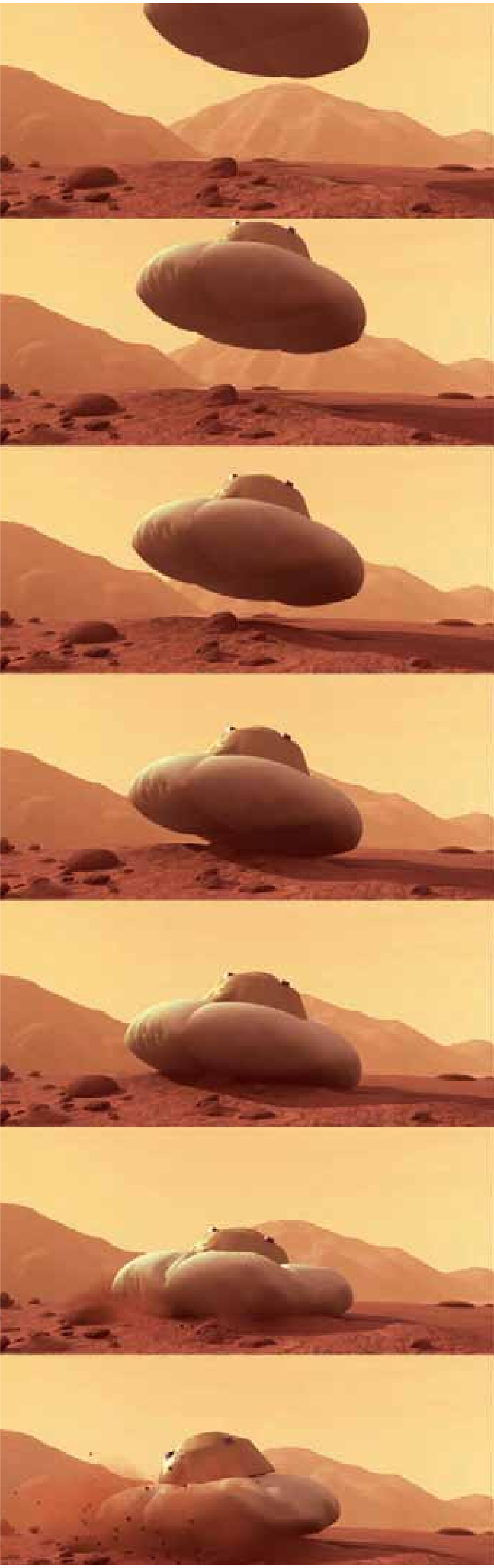
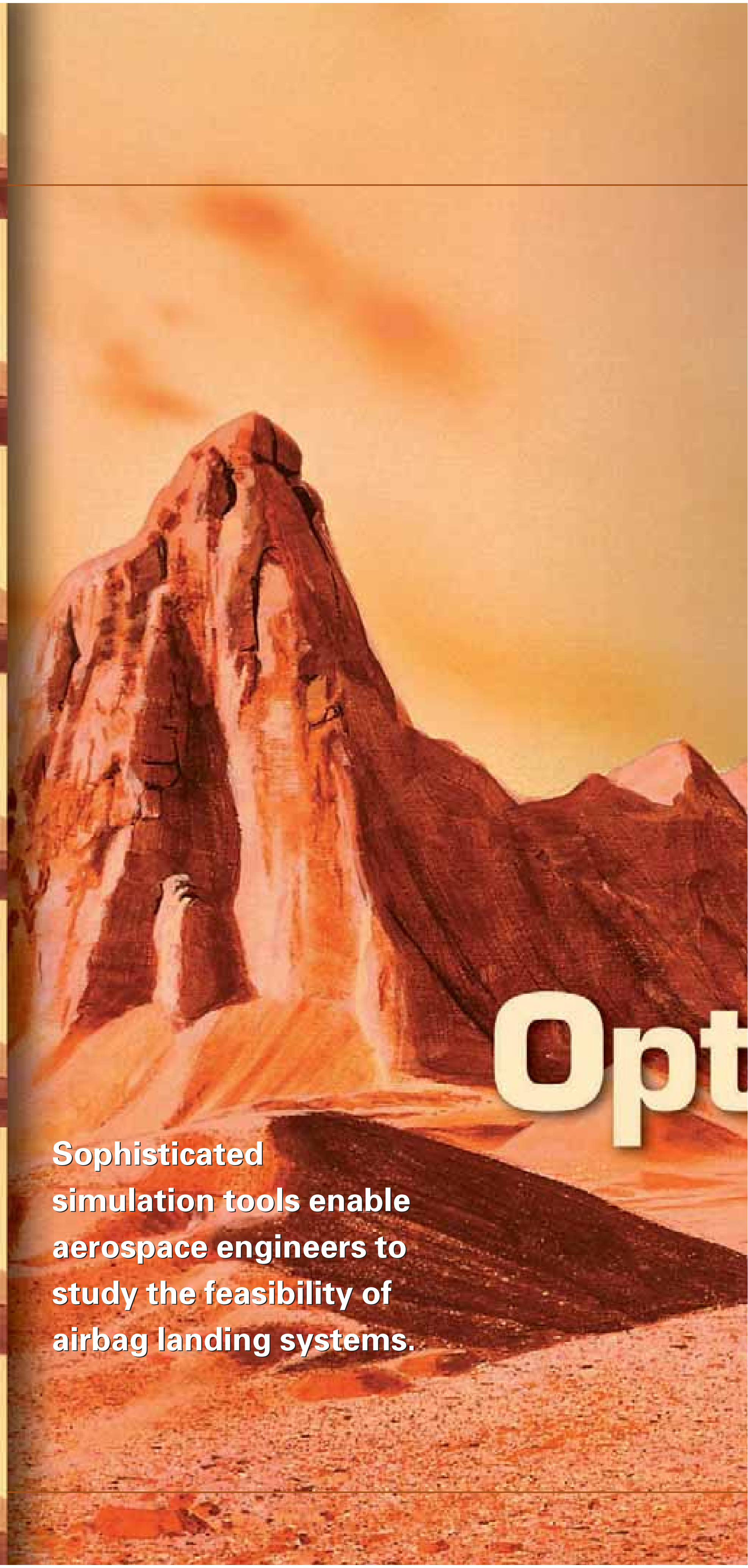
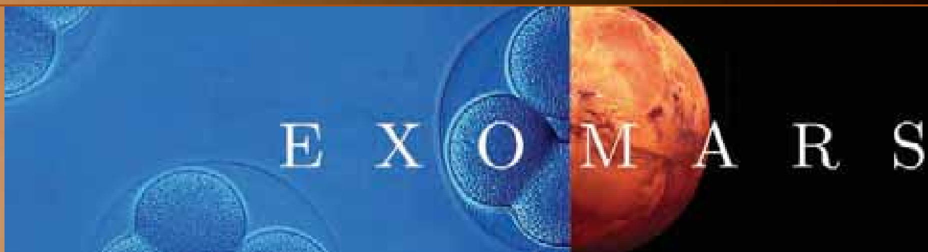




