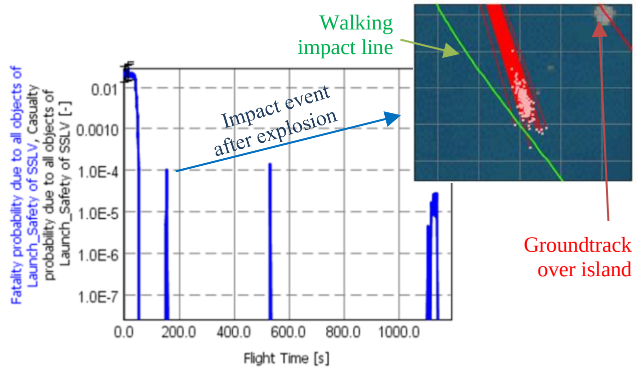

Fig. 3: Casuality and fatality probability during launcher ascent after explosion with increased probability during launch and close to islands.

3.5. Launch Range Safety Certification

Launch range safety analysis is required to archive a certificate from the national authorities that the launch vehicle is compliant with all safety regulations. The problem for start-up companies is, that many of their responsible governments have not passed a space law yet.

The most known standard is the US Federal Code of Regulation (CFR) 14.4 which is often referred to as FAA standard. Many new regulations refer to it, as it is the most comprehensive regulation. Other standards are the French Space Operations Act (FSOA), the Australian Flight Safety Code and Maximum Probable Loss (MPL).

The standards require the computation of flight corridors, blast wave, and casualty and fatality probability due to failures (Fig. 3).

During MDO launch range safety provides requirements on the staging, goundtrack, and walking impact line.

3.6. Interfaces to Discipline Tools

ASTOS provides an API for linking discipline models. Beside environmental models it is used to link aerodynamics codes like SOSE and propulsion design code like RPA and ESPSS [6]. A new FMI interface allows to use ASTOS as master and to call discipline tools as slave setting up a co-simulation.

4. SUBSYSTEM AND DISCIPLINE DESIGN

4.1. Trajectory and Vehicle Design

1.1.1. Design based on rocket equation

The rocket equation formulated by Tsiolkovsky allows to size the propellant and structural mass of each stage based on the

ΔV required to achieve a target orbit. Structural mass is typically defined as structural coefficient. Losses can be considered as additional ΔV.

As the trajectory and system is not known, related constraints, like splash down and phase burn durations, cannot be considered. Moreover, assumptions on performance losses are highly inaccurate.

1.1.2. Basic stage design with optimal control

Basic stage design with optimal control compensates the weak aspects of the rocket equation without looking in much more model details. The consideration of splash down constraint might change completely the stage design. Typically, this approach does not require any initial guess from an analysis performed with the rocket equation. The optimization process is highly efficient using mass estimation regression (MER) on stage level in combination with a sizeable engine performance based on constant specific impulse (Isp) depending on the propellant combination and optimizable thrust.

At a first step this design has no knowledge about the vehicle geometry beside the aerodynamic reference area and considers only a combined mass-flow of the two propellants.

1.1.3. Advance stage design with geometry

Advance stage design considers the first time the geometry. It manages the diameter of the stages, ensures that the tank size is large enough for the fueled propellant and that the nozzles of a stage fit into the stage diameter. Finally, the aerodynamics (CA, CNA) based on the axis-symmetric shape of the rocket is computed with a fast method. MER is used for inert mass estimation applied to structure, engine and other subsystems. The engine performance considers the physical relationship between Isp, mass-flow and efficiency analyzing the combustion in the chamber and expansion in the nozzle. Therefore, chemical equilibrium software is used like CEA [4] or RPA [5].

This approach still lacks an improved estimation of the inert mass which has the largest impact on the design. MER for several subsystems does not solve that problem unless the MER coefficients are updated by an external software, which performs a more detailed structural design in comparable time scales [6].

1.1.4. Detailed stage design with load cases

The detailed design considers the typical input for substructure layout: size and load case. This requires the split of the stage in substructures like cylinders, bulkheads, cones and struts (Fig. 4) [16], and the determination of the dimensioning load case for buckling and strength of each of those substructures [7] using a beam approximation.

