Optimisation and Reliability Technology Applied to a Mars Lander Concept

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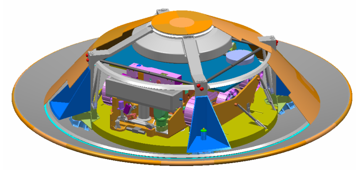
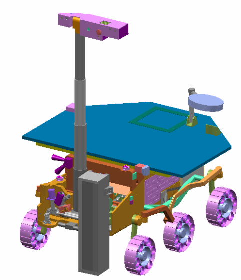
Presentation Outline

- Introduction to Design Concept
- Baseline Model and Response
- Response Surface Methodology
- Optimisation Study
- Reliability Assessment
- Conclusion

The ExoMars Project

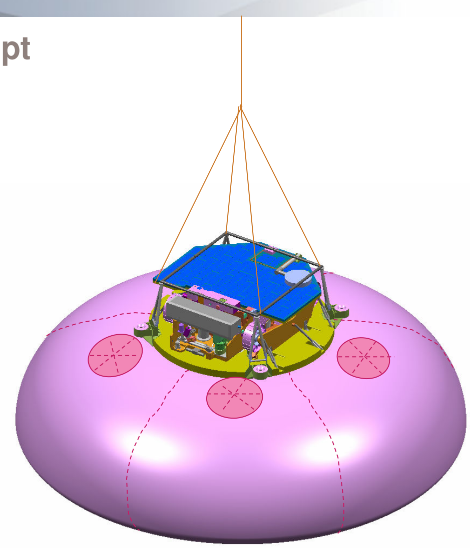
- ESA Aurora exploration programme
- 240kg mobile robotic exo-biology laboratory
- To search for extinct or extant microbial life on Mars
- Supporting geology and meteorology experiments
- Launch in 2011 or 2013
- Currently in Phase A – mission planning and concept design phase





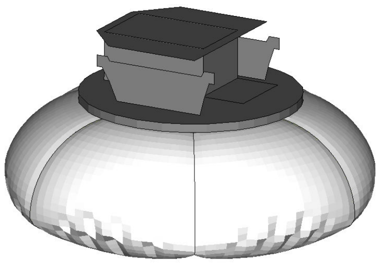
Airbag Landing Design Concept

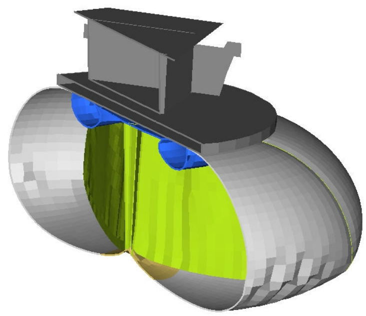
- Previous Landers utilise 'bouncing ball' concept : not vented, multiple bags completely surrounding self righting payload
- Approximately ten to twenty bounces before coming to rest
- Design concept considers vented (or "Dead-Beat") airbag coming to rest on second bounce
- Inflated with N_2 during descent under main parachute



Airbag Configuration

- Six identical vented chambers
- One “anti-bottoming” un-vented toroidal





Concept Venting System

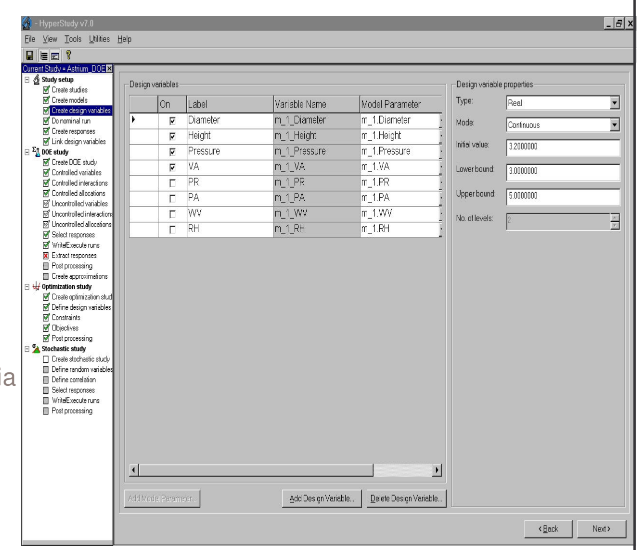
- Accelerometer trigger fires pyrotechnics to open vents (not pop pressure)
- Proposed trigger deceleration value of 65g (resultant at payload CofG) to limit peak payload deceleration to 70-80g
- All six chambers simultaneous vent when trigger threshold is obtained
- Failure modes:
  - Roll-over (payload overturns),
  - Dive-through (payload impacts rock)
  - Rupture (fabric tears)
- Full-scale terrestrial testing is difficult / expensive
- Virtual Design Approach Required

