DIGITAL INDUSTRIES SOFTWARE

Ensuring space mission success

Using Simcenter to overcome engineering challenges

Executive summary
One of the hardest engineering challenges is to cope with the extremely harsh environments man-made machines are facing in space. We will follow the mission profile of such an endeavor and illustrate several engineering challenges and how to handle them by using Simcenter™ software to ensure a successful space mission from start to finish. All products in the Simcenter portfolio are part of the Siemens Xcelerator business platform of software, hardware and services. This white paper will explore some of the challenges these machines or vehicles and their payload and passengers are facing.

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Introduction

This white paper discusses some of the key issues with space exploration today and how companies have leveraged the Simcenter portfolio to solve these challenges. Learn about how you can use Simcenter for simulation, testing, safety, reliability and more to streamline these processes. This white paper explains a hypothetical example of how a company by the name of New Horizon, creates a spacecraft named Daedalus and explains the entire process from design to the completion of the space mission. This paper leverages real-life space mission examples and customer case stories from companies like SpaceDot to demonstrate how Siemens Digital Industries Software customers used these solutions and how this hypothetical company used the Simcenter portfolio to efficiently tackle space exploration for long-term success.

Foreword

As we take a deeper dive into space explorations, let's look at a hypothetical example of how a company can reduce space payload prices by deploying reusable rockets, which is a key factor to achieve sustained success in the space industry. As an example, picture a start-up founded in the early 2000s called New Horizon. Let's say the company has mastered utilizing the reusable rockets as mentioned above. This allows New Horizon to effectively compete with established space agencies. The more well-established space agencies may face challenges due to their size and often rely on governmental funding. After its initial success of taking leadership in the transportation of payload into orbit, the company decides to set a new ambitious goal of colonizing Mars with the first manned crew to the red planet by 2028. There have been many missions to Mars, but all of them were unmanned and packed with lots of instruments to explore the planet and its hostile environment.

Building on these previous missions, there is a lot of research out there about the conditions and challenges for a successful mission to land on Mars and its environmental conditions for future colonists. These enable New Horizon's engineers to have some boundary conditions to develop their new spacecraft. For this example, this spacecraft is named "Daedalus". One key challenge to overcome here is a strong line of communication between the home base on Earth. This is why Daedalus will carry six communication satellites named "Planet Link", three of which will occupy Earth's orbit and three on Mars' orbit to reduce any delay due to no direct communication from a bad orbital position and view between Earth and Mars.

Its mission will be to launch into space, drop the three satellites into Earth's orbit, refuel in orbit and then proceed to its mission to Mars. After reaching their new home planet, the colonists will drop the remaining three satellites in Mars' orbit and start their landing approach and entry into the Mars atmosphere, landing vertically at their defined landing site. Future missions will then be able to join the first colonists and over time, the fuel gained on Mars will be able to power Daedalus and its predecessors for a return to their home planet Earth.

Before the start of Daedalus

A lot of preparations must happen before the actual start of the Daedalus, including engineering the vehicle. Throughout designing a spacecraft, engineers conduct many simulations and multidisciplinary optimizations (MDO). For this example, New Horizon's engineers will use HEEDS™ software in most of the spacecraft components as weight is a crucial factor in space flight and optimizing a design for weight and performance is crucial. This section focuses on various operations that happened during the actual start preparation phase. One of these operations involves fueling the rocket. Rocket fuel is pumped into the rocket's fuel tanks under cryogenic conditions and high pressure to keep the oxidizer and fuel liquid if they're using nonsolid fuel. This means that the fuel pumps need to operate under cryogenic conditions that have an impact on their operation in various ways but the strongest one is, of course, the structural integrity at extremely low temperatures in operation. This requires thermal and structural simulation of such pumps, valves and other components to avoid any failure and potential explosions like the accident of the SpaceX Falcon 9 on September 1st, 2019, where a buckled liner where helium is stored caused the ignition of the oxygen.

Reliability, availability, maintainability and safety simulations

Engineers should model such failures by using a model-based reliability, availability, maintainability and (RAMS) solution as provided by MADe®, part of the Simcenter portfolio. Engineers can model an entire propulsion system this way, considering every component and subsystem. The whole system can consist of individual components and subsystems and the team can add and propagate any type of failure mechanisms logically between the model levels.[1]

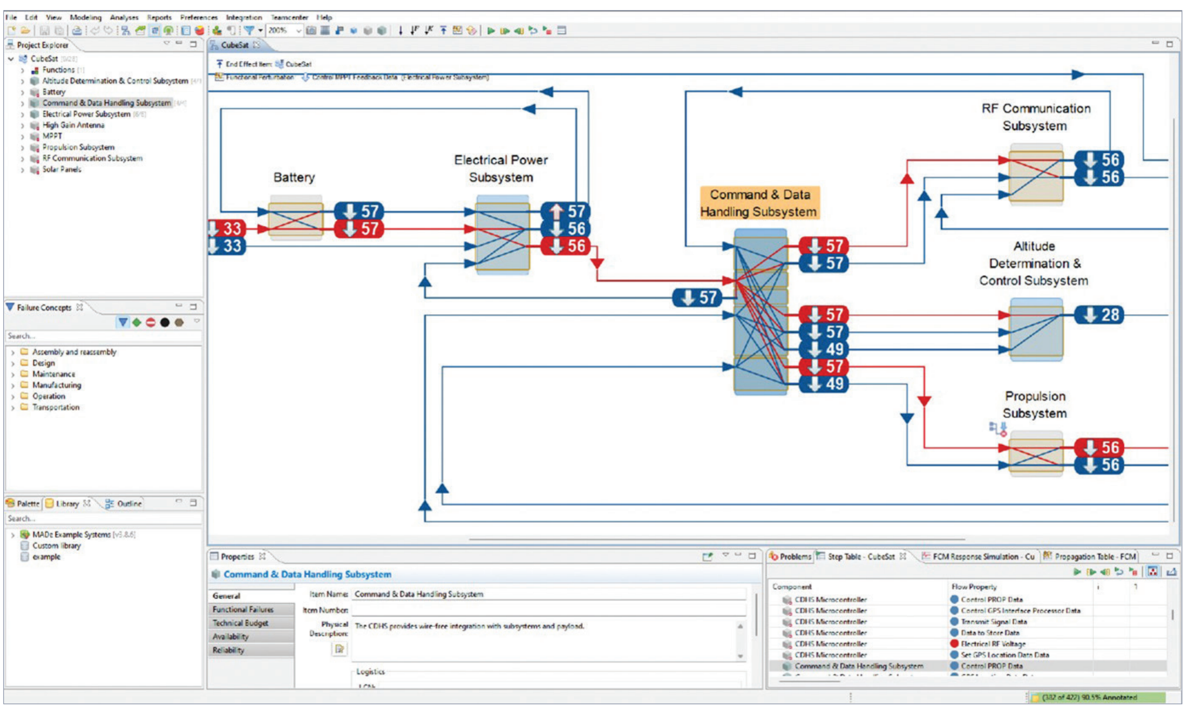

Figure 1. MADe environment of a small satellite model.