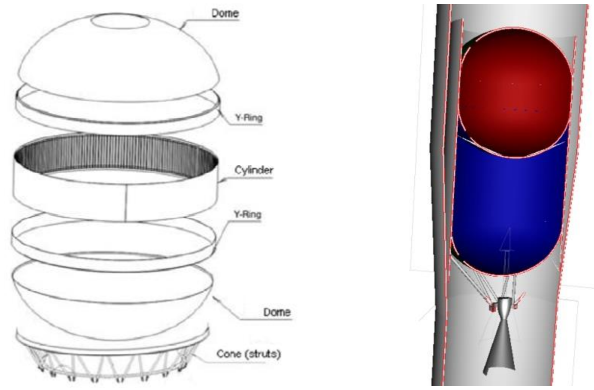

Fig. 4: Substructures (cylinder, dome, cone, struts) (left) and stage under fairing configuration of ASTOS (right)

This approach allows to estimate the structural mass with an accuracy of 5% to 10% without margin for subsystems. Hence, it is required to perform a mass estimation of all mass relevant subsystems, like avionics, feed system, pressurization system, and thermal protection, in addition.

1.1.5. Trajectory driven design margins

Design margins, which are typically considered and which are quite well to estimate, are mass margins, efficiency of the engine, and propellant reserve for de-orbiting.

Most often not considered are the following aspects: (1) unusable (residual) propellant, which remain in the tank, or which is vaporized during flight in the tank due to heating, (2) propellant reserve due to changing engine cut-off times resulting from guidance losses, (3) propellant reserve due to steering losses. They are simply unknown or are difficult to estimate without a discipline tool in the background.

4.2. Preliminary Structural Design

The typical approach for mass estimation is the definition of mass estimation regression based on existing data or based on results from expert tools. The critical aspect of regression of stage level is, that important details such as material, and included subsystems are missing. Considering the sensitivity of the inert mass this can cause a critical mass overestimation during first design loops.

Hence, it is obvious to separate the mass estimation into tanks, shell structures, engine and other equipment. That allows to consider specific materials, tank pressures, propellant temperatures and insulation, tank pressurization, feed lines, avionics and other elements separately.

If possible, the regression is performed as function of more than just one variable. For example, the mass estimation of a tank can be performed as function of the volume or surface. Or it can be performed on substructure level as function of basic geometric parameters, relative pressure and dimensioning load case [16].

Considering the need for verification it is useful to be able to produce a set of data points with expert tools.

4.3. Propulsion Design with ASTOS

ASTOS offers basically three levels for propulsion system design. The first performs a linear scaling of the thrust level. The second defines the optimizable parameters chamber pressure, mixture ratio, throat area and expansion ratio. A chemical equilibrium software like CEA [4] or RPA [5] can be used to compute the exhaust and characteristic velocity as function of those parameters. A similar approach can be applied for the Isp efficiency.

More difficult is the engine mass estimation. It is still an unprecise task of expert tools. Alternatively, a MER approach can be used for a subset of engines grouped into first stage and upper stage, and low-cost and high-performance engines.

The third approach allows the linking of an external user defined code or of an expert tool like ESPSS.

4.4. Propulsion Design with ESPSS

ESPSS offers a complete library for simulating propulsion systems using liquid rocket engines as well as hybrid rocket engines. It can be used to simulate simplified models of propulsion systems using only a few components like tanks and combustors or complete detailed systems including valves, pipes, filters, cavities, heat exchangers, etc. The ESPSS library includes a steady-state library, which can be used for pre-design and estimation of the most important parameters. The transient library then offers a comprehensive tool to simulate the transient behavior of liquid rocket engines, hybrid rocket engines, propellant management systems, turbopumps and pressurization systems. The EcosimPro platform, on which ESPSS is based, offers also its own optimization tool for optimizing parameters like orifice dimensions. ESPSS models give the complete freedom to model any propulsion system based on existing components and on user-defined components. ESPSS enables the user to validate different parts of the model like combustion chambers, piping, pressurization systems or others and then combine these parts in one model to simulate a whole system. For the MDO with an external optimizer like in ASTOS, there are some possibilities to export the simulation code from ESPSS like creating standalone decks or even c++ code. However, depending on the type of simulation there are some hurdles. If the ESPSS model is quite complex, a lot of data needs to be stored and reloaded for every optimization and simulation step, which can make the optimization very slow. Therefore, it is advisable to use simplified analytical models