CAE Software Tools

- LS-DYNA
  - Dynamic Relaxation (steady-state free fall condition)
  - Airbag functionality (Wang Nefske inflation model)
  - Advanced contact (internal fabric contact etc.)
- HyperMesh
  - Advanced LS-DYNA model build support
  - Comprehensive interface
- HyperView
  - Time dependent LS-DYNA animations
  - Multi results type environment (animations, X-Y data)
- HyperMorph
  - Airbag size optimisation
  - Rock height, pitch angle reliability variation

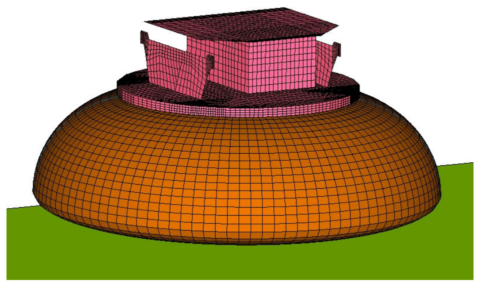
Altair HyperStudy

- A general CAE study tool that interfaces with FEA codes
- Process driven via GUI structure
- Baseline response evaluated within study setup
- Build response surfaces via DoE studies
- Optimisation Study
- Reliability Assessment



Baseline : Model Make-Up

- Airbag geometry modelled in approximate free fall configuration
- Airbag and Payload idealised using approx. 16,000 four noded shells



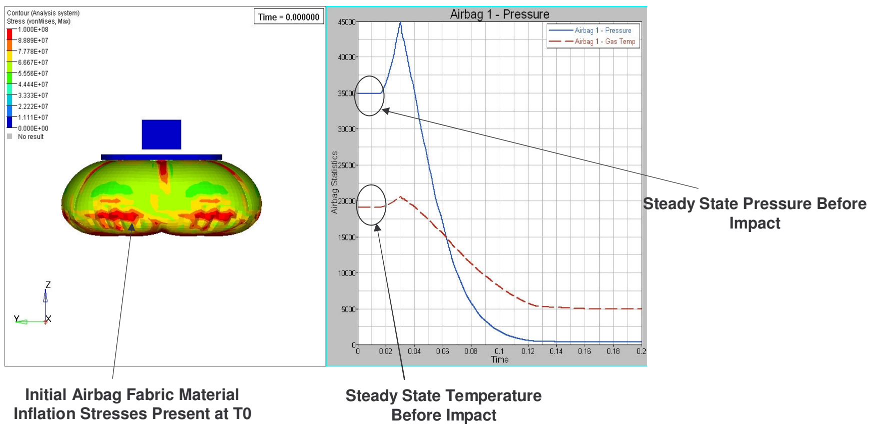
- Airbag – Mat Fabric, Payload – Mat Rigid with Inertia Tensor
- Single surface contact between internal fabrics, external airbag and target

Baseline : Loading Conditions

- Airbag Inflation
  - Inflation of bag to achieve specified internal pressure (iso-thermal)
  - Dynamic Relaxation utilised to achieve equilibrium condition
- Steady-State Free Fall Condition (Post Airbag Inflation)
- Two Load Cases – Flat Bottom & Inclined Rock Impacts
- Wang Nefske Airbag model - deceleration venting trigger
  - Cumulative time duration above threshold
- Airbag Gas Response During Impact is Adiabatic
- Mars Environment
  - Gravity 0.38g
  - Pressure 440Pa
  - Temperature 187K

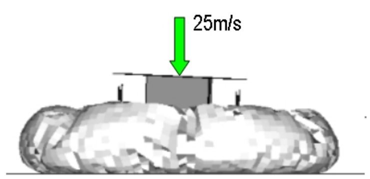
Baseline Response : Steady-State Free Fall Condition