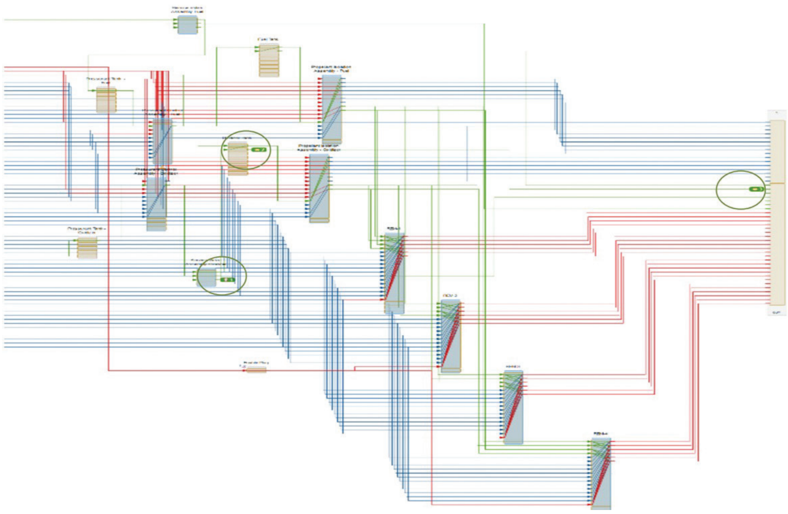

Figure 2. Failure injection and propagation through a larger system.[2]

These RAMS critical analyses allow New Horizon to uphold safety and mission assurance with high efficiency in their modeling process.

Another engineering challenge before the Daedalus even takes off includes analyzing the tank fueling sequence. The process involves carefully measuring and transferring the propellants from storage tanks to rocket tanks while ensuring that the fuel is at the correct temperature and pressure. The goal is to maximize the amount of fuel that the engineer can load into the rocket while minimizing the risk of accidents or fuel leaks.

During the filling of cryogenic fluid into a line that is at ambient temperature, some portion of the cryogenic fluid will vaporize before the line is cool enough to allow steady liquid flow. The purpose of system simulation is to study this cooldown process and assess the time it takes depending on various design and manufacturing parameters tolerances. It could assess the impact of the inlet valve opening characteristic on the cooldown of the line. The cryogenic line is modeled based on geometric parameters and material properties. The line is created by the assembly of the elementary block to create a spatial discretization and evaluate the state's evolution along the line (pressure, temperature and phase change).

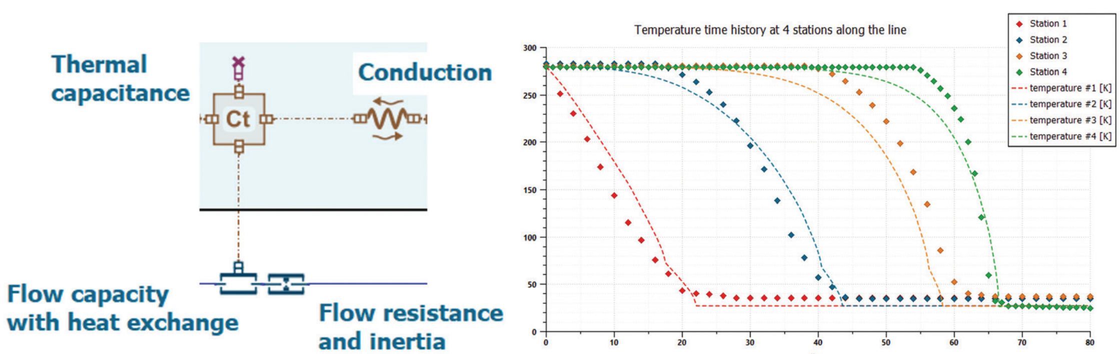

Figure 3. Elementary block used to discretize the cryogenic line (left). Temperature time history at the four instrument stations – saturated hydrogen supplied at 5.1 atm (right).

Launching into space

As soon as sparks are flying and the rocket engines are igniting, all hell breaks loose on board the Daedalus and in the near vicinity. The moment the engines start firing and a huge amount of thrust is building up to push the rocket with its colonists and payload into space, extreme temperatures are literally putting the launchpad's base into hell's fires and shaking up the payload.

Such immense forces and temperatures are exposing the launchpad structure and Daedalus' base to severe conditions while challenging the structural integrity. Simulation helps the New Horizon engineers ensure the fuel system with its pumps and piping works properly and the engine starts as well as keeping the engine nozzles cool enough to not melt away. This is a challenge for system and 3D computational fluid dynamics (CFD) and computational structural dynamics (CSD) simulation to ensure the proper operation under these conditions. Also, the entire Daedalus and its sensitive satellite payload and sensitive instruments are exposed to severe mechanical and acoustic excited vibrations, not to mention the colonists. The engineering team is using simulation and test equipment to analyze such scenarios and determine any potential failure during a launch and climb of the rocket as space systems are often one-of-a-kind. In space engineering, there is seldom room for prototyping.

Acoustic testing and simulation

The noise levels generated at launch can reach levels up to 146 decibels (dB) or higher inside the fairing and cause structural damages and jeopardize the functionality of instruments and subsystems. Launcher authorities require the Daedalus to also be qualified for acoustic loading. Before the spacecraft launch, the major subsystems such as solar panels, antenna and reflectors of the satellites are tested and exposed to acoustic pressures expected during liftoff and subsequent mission phases. Simcenter spacecraft acoustic testing solution operates in reverberation rooms and direct field environments. Its innovative closed-loop controller provides spatial uniformity of sound pressure level with additional control of overall sound pressure level responses.

Satellite acoustic testing is traditionally performed in acoustic reverberant rooms but it is costly and time-consuming. Direct-field acoustic noise (DFAN) testing is an alternative method that has gained a lot of attention in the last years. To replicate the acoustic loads, the DFAN technology does not require a dedicated reverberant facility but it can be realized with commercial loudspeakers and amplifiers in acoustically ordinary rooms. The test specimen is placed in the middle of a loudspeaker circle and gets excited by a direct acoustic field. Based on multi-input-multi-output (MIMO) narrow-band control algorithms, using Simcenter Testlab™ software allows the engineer to generate the required noise level (146dB) and field uniformity for spacecraft acoustic testing. This setup requires less cost compared to the investment and running cost of a reverberant chamber. The added value of the DFAN method is that you can move or transport the sound system to the manufacturing site. This is a key benefit since the payload doesn't have to be shipped to the test facility. The economic benefit for spacecraft manufacturers is clear: there is no need to build very expensive test facilities or to move payload and teams of engineers to a remote test center and increasingly efficient testing technology.

A test arrangement on a reflector shell of an antenna subsystem at Thales Alenia Space is shown in figure 4 below. The setup is comprised of 96 loudspeakers, stacked in 12 columns and adequately positioned in a circular configuration with 96 amplifiers that deliver the required power to generate a 147dB sound field. The setup uses Simcenter SCADAS™ hardware fitted with a MIMO controller combined with Simcenter Testlab software. 16 microphones around the test specimen are used to measure the sound field and generate corrected drive values to create a homogenous acoustic field.[3] To improve controllability of the test and uniformity of the acoustic field, many MIMO closed-loop control strategies have been investigated. Simcenter Testlab MIMO acoustic control software is using projection and optimization algorithms for a proper definition of test references for the MIMO random control process and an optimal selection of control sensors for acoustic field uniformity.