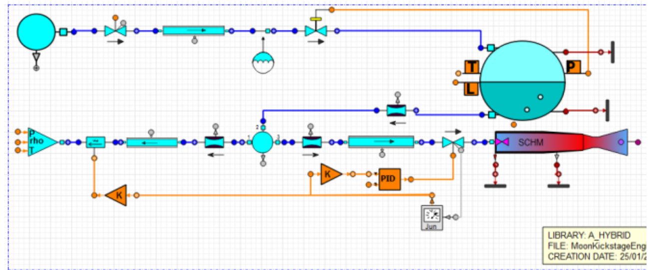

Fig. 5: Example of modelling a pressure-fed hybrid rocket motor with ESPSS

for the propulsion system to combine with ASTOS for the MDO. The simplified model will be much faster in computation time and require less data to be stored. The drawback is that a simplified model has less precision on performance prediction and the modeling of transient behavior. The ESPSS simulation can be then used to analyze the difference between analytical approximation and the complete simulation on the performance of the propulsion system and the flight vehicle. The analytic model can then be refined in order to improve the MDO result.

Fig. 5 shows a typical schematic of a model in ESPSS for a hybrid rocket motor having a propellant management system, a liquid oxidizer tank and a pressurization system. The represented model is considering four engines of which only one is actually modelled while for the other 3 engines, of the same type, only the oxidizer mass flow is modelled.

The design process of a propulsion system with ESPSS is iterative. First, a very basic model is created to simulate and evaluate the overall performance of the chosen propellants and engine cycle and to create a first mass estimation for the system. The data of the engine calculation needs to be validated also with test data or CFD simulations, as the 1-D simulation of the liquid or hybrid rocket combustor is not modelling combustion processes in detail. It is a basic calculation of the released heat from the combustion of the propellants and the heat flows through the chamber wall. The latter is small for a typical hybrid rocket motor but can be very decisive for a regeneratively cooled liquid rocket motor. The temperature and pressure that results from the combustion process in the chamber and a calculation of the expansion through the nozzle then is used to predict the thrust of the engine. Important parameters like injector pressure drop coefficients, combustion efficiency and nozzle efficiency are inputs for this calculation and need to be covered by other methods, i.e. experiments, CFD simulations or experience values. Combustion roughness and instabilities are not modelled in ESPSS either. In further steps the model can be more and more refined, including also modelling of control systems and thermal balances in the propulsion system. The simulation results of a very detailed ESPSS model can then be used to verify the precision of the simple models used in the trajectory optimization with ASTOS.

4.5. Aerodynamics Design

According to the sensitivity analysis the computation of aerodynamic forces has a quite low priority during design. Its impact is much higher for purpose of structural analysis and GNC design.

The easiest approach is to reuse a drag profile as function of Mach number of a similar rocket shape and to scale it with the aerodynamic reference area. Moreover, approximation methods based on the work of Barrowman can be used [8].

Finally, more sophisticated tools like Missile Datcom can be applied. Due to the increased computational effort it makes sense to perform the aerodynamics computation not at each iteration or even perturbation step of the AAO method.

4.6. Avionics Design

The impact of the avionics on the design optimization is only its mass. This concerns the mass of the TVC system, which is typically a function of the maximum thrust, and the mass of the attitude control system including its propellant, which is typically not known at that time point, and masses for electronic components and harness.

The share of the total mass is typically with in the uncertainties of the structural mass estimation. But with increasing accuracy of structural mass estimation and especially for micro launch vehicles, at least a first estimation should be considered.

4.7. Cost as Design Criteria

Cost is the most important design criteria and likewise the most difficult to obtain. Typically, a cost estimation regression (CER) is performed. The various approached differs on the subitems on which CER is applied and on the dataset, which is used to derive the coefficients for CER.

The most critical aspect is the scarcity of data. It is even more critical than that of MER on stage level, as companies have completely different manufacture capabilities and cost structures. Moreover, it is questionable how data of the past 60 years can be applied on NewSpace developments.

