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Analysis, Optimization and Probabilistic Assessment of an Airbag Landing System for the ExoMars Space Mission

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Vented airbag systems offer an attractive means of cushioning the landing impact of robotic planetary spacecraft. This type of airbag absorbs the impact kinetic energy by exhausting the inflation gas through vent patches in a controlled way that aims to bring the lander to rest with minimum rebound, limited deceleration and in an upright attitude. Such systems are characterised by highly non-linear behaviour. This, coupled with the difficulty of adequate terrestrial testing results in an analytical approach to design that relies on explicit finite element (FE) analysis. However, the simulation of an impact of a few tenths of a second duration typically requires tens of hours of CPU time, making it impractical to optimise a design using a trial end error approach and to perform the large number of analysis runs necessary for a probabilistic assessment of varied landing conditions. This paper presents a methodology for overcoming these problems with reference to a vented airbag design for the ESA ExoMars mission. The approach utilises the Moving Least Squares Method (MLSM) to fit high quality approximations to multi-dimensional response surfaces from a relatively small number of FE analysis runs. This method is well-adapted to highly non-linear and noisy response surfaces that are typical for this problem. The surrogate response surfaces were used to locate an optimum in the design parameter space and to perform 10,000 sample point Monte Carlo runs in a probabilistic assessment of reliability due to varying landing conditions.

I. Introduction

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 (Fig. 1).

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 240kg 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 150kg. The planned launch is by Soyuz ST from Kourou, French Guyana, in 2011 with an arrival at Mars in 2012. After a

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journey of over 500 million kilometers taking nine months, the success or failure of the ExoMars mission will depend on what happens in the landing phase. 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.

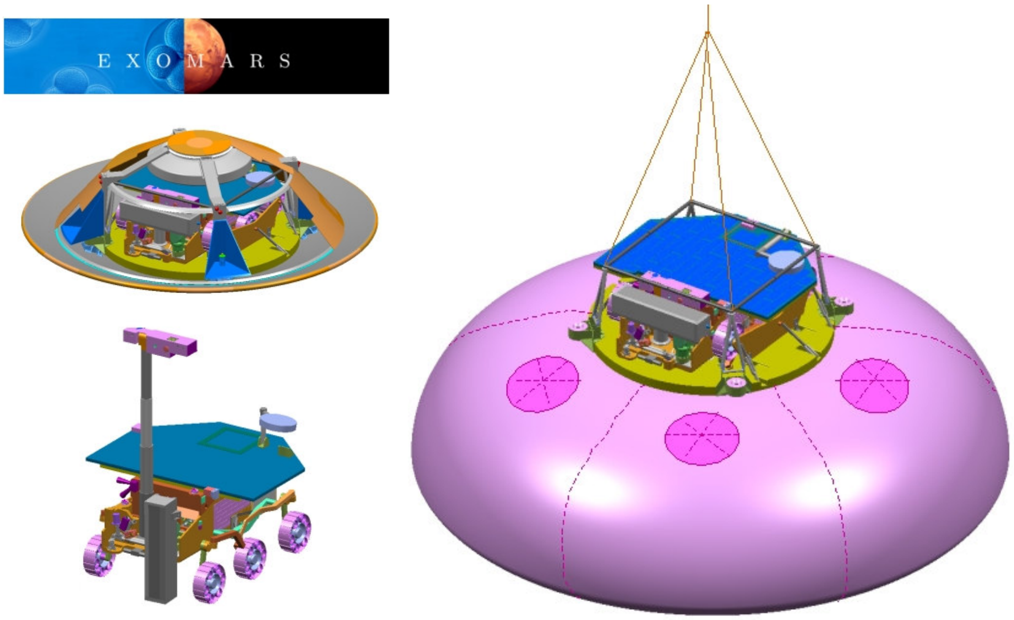


Figure 1. Exo-Mars landing system.

II. Airbag Concept Selection

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 55mph (25m/s) to coming to rest, takes typically less than 100 milliseconds and results in decelerations of up to 80g.

In the design concept proposed for ExoMars (Fig. 1), 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.

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-related 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.

III. Possible Failure Modes – 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 rupture 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.

IV. Analysis Approach

Following the ExoMars mission study for ESA, EADS Astrium decided to investigate 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 Ltd (UK) to apply recent developments in its HyperStudy[1] generic parametric study, design of experiments (DoE), approximation, optimization and stochastic study tool to this problem.