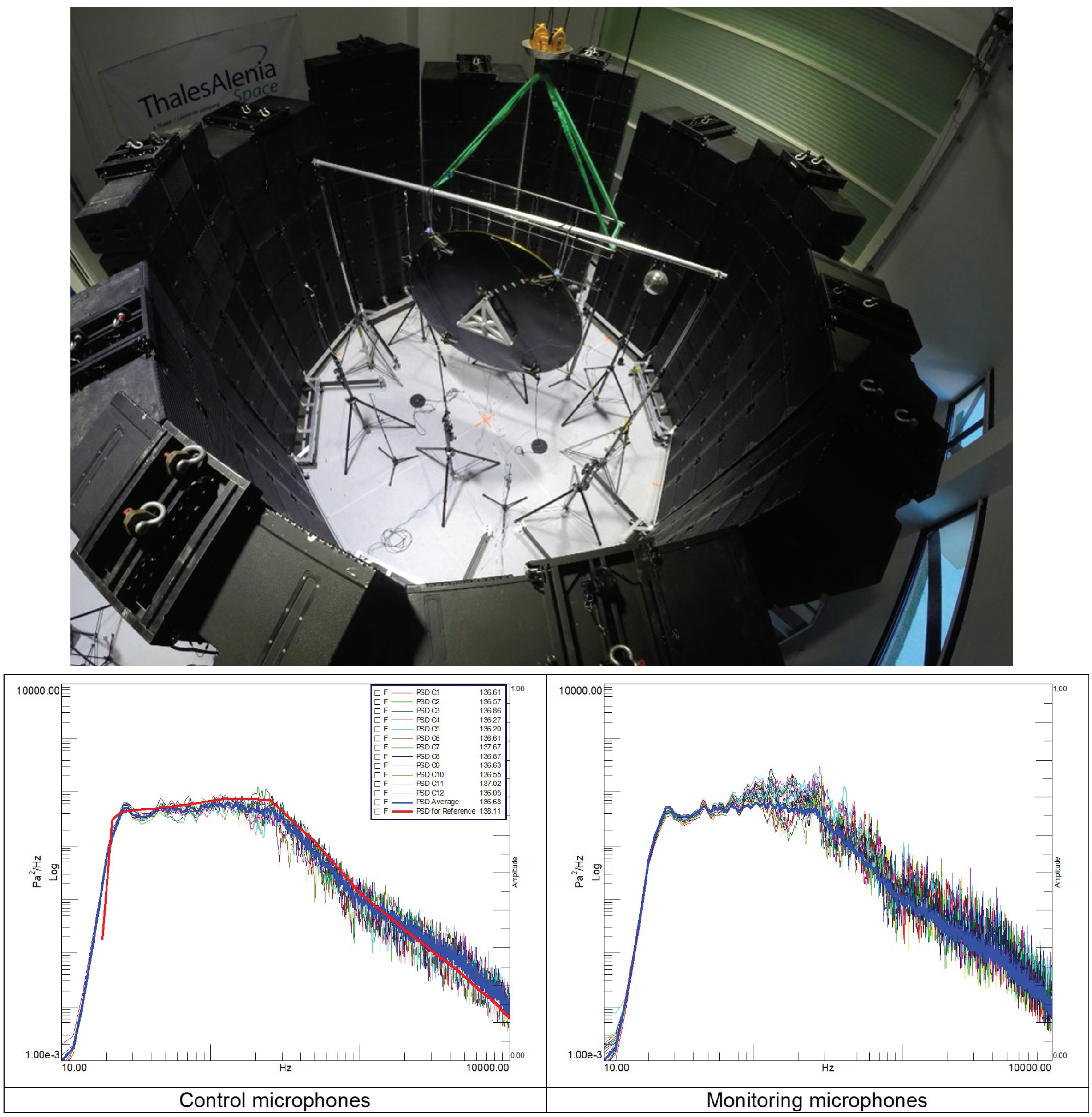

Figure 4. Direct field acoustic noise (DFAN) test on a Thales reflector acoustic response on satellite dish control and measurement channels.

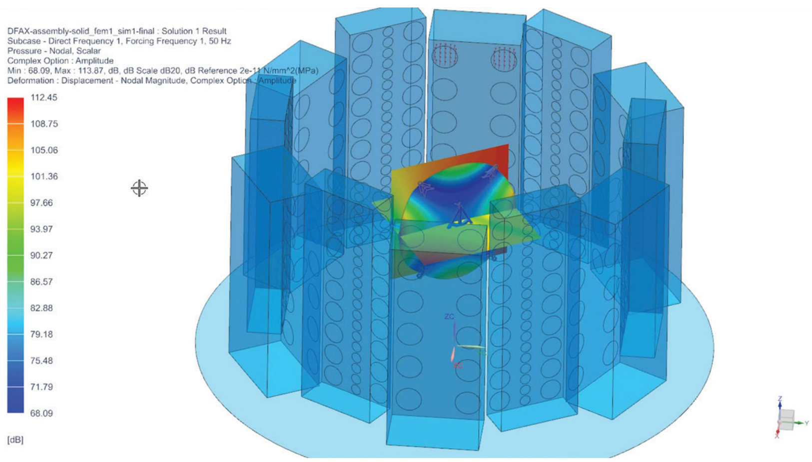

Figure 5. Digital twin of a DFAN test designed in Simcenter 3D to de-risk the test and predict the performance including uniformity check and structural response of the test item.

The comprehensive digital twin can play a significant role in supporting test campaigns before the actual physical test is conducted. For this reason, New Horizon engineers use Simcenter 3D to design and optimize the test setup, making it more efficient and safer. At the same time, Simcenter R&D team is researching ways to reuse the same digital twin models to estimate acoustic and structural responses in real time, even in locations where no physical sensors are present. The goal is to supplement the limited data obtained from sensors during the test with data from virtual channels, allowing for full-field monitoring.

Rocket engine CFD simulation

It actually is rocket science, but everyone surely knows that a rocket continuously accelerates toward space to reach the escape velocity required for its mission path and fights the gravity of Earth and the atmospheric drag in doing so.

During that climb, a lot can happen as the history of space missions shows. A few examples are the recently failed launch of Starship where several rocket engines failed, which caused a change in the plume of the rocket with stronger shock waves causing disturbances and of course the loss of control. The first simulations done on such a plume from the failed engines show the strong shockwaves as seen in video footage from the start and can help to understand the accident better.

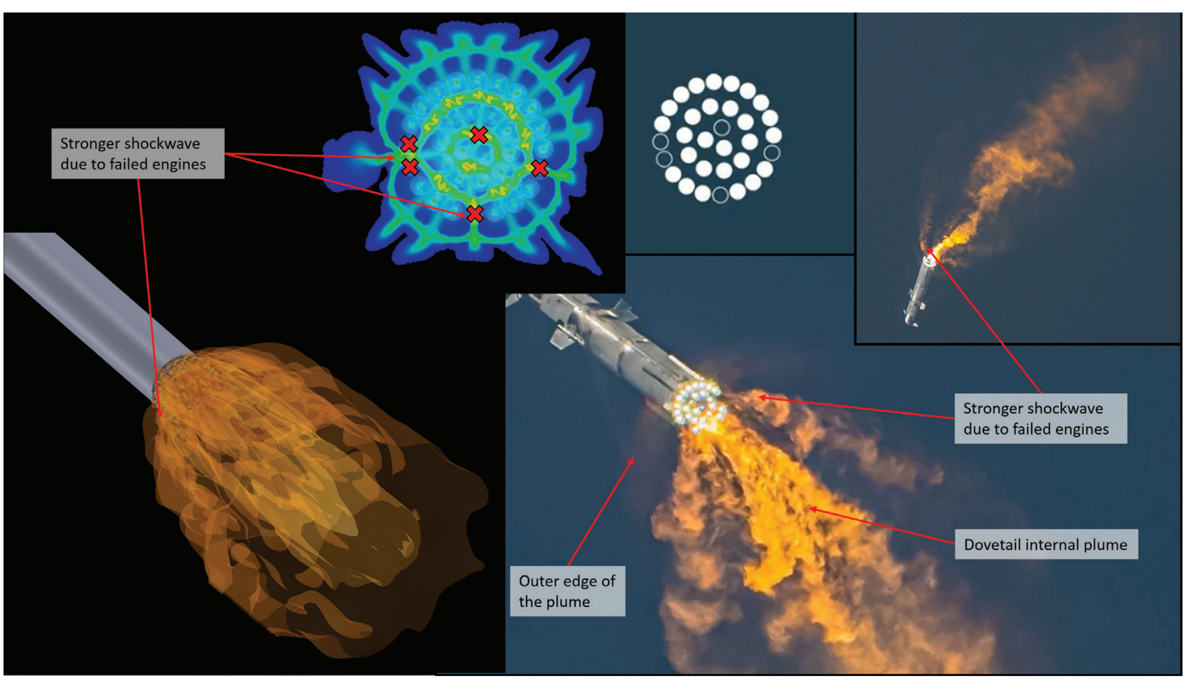

Figure 6. Simcenter FLOEFD™ simulation of the failed Starship engines and the changed plume. (Source: Sergio Antioquia Cuesta)

Other failed launches can cause by failing stage separation sequences. Several satellites were lost in a SpaceX launch on August 3rd, 2008, where a residual first-stage thrust led to a collision with the second stage.