On the other side, it has to be considered that most microlauncher companies start their work on a technical baseline and that they have primarily to sell their idea. Normally they don't perform a wide trade-off to identify the most cost-efficient system for their mission target.

5. APPLICATION CASES

5.1. Nanolauncher Design Case

The objective of the nanolauncher design was the identification of a commercially most attractive launcher concept for a payload of 6 kg. The result can be interpreted as the smallest reasonable launch vehicle.

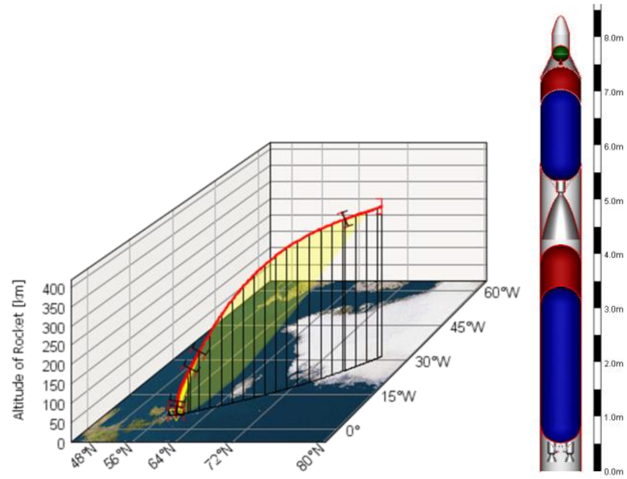

Fig. 6: NEUTRINO design and ascent trajectory from Scotland to SSO

First, several propellant combinations have been invested using simple models, which guarantee for fast computation time. In total several dozen design optimizations had been performed. The special aspect was, that due to the small payload mass, any subsystem weight had a potential impact on the design. Hence, masses for avionics had been estimated, but kept constant for all configuration of same type. Because of the unusual small size of the vehicle, dedicated MER tables for tanks have been computed. First trade-offs have shown, that the sizing limitation is the minimum wall-thickness for production, which had been assumed with 1.5 mm.

Three of those concepts have been selected based on the cost, which had been computed using AI-TRANSCOST [9]. Those are HTP95 and RP-1, LOx and RP-1, and full solid.

The promising concept was a three-stage launch vehicle based on HTP 95% and pressure-fed engines. This solution was especially attractive as the resulting length of the rocket was only 8.7 m, which had been considered as cost saver for production and logistics.

In a further step a detailed design optimization under consideration of dimensioning load cases for structural sizing and chemical equilibrium for engine sizing was performed. The final GLOW was determined with 2.6 tonne. Due to the extreme small payload only a solid motor without attitude control was selected as kick-stage for final orbit insertion. Fig. 6 depicts the sectional drawing of the design and the ascent trajectory with station visibility cone from the launch site. The sectional drawing considers a gas generator for production of the pressurization gas. Other designs model also the tank for pressurization gas including feedlines.

5.2. Hybrid Rocket Motor Design

Hybrid rocket engines are a promising alternative for liquid or solid rocket motors in certain application like sounding rockets [10], small launch vehicles [11], orbital propulsion [12] or planetary landers and return rockets [13]. A study using hybrid rocket motors on a lunar lander was conducted [14, 15]. ASTOS in combination with a user defined propulsion model for hybrid rocket engines was used, in order to not only optimize the trajectory but also the sizing of the propulsion system. For this, an analytical model of the hybrid rocket motor was implemented in ASTOS. In this analytical model, the oxidizer mass flow into the combustion chamber is the control value for ASTOS. Additionally, some constant parameters can be changed by the optimizer as well, like the rocket engine geometry. With these geometrical parameters like fuel grain length and diameter as well as the oxidizer flow the regression rate of the hybrid rocket fuel is calculated. Together with the density of the fuel this results in a mass flow of the fuel and the mixture ratio for the combustor. The combustion data of the hybrid rocket engine is read from a table which had been created with NASA CEA. In this way, the optimizer can directly optimize the hybrid rocket motor size and geometrical data to improve the performance of the motor and adjust the trajectory at the same time. The three staged lunar lander vehicle was analyzed with paraffin-based fuel and the following two oxidizer options: Liquid oxygen and hydrogen peroxide. Liquid oxygen offers the higher performance, however as it is cryogenic, the storability is limited to a few hours or days. The advantage of a hydrogen peroxide system is the long-term storability, the high density of the liquid propellant and the high mixture ratio for optimum specific impulse, resulting in a quite compact design.