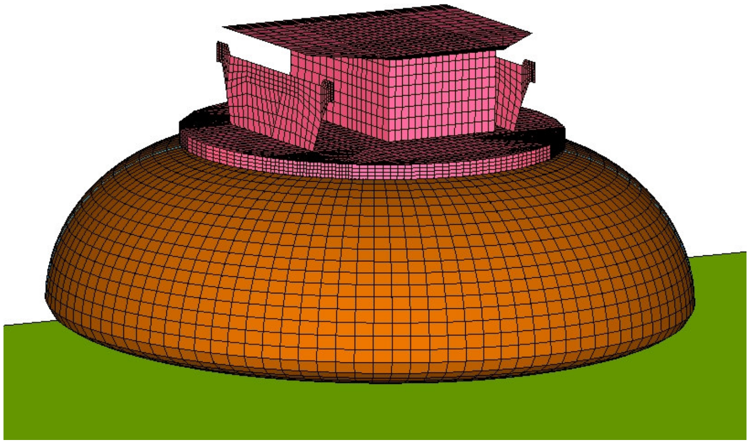


Figure 2. Finite Element mesh of baseline lander model.

In order to limit the scope of the study, the optimization was restricted to four main design variables, and the probabilistic assessment was restricted to four landing condition variables, although these were chosen to cover all types of variable and statistical variation expected. 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 behaviour on a number of available software tools. In this case, LS-DYNA[2] was used with a modified Wang-Nefske airbag gas model for inflation and venting (Fig. 2). The landing success criteria were 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 (Fig. 3), and (2) an impact with an additional 16.3 m/s horizontal velocity component due to wind, a pitch-down attitude of 20 deg and a 10 deg up-slope landing site with a 0.5m high rock contacting under the leading edge (Fig.4). These cases were selected because they result in conflicting requirements and force a compromise solution in the optimization problem.

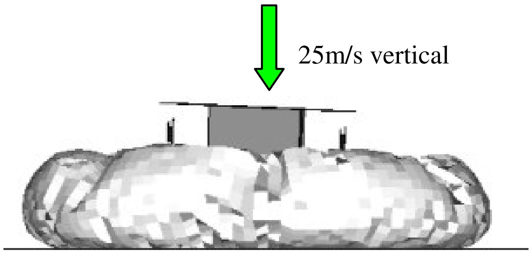


Figure 3. Vertical drop case.

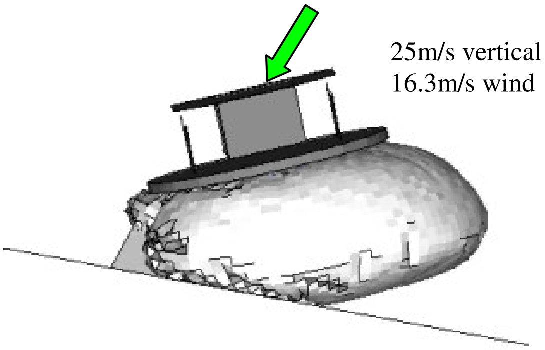


Figure 4. Rock impact case

V. 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 are traditionally the most time-consuming to implement because of the FE model re-meshing required. This was automated using Altair HyperMesh and HyperMorph[3] tools to re-mesh the model using geometry scaled from the primary diameter and height dimensions (Fig. 5).

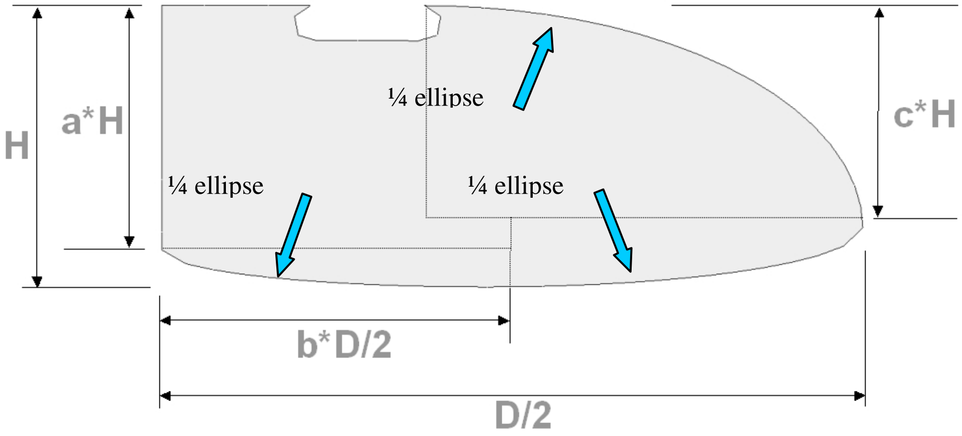


Figure 5. Airbag cross-section geometrical relationships

VI. Surrogate Model Building

One of the main problems in this optimization and probabilistic study 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 design variables, such as inflation pressure, airbag diameter, vent size etc. N design variables results in an N-dimensional response surface (N = 4 in this study). 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 nonlinear responses.