Opt

Sophisticated simulation tools enable aerospace engineers to study the feasibility of airbag landing systems.



After a journey of over 500 million kilometers taking nine months, the success or failure of the ExoMars mission will depend on what happens in the last meter and last one-tenth of a second. Controlling this final short but critical phase of the flight is the job of the airbag landing system.

In 2004, when a team led by EADS Astrium (with EADS Space Transportation and Analyticon Ltd.) performed a phase A mission study for the European Space Agency (ESA), it quickly became apparent that the landing system presented one of the biggest challenges, and one which was going to greatly influence the design of the rest of the spacecraft. Landing spacecraft on Mars is well known to be a risky business, with an overall success rate of only about 50%.

Several descent and landing system concepts were, therefore, assessed during the study, ranging from fully controlled liquid fuel rocket stages through to more passive concepts incorporating parachutes and airbags. One of the most attractive, because of its low mass, was a system using a large, high-efficiency, ring-sail parachute and a vented airbag.

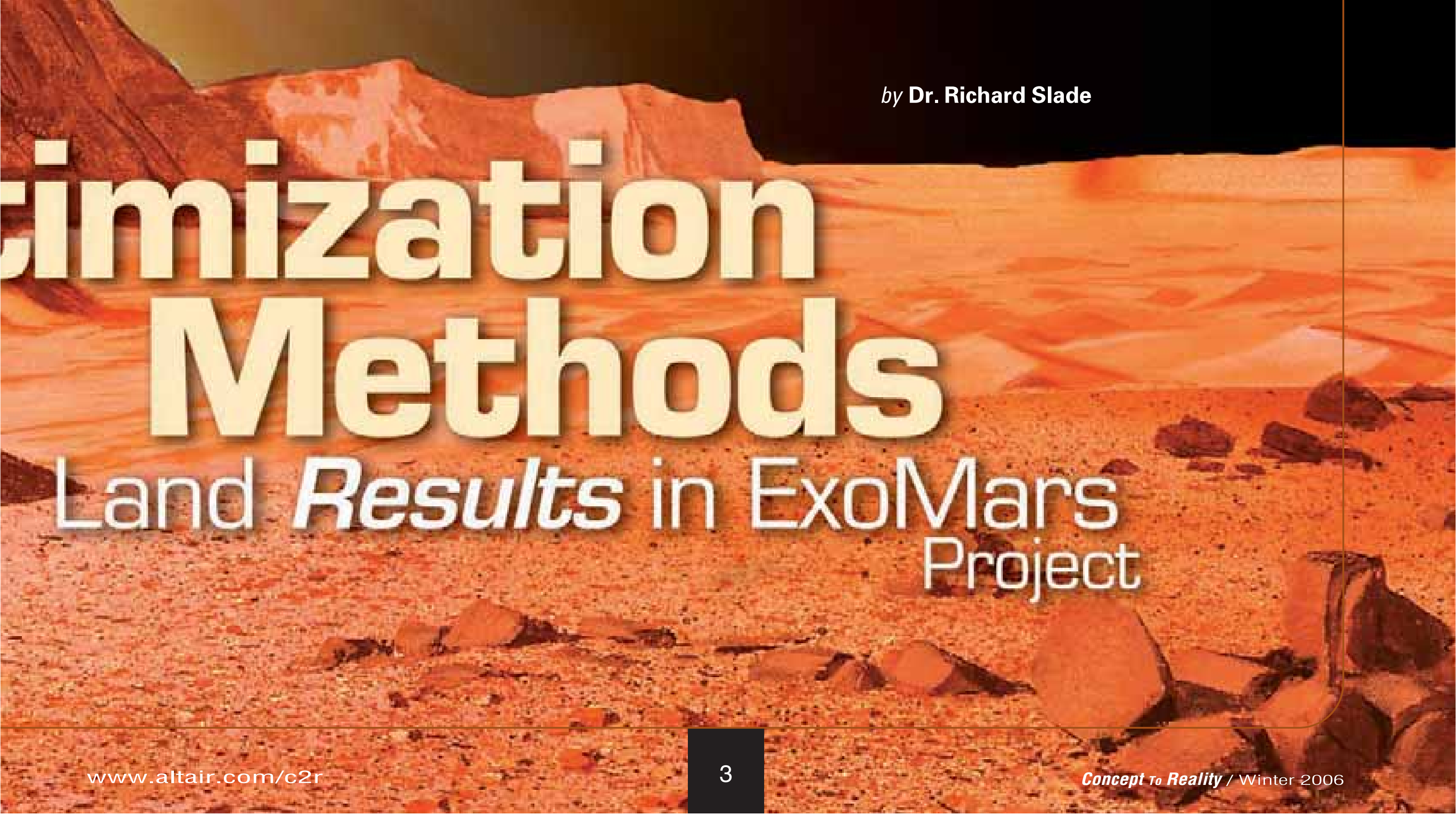
Vented Airbags

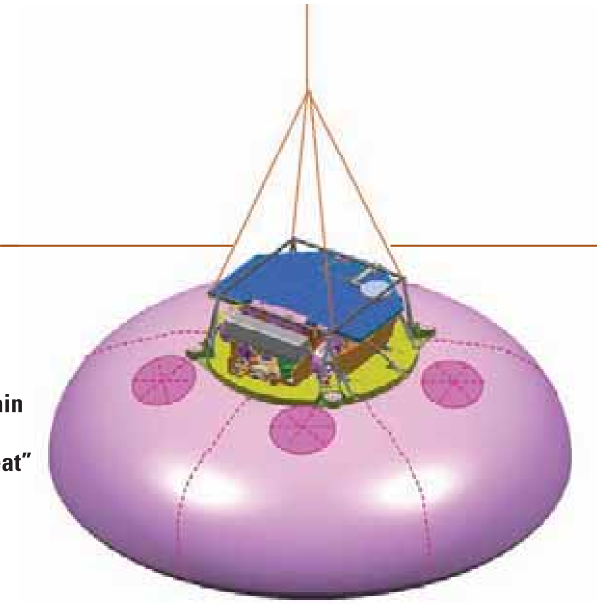
A vented airbag cushions the final impact by expelling the inflation gas through large vents that are opened during landing. The objective is to bring the vehicle to rest within a single compression stroke with minimum rebound.

As the compressed gas is forced through the vents, the ideal airbag behaves like a critically damped spring-damper system. Hence, it is often known as a "dead-beat" airbag. The impact duration, from making initial contact at about 55 mph (25 m/s) to com-

by **Dr. Richard Slade**

timization Methods Land *Results* in ExoMars Project





ExoMars Rover descent under main parachute with inflated "dead-beat" airbag

ing to rest, takes typically less than 100 milliseconds and results in decelerations of up to 80g.