Rocket engines are important to control with regards to thermal management as well as ignition and shut down and re-igniting them if needed such as for the reusable stages. The hot plume can propagate behind the nozzles and increase the thermal impact on the rear of the rocket stage, especially during the landing of them when close to the ground but also from the interactions between the various nozzles with the complex flow and its interactions. There are many reasons for failing engines and the New Horizon team used simulation to investigate before and after any such events to learn from any mistakes. Spacecraft are equipped with many sensors and cameras as well as cameras on the ground that are trained on the starting vessel to provide a lot of data on every start and can help improve the designs of future spacecraft.

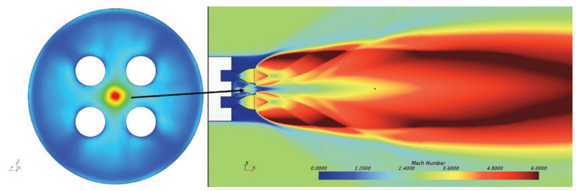

Figure 7. Heat reaching behind the engine nozzles with mean of heat boundary heat flux (left) and Mach number at low-pressure high altitude (right).

Such stage and booster separations can be tricky. Hypersonic flow with shockwaves interacting with the separating bodies as well as such residual thrusts can cause an unwanted movement that can lead to a collision. This requires New Horizon's engineers to run Simcenter STAR-CCM+™ software simulations with overset meshes and six degrees-of-freedom (6-DOF) simulations on the Daedalus.

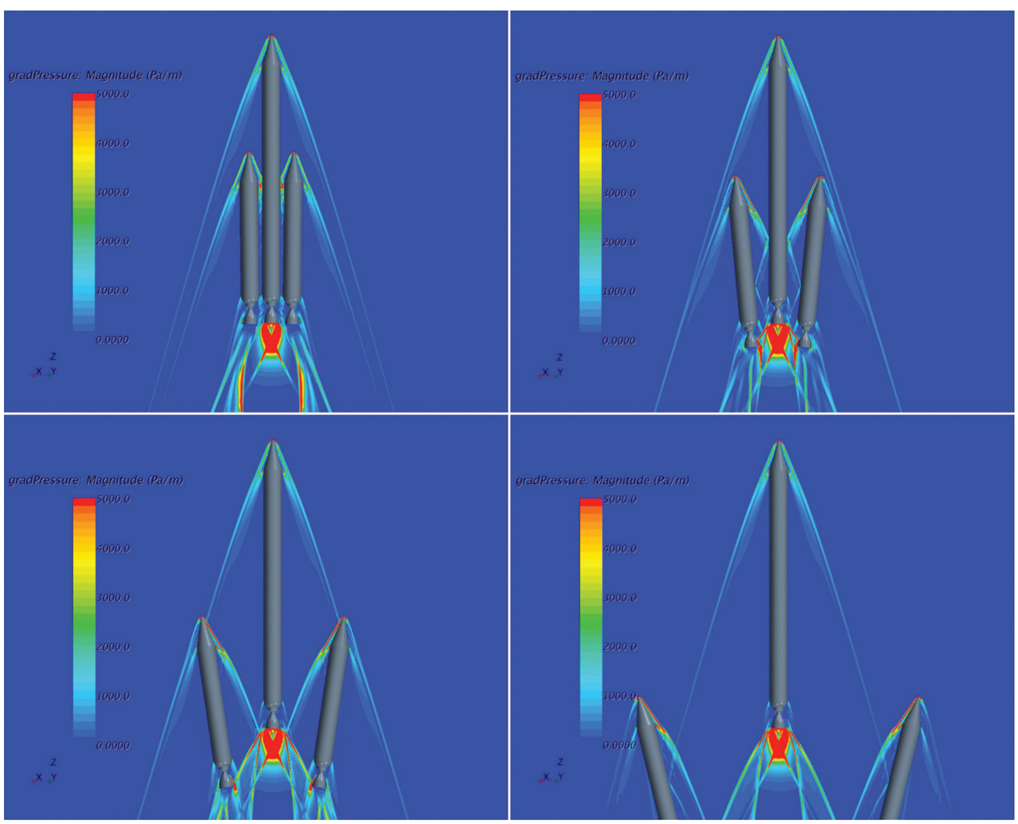

Figure 8. Overset mesh with 6-DOF dynamic fluid body interaction (DFBI) motion of the Delta IV Heavy at Mach 4, showing pressure gradient (Pa/m) at various stages of the booster separation with interacting shock waves and plume.

Vibration and shock simulation

During booster and stage separations, the payload and crew experience several high-energetic shocks and vibrations that are propagating through the spacecraft. Vibrations result from the acoustic loads as well as from various devices in the Daedalus from payload to fuel tank sloshing. The shocks result from pyrotechnic devices to separate boosters and launcher stages and may cause damage to the payload's electronics and compromise the functionality of mechanical parts, developing stress fractures and in some cases, shattering. Because of their high-accelerations and frequency content, many hardware elements and small components are susceptible to pyro shock failure while resistant to a variety of lower-frequency environments, including random vibration.

Engineers can use prediction of payload shock response simulation to validate test environments to ensure proper payload qualification and leverage Simcenter tools to test and simulate such events. At lower frequencies, a finite element analysis (FEA) approach is used by first performing a transient response analysis from which an acceleration time history is obtained. A shock response spectrum (SRS) is being developed by the New Horizon engineers, from this time history, Simcenter 3D Response Dynamics can then convert it into the frequency domain that is computationally efficient and shock response analysis can be performed.

Another approach at higher frequencies is to perform a statistical energy analysis (SEA) with Simcenter 3D Acoustics software, using a lumped-parameter model approach with simplified geometries to obtain the SRS and fully qualify the shock spectra.

In addition, the rocket motors high levels of acoustic noise induce high vibro-acoustic responses in spacecraft structures with large surfaces such as instrument panels. Panel-mounted units or components are excited via their interfaces to the panels. The New Horizon engineers evaluate the dynamic response of such a component using random base excitation analysis in Simcenter 3D Response Dynamics.