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 permutation genetic algorithm [4], [5].

Once set up, the FEA runs were performed, 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 [6], [7].

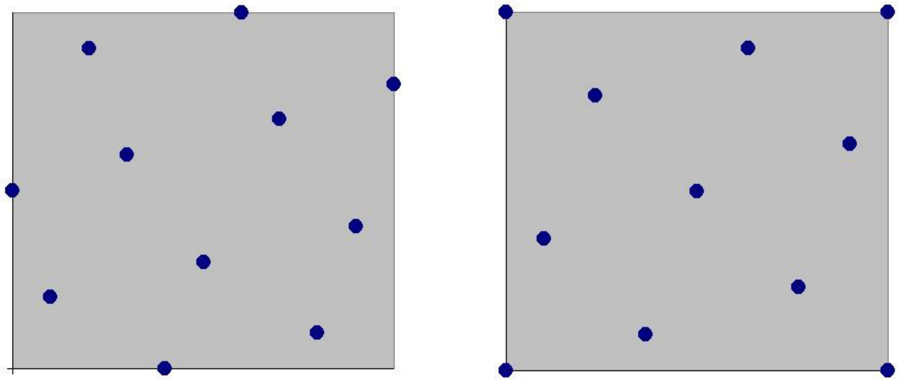


Figure 6. Example of a two design variable 11 point Uniform Latin Hypercube DoE (left) and the Extended Uniform Latin Hypercube DoE (right)

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 and spiky edge "cliffs." Fig. 7 (left) gives an illustration of this using a two design variable example of a classic Rosenbrock's banana valley function that is spoilt by a large amount of noise outside the shallow curved valley which can be considered as the area of interest. To minimize this function, a good quality approximation of the valley should be obtained whilst ignoring numerical noise outside the valley. Fig. 7 (centre) shows the capped function and Fig. 7 (right) shows the MLSM approximation of capped function. This shows that MLSM is capable of producing a high quality approximation of a highly nonlinear function.

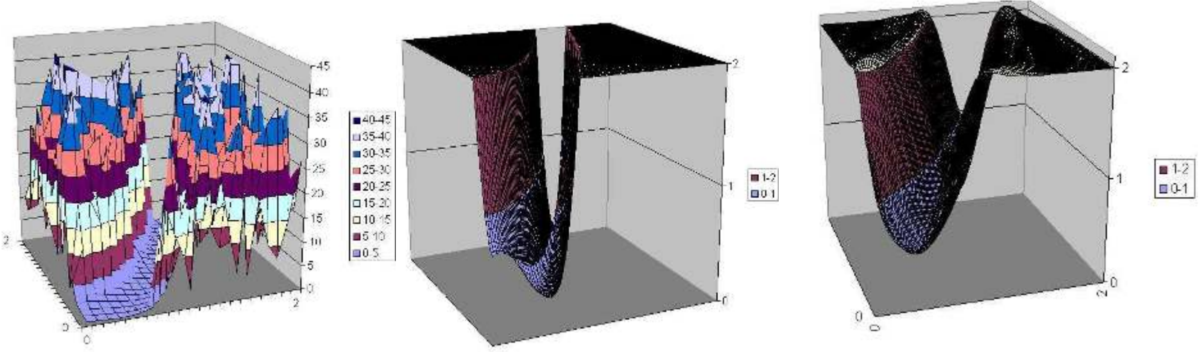


Figure 7. Example of the Rosenbrock's banana valley function with numerical noise (left), the capped function (centre) and MLSM approximation of the capped function (right)

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 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 may have been too constrained and could probably be increased to improve the design.

VII. Probabilistic Assessment 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. Variation of the rock height and the pitch angle are illustrated by Fig. 8. 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 figure for the simple venting strategy. However, it could be extended to calculate overall reliability for this and other venting strategies.