In the design concept proposed for ExoMars, the stowed rover is mounted on the top of a stiff circular platform with the packed airbag fitted underneath. During terminal descent under the main parachute, the airbag is inflated to provide a protective envelope that extends below and beyond the edge of the platform.

The main envelope is divided into six compartments by impermeable radial diaphragms, and each compartment has a large vent patch to the outside atmosphere on its upper surface. Inside is an inner toroidal bag positioned directly under the platform, inflated to a higher pressure than the main compartments. This "anti-bottoming" bag is not vented during the impact but provides a final landing cushion to absorb the residual kinetic energy after the main compartments have vented.

Unvented Airbags

An alternative airbag concept is the unvented, or "bouncing ball," type used for Mars Pathfinder, Mars Explorer Rover and Beagle2. It has a long space heritage going back to Russian moon probes of the 1960s. Here, the payload is completely enveloped by the inflated cushion, and there is limited energy dissipation during impact, resulting in many bounces before finally coming to rest in an unknown attitude. This landing system is consequently much heavier than the vented dead-beat airbag type because the airbag itself is much larger, and a robust protective structure with a self-righting capability is necessary around the rover.

The vented airbag offers a lighter solution. Although it has no space heritage, it has been employed in numerous terrestrial applications, such as low-level supply dropping and the recovery of remotely piloted vehicles, launch vehicle boosters and aircraft crew escape capsules.

What Can Go Wrong?

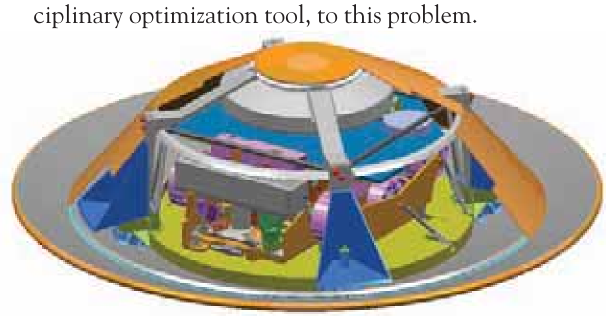
The primary concern with a vented airbag is the possibility of overturning during landing, a failure mode not present with the unvented bouncing ball type. Excessive bounce is also a problem, since only the anti-bottoming bag provides limited protection against a second impact.