A random signal, typically an acceleration power spectral density (PSD), is applied at its base, which is assumed to be rigid. The results from a random base excitation analysis compute the following results:

- Peak or root mean square (RMS) acceleration, displacement, velocity, multipoint constraint (MPC) force, single-point constraint (SPC) force and grid point force
- Peak or RMS stress, strain and force
- Peak and RMS failure indices, strength ratios (laminates only) and margins of safety

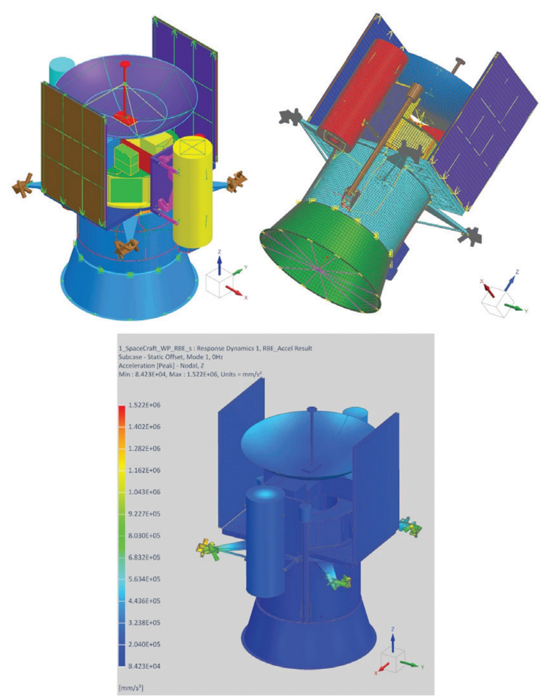

Figure 9. Spacecraft model, base acceleration was applied at central node at the bottom (top), RMS Z-acceleration contours (bottom).

SpaceDot, an interdisciplinary student team supported by the University of Thessaloniki, uses Simcenter 3D software modeling capabilities and Simcenter NASTRAN® software to solve the structural simulation.[4] Simcenter 3D helps the team reduce the time required to set up and prepare a simulation. The Simcenter NASTRAN solver minimized the required run, specifically for the dynamic solutions. The random base excitation solver then only required a couple of minutes to output the requested results that sped up the design process of the structural subsystem. According to the results, the team modified the satellite's components to increase the stiffness and strength or to reduce weight and reduced the mass of the payload's primary structure by 30 percent while still maintaining sufficient stiffness and strength to protect the experiment in the launch environment.

The SpaceDot team also had to make a few modifications during the design phase to achieve an optimal layout and a functional system. During the various design iterations, the team was able to rerun the analyses on the fly without compromising accuracy due to the integrated design-simulation (CAD-CAE) nature of Simcenter 3D.

The combination of test and simulation are very important for New Horizon's engineers. Using both methods to validate and improve the correlation of the models helps to improve the accuracy of test and simulation as well as provides a better understanding of the mechanics of the devices. One such application is also the modal survey testing that is used to validate the entire FEM and correlating frequencies, mode shapes and damping assumptions. A modal survey test consists of injecting forces, using electrodynamic shakers at several carefully chosen inputs. The validated models are important, among other things, to predict the launcher vibrational characteristics, the aeroelastic stability and the dynamic environments to identify which payloads and onboard equipment are submitted during the launch.

An example of a program where a modal survey test was recommended is Radarsat, a Canadian Space Agency project. The coupled loads analysis for this particular program revealed that damage during launch could occur on the synthetic aperture radar (SAR) panels.[5] Those four panels have almost identical geometry and are stacked closely together in the launch configuration.

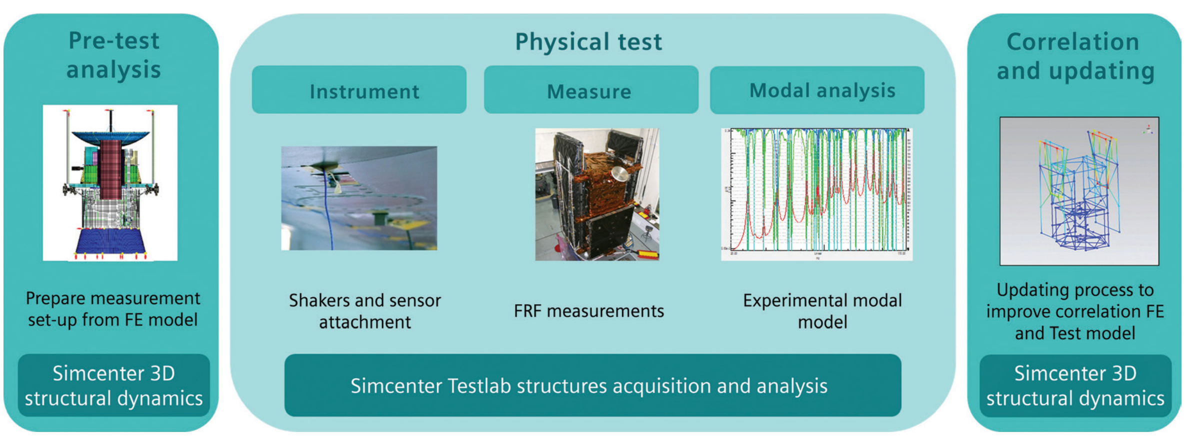

Figure 10. Modal survey of the Canadian Space Agency Radarsat satellite. Different stages of the verification process: from test preparation to the test execution, analysis and reporting (right).

Earth's orbit: Satellite deployment and refueling

After the Daedalus made its way successfully into Earth's orbit and the colonists as well as the payload experience weightlessness for the first time, a whole new environment greets them – the empty vastness of space. Here, new conditions challenge the Daedalus and the payloads with increased solar radiation outside of the Earth's atmosphere and no convective cooling as used on Earth.

On-orbit heating/cooling of spacecraft across mission profile

The impact of solar radiation on the Daedalus and its satellites can increase the cooling load, degrade the material properties of the structure and possibly lead to catastrophic failure of their missions. It is necessary to investigate the effect of the exposure to solar radiation on the thermal distribution of a spacecraft due to:

- The heating from solar radiation; spacecraft travel in space at different elevations and receive heat from the sun and dissipates heat into the surrounding atmosphere
- Surface charging and discharging; the energy conservation between the heat conduction within the spacecraft
- The radiative heat dissipation into the surroundings while accounting for the dynamics of the space vehicle (rotational motion)

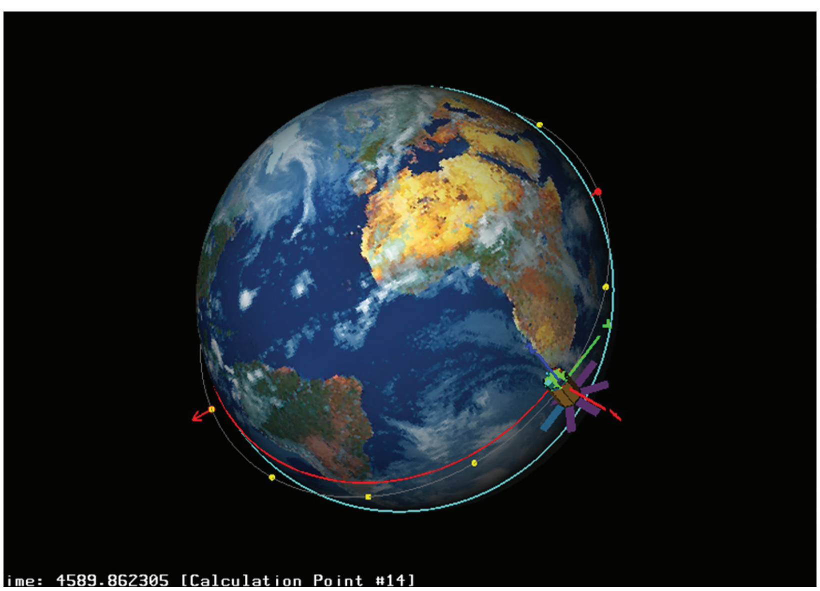

Figure 11. Orbital heating modeling.

Additionally, engineers must consider the solar load, shielding material, onboard equipment location, thermal control and air conditioning systems during the design stage of Daedalus and its satellites.