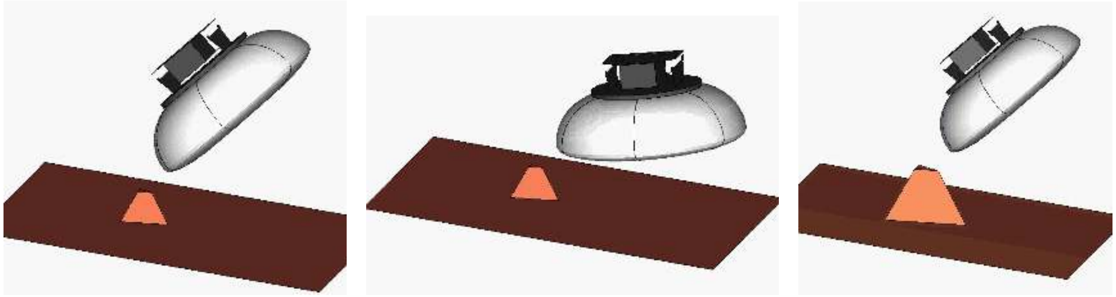


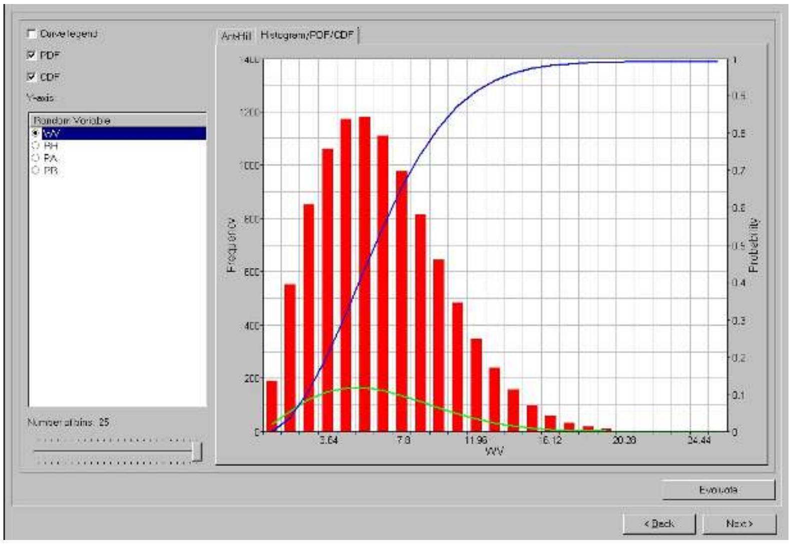
Figure 8. Rock height and pitch angle variable manipulation for reliability study

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 0.5% 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[1] 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, including variations to the geometry using batch operation of HyperMesh, submitting the runs for batch processing and approximating response surfaces to the FEA results used 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 (Fig. 9), which gave the best fit to model data from the European Mars Climate Database (EMCD v3.0) [8]. This 3D global circulation model for the Mars atmosphere gives data on a 5° longitude x 5° latitude grid at 32 heights for 2 hour intervals during the Martian day averaged for each of the 12 ‘seasons’. For the ExoMars mission, the wind velocity data were limited to the 45°N to 45°S central latitude band in Season 12 and assumed the Mars Global surveyor dust-loading scenario. The idealized Rayleigh PDF matched the EMCD model data mean resultant wind velocity of 7.06 m/s, but had a slightly higher standard deviation of 3.69 m/s (compared to 3.45 m/s from the EMCD data). The rock size distribution was based on the exponential PDF model proposed by Golombek[9] for a given general rock abundance (Fig. 10). This fits the probability distribution model parameters to observed rock sizes at the Viking and Mars Pathfinder landing sites on Mars. For the ExoMars mission, a landing site with an overall rock abundance (i.e. fractional area covered in rocks) of 20% was considered and rock heights were assumed to be half the rock diameter. This resulted in a distribution with a mean rock height of 0.196 m and standard deviation of 0.196 m. The pitch attitude angle and rate, due to motion whilst suspended underneath the main parachute, were idealized as Gaussian normal distributions with zero means and 3-sigma levels set to ± 30deg and ± 20deg/s respectively. 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. Fig. 11 shows a typical HyperStudy anthill plot for payload rotation versus pitch attitude.

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.



☐ Curve legend

☑ PDF

☑ CDF

Y-axis:

Random Variable

● WV

○ RH

○ PA

○ PR

Number of bins: 25

Figure 9. Weibull PDF and CDF of wind distribution for Monte Carlo simulation in HyperStudy