A goal in the design of the airbag geometry and the venting control system is, therefore, to kill as much of the kinetic energy as possible in the first impact while controlling the attitude of the platform.

Other failure modes, common to both types of airbag, are exceeding the payload deceleration limit, which in the extreme case involves the payload striking the ground directly, and rupturing of the airbag fabric. Fabric rupture is less critical for the vented type since the area of local tears is generally small compared to the large vent areas, although these can upset the venting control.

A New Analysis Approach

Following the ExoMars mission study for ESA, EADS Astrium was interested in investigating the potential of the vented airbag concept, in particular to develop methodologies for optimizing the design and determining the landing reliability or robustness of such a system. A research and development initiative was therefore initiated in 2005 with Altair Engineering's UK office to apply recent advancements in Altair HyperStudy, a parametric study and multi-disciplinary optimization tool, to this problem.



ExoMars Descent Module with stowed Rover and packed airbag

In order to limit the scope of the study, the optimization was restricted to four main design variables, and the robustness assessment was restricted to four landing condition variables. A simple venting strategy was adopted based on triggering all of the compartment vents simultaneously once a resultant acceleration threshold was exceeded. More sophisticated strategies (opening the compartment vents at different times) and alternative sensors to accelerometers (such as pressure transducers and radar or laser-based range-finders) are possible, but the simple concept was retained in order to establish its capabilities before moving to more complex systems.

Explicit nonlinear finite-element analysis (FEA) has been successfully used to simulate airbag behavior on a number of programs. In this case, LS-DYNA was used with a modified Wang-Nefske airbag gas model for inflation and venting.

The problem with this approach is the long run times necessary for each impact analysis. Typically, tens of hours of CPU time are required to simulate an impact of a few hundred milliseconds duration. A trial-and-error approach to optimizing the design can, therefore, become a lengthy process, and a Monte Carlo robustness analysis requiring thousands of runs is impractical.

To overcome these problems, an approach using approximated, or surrogate, response surfaces — which is built into HyperStudy — was used. A response surface gives the value of a key output variable, for example the peak deceleration of the payload center of mass as a function of a number of input variables, such as inflation pressure, airbag diameter, vent size, etc. N variables results in an N-dimensional response surface. By approximating the surface, rather than generating it from every combination of the design variables, the number of FEA runs can be reduced to a practical number.

Once generated, the surrogate response surface provides a powerful means of either optimizing a design — maximizing or minimizing a response as a function of design variables subject to constraints — or analyzing its robustness — performing Monte Carlo simulations to determine whether a response exceeds a failure criterion due to statistical distributions of the variables.

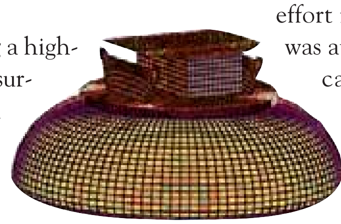
The key to this approach is making a high-quality approximation to a complex surface from a limited number of FEA runs. This requires selecting the combinations of variables to give a representative distribution over the N-dimensional design space (known as the Design of Experiments, or DOE) and sophisticated algorithms to generate a surrogate surface that gives a good fit to highly non-linear responses.

ExoMars Project

ExoMars is the European Space Agency's (ESA) first "flagship" mission in its Aurora exploration program of the solar system. Its objective is to land a rover on Mars with an exobiology payload to search for signs of extinct or existing microbial life.

The rover is equipped with a drill for acquiring samples from two meters below the harsh environment at the surface and an on-board analytical laboratory containing a number of different instruments. As originally conceived, the rover weighed 240 kg and included 21 science instruments in addition to the sample acquisition, preparation and handling systems.

The scope of the science payload has recently been downsized, and the rover mass reduced to 150 kg. The planned launch is by Soyuz ST from Kourou, French Guyana, in 2011 with an arrival at Mars in 2012.



The Optimization Problem

The optimization problem was originally defined in terms of minimizing the mass of the airbag system (fabric, gas and gas storage device) as a function of four selected design variables: airbag diameter, airbag height, inflation pressure and vent area, subject to passing several landing success criteria under two prescribed landing cases.