As such, the structure of a spacecraft will attain thermal instability with its space environment due to temperature variation along the outer and the inside surfaces of the space vehicle. In general, solar radiation is incident from a fixed direction, one side of the space vehicle body will shine bright and the other side remains dark. This will induce temperature variations across the body of the spacecraft in the absence of any rotational dynamics. Consequently, the space astronauts, onboard electronic equipment and cryogenic-fuel tanks gain severe heat on the bright side and lose heat from the dark side.

Using Simcenter enables the New Horizon engineers to design and validate the Daedalus and its satellites to ensure low and uniform temperature distribution on the spacecraft, therefore extending their lifetime and protecting all on-board electronic equipment.

The thermal control and vehicle dynamics play a pivotal role during the design stage of the Daedalus and its satellites.

- The design process of any space vehicle such as satellites requires detailed thermal characteristics in addition to the dynamics analysis of the vehicle motion to guarantee no thermal stresses due to high temperature fluctuations on the vehicle structure as well as on the payload

- To avoid severe thermal stresses that may damage onboard electronic equipment, the temperature variation of the entire vehicle should be kept within the appropriate range during the entire mission
- Since material tensile strength decreases with elevated temperature, it is important to study the effect of rotation and solar radiation on temperature distribution around and inside the spacecraft

Controlling the thermal characteristics is mandatory for the safe operation of the Daedalus and its satellites. Modeling of the thermal behavior is then associated with heat radiation effects and thermally induced vibration may exist at the high temperature gradients. Therefore, a coupled-thermal structural analysis for an altitude maneuvering under solar thermal loading and maneuvering dynamics is very important in the analysis.

Central to Daedalus' thermal control management is the spacecraft thermal control system (TCS), which comprises of active and passive systems.

Active systems comprise of:

- Thermostatically controlled resistive electric heaters to keep the equipment temperature above its lower limit during the mission's cold phases
- Fluid loops to transfer the heat emitted by equipment to the radiators[6]

Passive systems comprise of:

- Multilayer insulation (MLI), which protects the spacecraft from excessive heating or cooling
- Coatings that change the thermo-optical properties of external surfaces
- Thermal fillers to improve the thermal coupling at selected interfaces
- Thermal washers to reduce thermal coupling at selected interfaces
- Thermal doublers to spread on the radiator surface the heat dissipated by equipment
- Mirrors to improve the heat rejection capability of the external radiators and at the same time to reduce the absorption of external solar fluxes

The case study of the Mars Curiosity Rover helped New Horizon engineers understand how to leverage Simcenter solutions to design active and passive TCS. It also provided them with valuable insights into the importance and requirements of thermal control not only in space but also on the surface of Mars.[7]

Vibrations and multibody dynamics in space

In weightlessness, Newton's third law becomes a whole new meaning – "for every action in nature, there is an equal and opposite reaction". Maneuvering in weightlessness becomes trickier, and one thing satellites are using is a reaction wheel. These devices are used to maintain their orientation and provide three-axis altitude control but they also cause micro-vibrations in the satellite that impact the sensitive cameras and laser communication system's accuracy, which can lead to blurring of images. Scientific and Earth observation missions call for stringent requirements regarding the micro-vibration environment on board a spacecraft.

But also, larger shocks can occur during fairing jettison, the release of the satellites from the launcher and the docking with the fuel depot, similar to the booster and stage separation. On satellites, the deployment of appendages such as solar arrays, antennas or scientific instruments on deployable booms can cause such shocks as well. Here in particular, the multibody dynamics analysis helped simulate the correct and successful deployment of the Planet Link satellites' solar arrays.

Unsuccessful deployments of solar arrays, antennas and other spacecraft deployable appendages are one of the main causes of initial satellite failures and reduction in their capabilities with, on average, one failure occurring every two years. Because the spacecraft is brand new but cannot perform as designed and meet its mission objectives, deployables' failures result in extremely large insurance claims and in the case of the Planet Link satellite can have a severe impact on the communication quality and reliability between Mars and Earth.

Using Simcenter 3D motion simulation enabled New Horizon engineers to understand and predict the fundamental behavior of mechanisms from static to dynamic and kinematic mechanisms. It provides accurate results for reaction forces, displacement, velocities and accelerations for rigid and flexible bodies. The loads obtained from the simulation can also be applied to structural analysis and durability, noise and vibration studies.

Satellites in the inner solar system usually rely on photovoltaic solar panels to derive electricity from sunlight. This enables the power to run instrumentation or electrically powered spacecraft propulsion. Deployment failure could completely compromise the satellite and the mission profile. However, the Daedalus uses solar arrays to reduce the load on its power plant during the long flight to Mars. For example, rapid deployment of solar panels can induce undue stresses on the panels and damage the photovoltaic cells. Solar panel deformation due to deployment can be modeled with Simcenter 3D Motion Flexible Bodies, which helps increase the accuracy of multibody models by considering component deformations when simulating the motion of mechanisms. This approach allows engineers to combine the standard multibody simulation technology with a representation of body flexibility using a set of deformation modes.

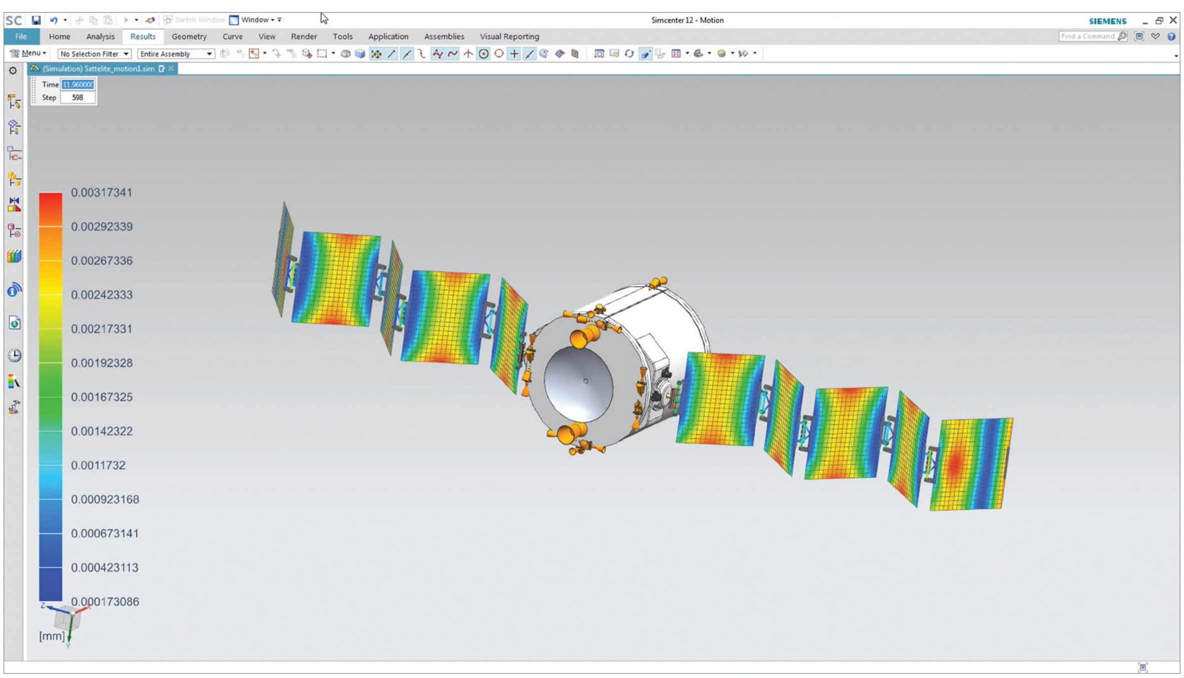

Figure 12. Solar array deployment analysis.