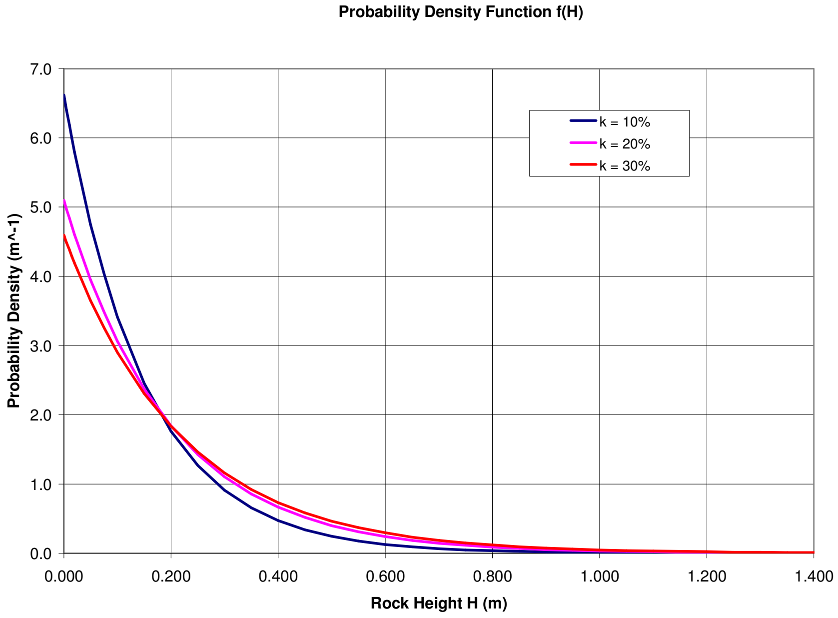
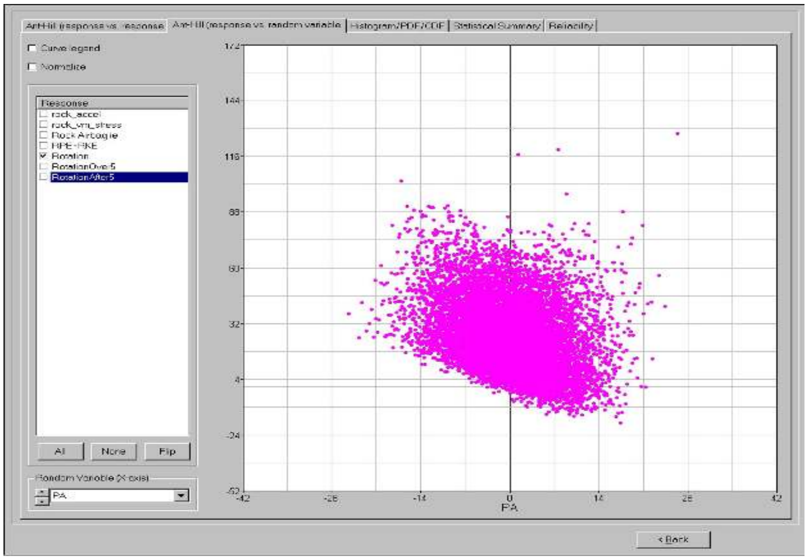


Figure 10. Exponential PDF of rock height distribution for Monte Carlo simulation



☐ Curve legend
☐ Normalize

Response
☐ rock_accel
☐ rock_vm_stress
☐ Rock Airbagie
☐ RPE-RKE
☑ Rotation
☐ RotationOver5
☐ RotationAfter5

Random Variable (X-axis): PA

Figure 11.   Responses for payload rotation vs. pitch attitude, anthill plot in HyperStudy

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 (to a 3-sigma limit of ± 20deg) 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.

VIII. Conclusion

The fact that only one of the DOE runs gave a result that met the desired targets is indicative of the small range of designs that would give satisfactory system performance for both the vertical drop and rock impact baseline analyses. This illustrates the value of performing the optimization process in order to identify a design that gives the best opportunities to achieve satisfactory reliability performance. In this particular case, the value of the process is increased due to the difficulties involved in replicating the necessary environmental conditions necessary to perform physical system tests.

The subsequent reliability analysis is an objective means of assessment of the probability of achieving a successful landing, which is the ultimate measure of the success of the system design. The reliability figure obtained for a given design can be used as a 'figure of merit' for comparison with alternative designs. Use of the surrogate model also allows simple adjustment of the various controlled and uncontrolled variables through changes to the sampling matrix to reflect different variable PDFs. This enables the design team to quickly gain an understanding of the sensitivity of a given design to the various environmental influences that would otherwise be very difficult to quantify or see in global terms (e.g. the fact that reducing pitch angle/rate is likely to significantly improve system performance is an important fact that may not otherwise have been apparent).

Whilst the number of variables for each of the DOE cases was limited to four, the process of the surrogate model construction using Moving Least Squares Curve fitting in HyperStudy has been demonstrated. This process has allowed a DOE that is practical in CPU cost terms to approximate effectively the full range of variable relationships in each case. The subsequent optimisation and reliability analyses performed on the surrogate models have been demonstrated effectively and the results have given valuable knowledge and design direction for the project that otherwise could not have been known.

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