Geometric variables are particularly important for optimizing the design, but they are traditionally the most time-consuming to implement because of the effort required to remesh the FE model. This was automated using HyperMesh's morphing capabilities to remesh the model with geometry scaled from the primary diameter and height dimensions.

The landing success criteria were

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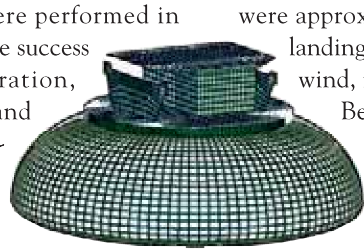
defined in terms of the peak deceleration, residual energy, attitude angle limits and fabric maximum stress. The prescribed landing cases were: (1) a 25 m/s vertical velocity impact onto a hard flat surface, and (2) an impact with an additional 16.3 m/s horizontal velocity component due to wind, a pitch-down attitude of 20° and a 10° up-slope landing site with a 0.5 m high rock contacting under the leading edge. These cases were selected because they result in conflicting requirements and force a compromise in the design variables.

The combination of design variables for performing the FEA runs was based on a Uniform Latin Hypercube, with the addition of the corner points, to give uniform filling of the design space. This DOE test-point plan, known as an Extended Uniform Latin Hypercube (EULH), was generated by a genetic algorithm.

Once set up, the FEA runs were performed in batches, and approximations to the success criteria responses (peak deceleration, residual energy, attitude angles and fabric stress) over the complete design space were estimated using an advanced Moving Least Squares Method (MLSM). This method results in a better representation of the response surface where it is highly nonlinear.



For example, the peak deceleration response exhibited a "shallow valley" between the vent trigger level and the maximum acceptable to the payload, surrounded by "steep cliffs" with high noise levels for designs where the airbag made hard contact with the ground. By capping the responses in the "failed" region and adjusting the closeness of fit parameter, the MLSM produced a high-quality approximation in contrast to a conventional least squares approximation, which distorts the area of interest (the "shallow valley") while trying to fit to the steep edge "cliffs."

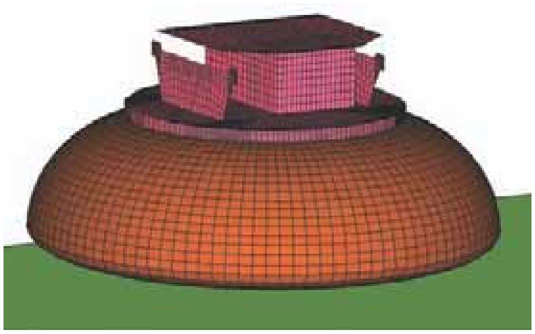
Results of the optimization exercise showed only a small "sweet spot" that met all of the landing success criteria. Since there was little variability in the airbag system mass in this region, the selected "optimum" design was instead based on minimizing peak deceleration and residual energy responses.

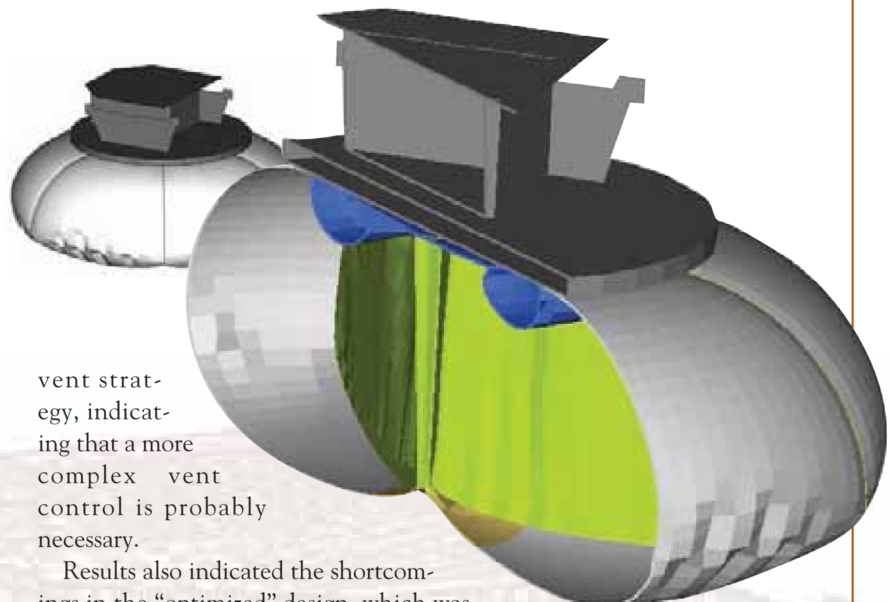
By performing FEA of the selected design, it was possible to confirm the validity of the approximated response surfaces. The optimized design resulted in vent areas at the maximum of the prescribed range, indicating that this parameter had probably been too constrained and could probably be increased to improve the design.