The long trip to Mars

The shortest time to reach Mars is somewhere between five to ten months depending on the launch window. That's a lot of time for the colonists to train their Sudoku skills or play with a match-three puzzle games. But besides the psychological toll on the colonists, the most important thing is the proper operation of the Daedalus and all its systems. Any failure of a system would require repairs without spare parts from Earth and stored spare parts are scarce for such a mission and should last for a longer time than a few months into the trip. Most important systems should therefore run under the harsh environment of space and the life support system is one of them. Having a proper ventilation system for good oxygen distribution as well as a detection system for any smoke of a smoldering electronics component or worse is key to survival.

A great source of financing for the Daedalus was the opportunity of running scientific experiments by some of the scientists among the colonists. Those experiments can focus on zero gravity, the impact of solar radiation on plants and humans and many more. Some of these experiments require additional thermal and flow considerations as well as structural simulations or data acquisition during the experiment execution. Any such experiment will have to comply with the requirements for safe operation on a spacecraft as well as of course the requirements of the experiment. An example would be the FreqBone bioreactor project designed by Voxdale and built by QINETIQ for experiments on cow bones.[8] The goal was to analyze living bones on how microgravity, vibrations and solar radiation would impact the density of bones from astronauts on long journeys such as the Daedalus to other planets or simply staying in Earth's orbit such as on board the International Space Station (ISS). The bone chamber had to be under 10 kg and be able to keep an internal temperature of 37.2 Celsius (°C), plus or minus 0.1°C. Thanks to experiments like these, we know now how to keep our Daedalus colonists healthy during such a long trip and any consequences from their stay on Mars with only 40 percent of the Earth's gravity.

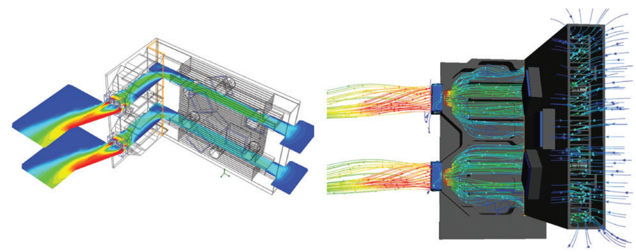

Figure 13. Predicted CFD velocities cut plots (left) and flow streamlines through the fan system (right).

A key aspect of the trip to Mars, however, is the restart of the Daedalus' engines to leave Earth's orbit as well as the braking maneuver to enter Mars' orbit. To accurately predict the start-up, engineers needed to maneuver the engine to correctly simulate each subsystem. Such an integrated system simulation model developed allows for a better prediction of the real flight conditions and their impacts on the engine start-up. The New Horizon engineers built such a system by connecting models coming from different engineering disciplines: 1) thermal analysis in an orbital environment, 2) spacecraft flight dynamics, and 3) rocket engine transient modeling. They used the Simcenter Amesim™ platform to combine these three models and create an integrated one, to simulate a sequence of maneuvers such as the ballistic flight segment followed by an engine re-ignition.

Conducting this modeling of rocket engine cooling jacket thermal behavior in space and its impact on the engine start-up, they seized the benefits of an integrated model. First, it facilitates the connection between models delivered by different engineering disciplines and the reuse of existing models. Secondly, it allows the simulation of complex missions with operating conditions that are not easily reproducible during ground conditions firing tests.

To accurately simulate real flight conditions, it is necessary to represent the effects of solar radiation on the engine nozzle. To achieve this, the engineering team utilized a specific 3D-based simulation in Simcenter 3D Space Systems Thermal. They extracted for the given orbit, season, attitude and location over the planet, the solar flux irradiation. The trajectory simulation is fed to the space thermal modeling. It computes heat loads resulting from direct solar flux, albedo and planet infrared (IR) using a radiosity approach to determine the reflection and absorption of the incident flux throughout the model.

The regenerative cooling jacket model has been adapted to consider orbital heating and radiative heat exchanges computed. During this illuminated flight segment condition, with an average solar intensity applied, engine re-ignition is impacted by the heat balance due to the heat accumulated during the previous combustion, the orbital heat loads and the heat released from radiation by the cooling jacket. It typically delays the restart and the combustion operating point is reached later with a lag in the engine performance.

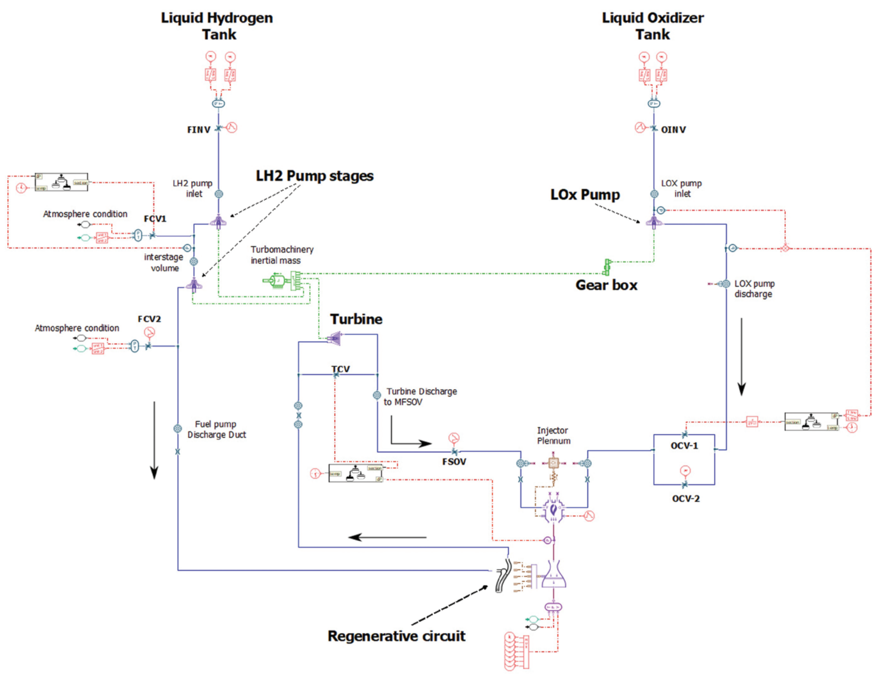

Figure 14. Simcenter Amesim simulation model of an expander engine model.

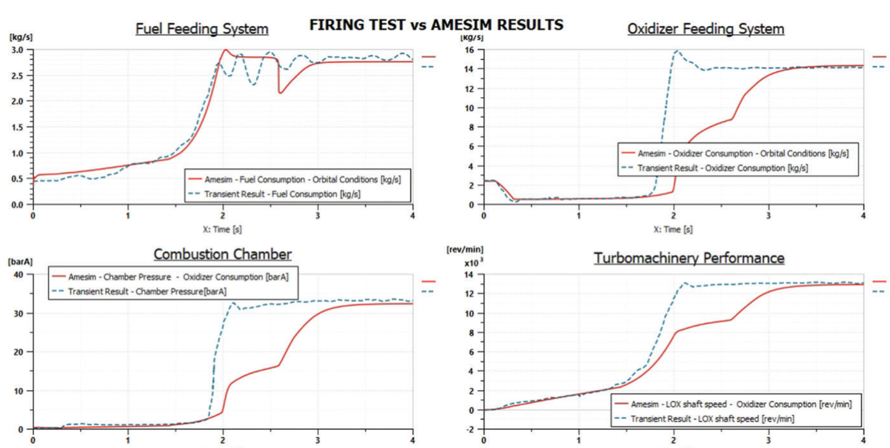

Figure 15. Simcenter Amesim simulation results – engine time-to-accelerate.