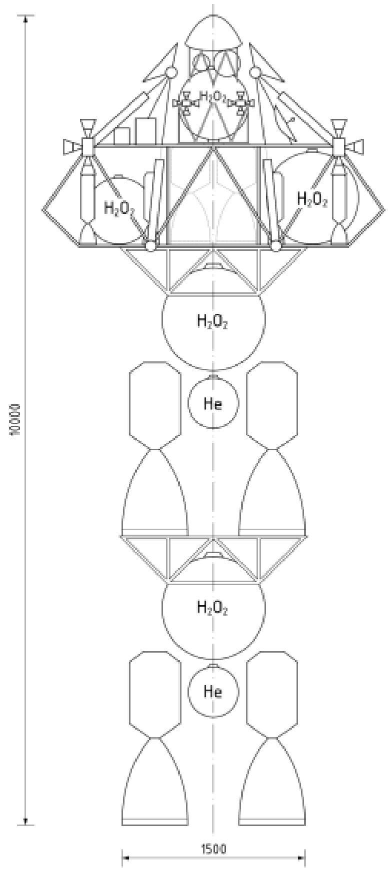

Fig. 7: 3-stage landing vehicle

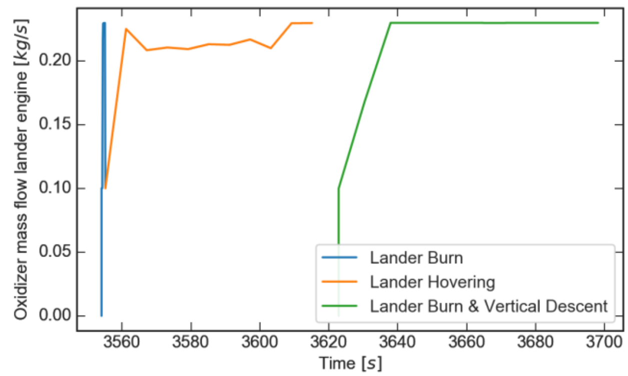

Fig. 8: Oxidizer flowrate during landing phases

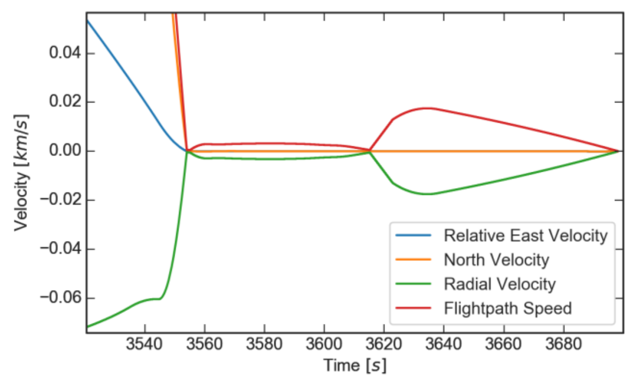

Fig. 9: Velocity during landing phases

Fig. 7 illustrates the landing vehicle with 3 stages, of which the 3rd stage is the landing vehicle. The two kick stages are identical and have 4 motors each. The triangular lander has 6 smaller motors.

Fig. 8 shows the control of the oxidizer mass flow rate as a result of the optimization for the lander vehicle for a single engine. Fig. 9 shows the corresponding velocity profile of the lander during the final descent. During the mission time from 3560 s to 3620 s there is one minute of hovering about 1000 m above the ground.

6. CONCLUSIONS

The paper summarizes the different modeling approaches and workflows for MDO dedicated to launch vehicles. It presents how such a task can be performed with the ASTOS software and with EcoSim Pro/ESPSS. It points out critical aspects.

The ASTOS software in combination with expert tools provides a comprehensive capability for the design of launch vehicles.

Further improvement is required for an integrated cost estimation and cost-driven optimization.

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