The Robustness Problem

The most important question to be answered for the vented airbag concept is: What is the probability of a successful landing? An answer permits a proper trade-off of mass and risk with unvented airbags and other landing concepts.

The methodology for quantifying the landing success probability under a range of landing conditions was developed using the same surrogate response surface approach used for the optimization problem. In this case, the success criteria (peak deceleration, residual energy, attitude angles and fabric stress) were approximated as functions of four important landing case parameters: lateral velocity due to wind, rock height, pitch angle and pitch rate. Because these represent only a subset of the landing variables, the output of this robustness assessment gave a "figure of merit," rather than a true reliability fig-





Baseline airbag FE model showing internal diaphragms (green) and anti-bottoming toroidal bag (blue)

ure, for the simple venting strategy. However, it could be extended to calculate overall reliability for this and other venting strategies.

The ability to estimate reliability is particularly important because of the difficulty of simulating Mars conditions in tests on Earth. Low atmospheric pressure (typically about 1/2% of Earth at sea level) results in sonic flow conditions through the vents, and the lower gravity (38% of Earth) affects rebound. Full-scale drop testing requires very expensive vacuum tower facilities and limits the number of landing cases that can be simulated. Hence this approach, using an FE model validated by a small number of tests, provides a powerful tool for assessing performance over a much wider range of conditions. It is also valuable in the determination of "worst cases" to test.

Altair's HyperStudy was used to manage the problem, producing the DOE analysis plan by means of an Extended Uniform Latin Hypercube, setting up the model boundary conditions. These included variations to the geometry, submitting the runs for batch processing and approximating response surfaces to the FEA results using the Moving Least Squares Method.

Once the response surfaces were generated, it was relatively simple to perform a Monte Carlo analysis using probability density function (PDF) models for the different environmental variables. Wind velocity was idealized as a Rayleigh PDF, the rock height distribution was based on an exponential PDF, and Gaussian normal distributions with zero means were specified for the pitch attitude and pitch rate. Ten-thousand point Monte Carlo analyses were performed on the response surface approximations in a few seconds to determine whether the airbag passed or failed each of the landing success criteria.

The probability of a successful landing was determined to be only about 69%. To some extent, this reflected the limitations of the simple simultaneous vent strategy, indicating that a more complex vent control is probably necessary.

Results also indicated the shortcomings in the "optimized" design, which was believed to have a too-restricted vent area. Examination of the Monte Carlo results also showed that negative pitch attitude (downwards trailing edge making first contact) was a particular problem, and not reflected as a design case in the original optimization. This was also apparent in some of the DOE FE runs.

With the surrogate response approximations available, it was relatively simple to study the effect of constraining the variability in the landing conditions. For example, wind speed and rock size variability can be reduced by targeting more specific landing sites and times, and changes in the parachute design can reduce the variability in pitch attitude and rate. By modifying the PDFs accordingly, it was possible to increase the overall reliability to 80%, with the reduction in pitch angle range providing the biggest contribution to the improvement.

Although a sufficiently robust vented airbag design was not produced, the study successfully developed methodologies and specific enhancements of the response surface approximation method for both design optimization and the quantitative assessment of reliability. It is hoped that these useful tools can be utilized in airbag design for later phases of the ExoMars project. C2R

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