Entry into Mars orbit and the decent into atmosphere

After a long voyage, the Daedalus and its crew made it to Mars and the braking maneuver has already been initiated and luckily, the New Horizon engineers have done a great job in simulating the engine restart under these conditions after such a long time being offline.

The next step is deploying the next three Planet Link satellites in Mars orbit with somewhat changed operating conditions. The same conditions from Earth's orbit don't apply here, as the sun is further away with less solar irradiance in Mars orbit. In the higher earth orbit, the solar irradiance is around 1,360 W/m² while in Mars' orbit, it is around 585 W/m² and with that only around 43 percent. This changes the requirements on the satellite's TCS and one might think that a system designed for more solar radiation should make it easy to operate under less severe conditions. That might be right, but the system is also heavily overdesigned and saving weight in space flight is always a goal. So the actual satellites that might look the same as the ones orbiting Earth have a slightly different TCS. These optimizations can be easily done with HEEDS, which is also able to link between different simulation tools for optimizing systems not only thermally, but also structurally. As the system changes, the modal analysis might need to be repeated or micro-vibrations propagate differently due to a change in the mass and therefore the overall system's response to such vibrations, etc.

Atmospheric re-entry

The re-entry into any atmosphere dense enough to cause aerothermal heating at extremely high velocities will require a thorough investigation of the heat shielding of the spacecraft. Although the density of Mars' atmosphere is only a fraction of Earth's atmosphere density. The density on the surface of Mars equals the density in 35 kilometers (km) elevation on Earth. With that, the re-entry is not as severe as on Earth, but also the lift of any aerodynamic lifting body design of a spacecraft will be reduced drastically. Nevertheless, the re-entry will be a "hot" topic for the engineers of New Horizon, as no one wants to fail on the last few meters.

At such hypersonic speeds, the gases in the atmosphere ionize, molecular dissociation and chemical reactions appear, causing extremely high temperatures only proper heat shields can withstand and allow for a safe landing on the planet's surface.

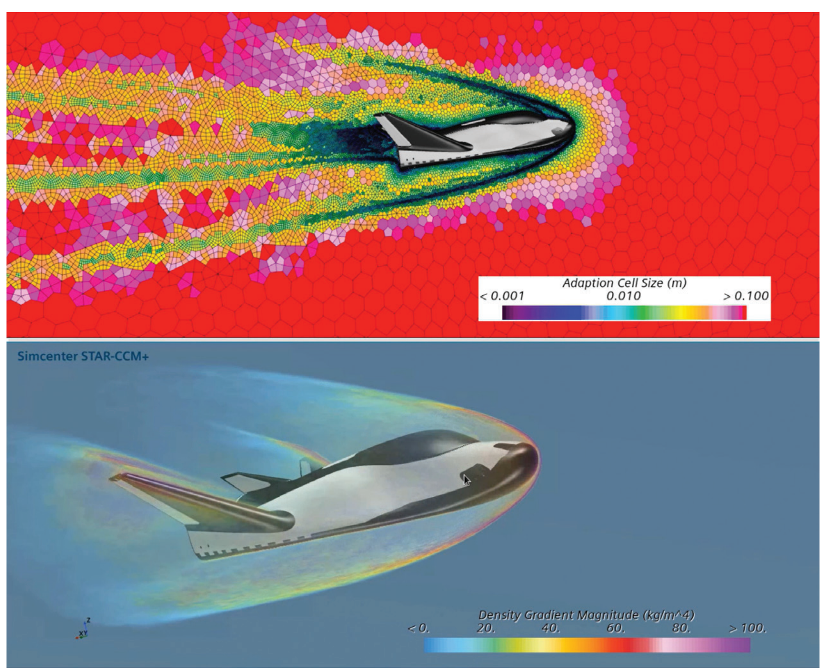

Figure 16. Re-entry Simcenter STAR-CCM+ simulation of Sierra Space's Dream Chaser at Mach 10 with adaption cell size (top) and rendered density gradient magnitude (bottom).

Touch down on the colonists' new home... Mars

The engines must re-ignite again for the safe vertical landing to decelerate the Daedalus. Again, the conditions have changed. Residual heat from the re-entry, different environmental conditions and the need to ignite at the right moment, put the engines to their final test in the Daedalus' mission.

The last hurdle before the crew can set the first foot by mankind on Mars' surface is the safe touchdown of the Daedalus and the impact of that on the passengers strapped into their seat. This final strong shock needs to be overcome by the landing struts and the Daedalus' general structure if it is to launch back to Earth at some point in the future.

Such landings can vary a lot based on the way the spacecraft touches down on the planet. Historic landings have been with space capsules either on parachutes onto solid ground or splashdowns in the ocean. These landings are of course the hardest if there is no final burst by some engine to take the last bit of kinetic energy out of the landing. Especially the splashdown requires a multiphysics simulation to take into account the impact on the water with its speed, impact angle, sea state and the effects on the final loading on the astronauts' body and capsule structure.

A multiphysics digital representation is possible by combining CFD, structural and occupant simulation.

1. In the first step, the water impact of the vehicle is modeled within Simcenter STAR-CCM+, which uses a hybrid modeling technology for the multiple phases involved. The initial impacting conditions the overall motion of the vehicle and the pressure distribution loading on the structure are calculated over time.
2. In the next step, a structural dynamics analysis is performed to assess the structural integrity due to the propagation of the impact loading and the specific motion of the structural parts that interact with the occupant and restraint system. For the safety performance of the vehicle, the motion of the floor and seat connection points are derived. These are the key structural parts that interacted with the occupant and safety system. Additionally, structural loading is analyzed to assess the safe egression of the occupants and water entry.
3. In the third step the human body dynamics of the occupants is calculated using efficient multibody dynamics analysis in combination with explicit FE analysis of the restraint systems. A Simcenter Madymo™ model is built that includes an occupant, a seat and a safety belt. After the simulation, injury values for the neck, lumbar spine and head are assessed according to the industry safety standards in aviation, automotive and lifeboats.
4. Finally, a parametric study can be executed using HEEDS on the effects of muscle strength reduction, due to long space travels in combination with a variation in landing conditions and safety system parameters. This method ensures an efficient and robust simulation toolchain for capsule splash-down analysis that accelerates capsule design optimization and minimizes injury risks for astronauts.

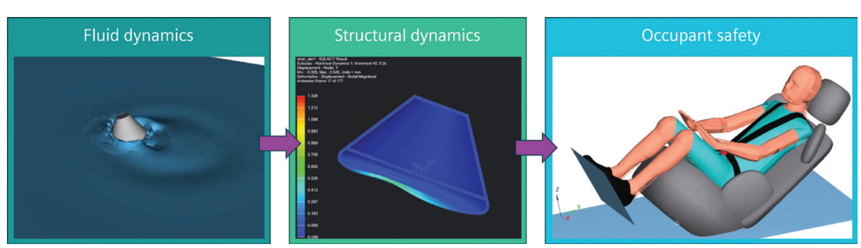

Figure 17. Splashdown occupant safety engineering stream involving three engineering disciplines.

With that, the New Horizon team and the colonists achieved their target successfully thanks to thorough engineering work and the application of the digital twin throughout the development of the Daedalus and its satellites.

While this fictional story does not encompass all the potential simulations that engineers may undertake to ensure a successful space mission, it does offer insight into several applications, their requirements and purposes. To learn more about the many other applications that the Simcenter portfolio can assist you with in designing your successful space mission, please contact your Siemens sales representative.

Please note that the names of the New Horizon company, its spacecraft Daedalus and the Planet Link satellites are entirely hypothetical and do not represent any real companies and spacecraft. Additionally, no humans were harmed during the voyage of the Daedalus.

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