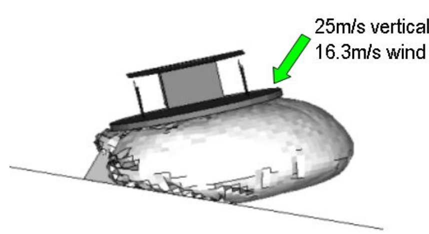
- Airbag inflated specifying mass flow rate to achieve target internal pressure
- DR determines initial airbag stresses and steady state pressure and temperature at T0



Baseline : Impact Load Case Comparison

- Load Cases chosen to give conflicting design requirements



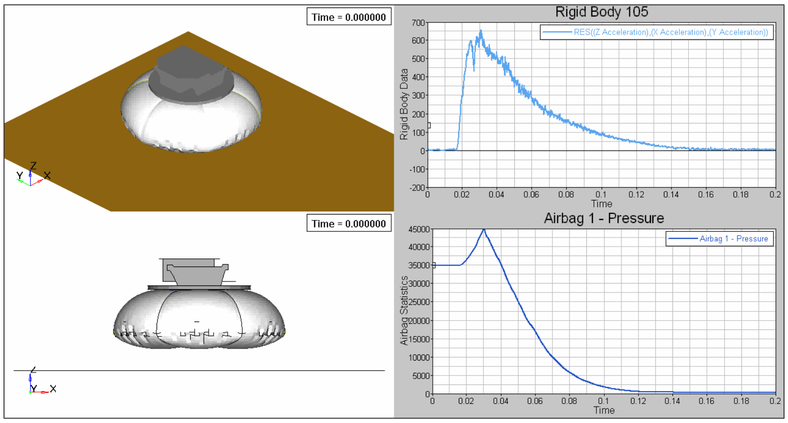


- Flat Bottomed Impact
- Vertical Velocity 25m/s
- Favours 'Tall' airbag designs
- Favours 'Narrow' airbag designs
- Tall, Narrow airbag makes most effective vertical energy absorber

- Inclined Rock Impact
- Vertical Velocity 25m/s
- Lateral 'Wind' Velocity 16.3m/s
- Favours 'Wide' Airbag designs
- Wide airbag makes most effective rock intrusion absorber

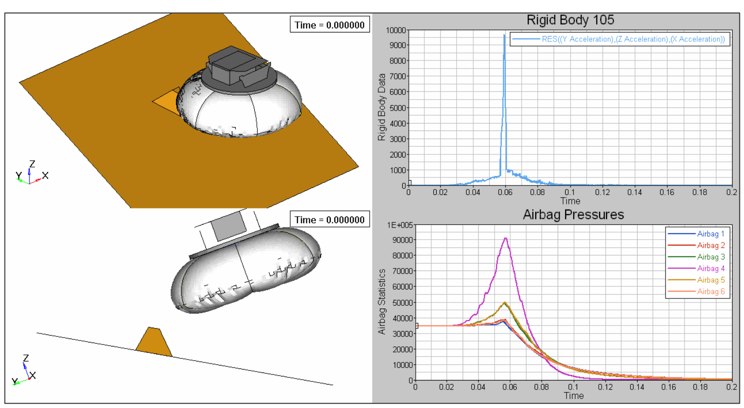
Baseline Response : Flat Bottom Impact

- Peak Filtered Deceleration 66g (Target <70g)
- Peak Airbag Material Stresses 135MPa (Target <533MPa)
- Constraints Satisfied by Baseline



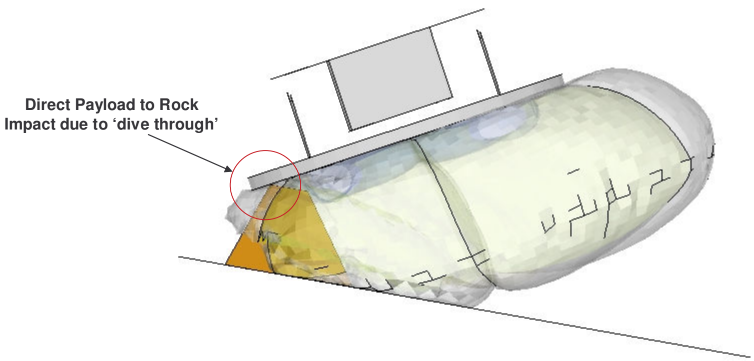
Baseline Response : Inclined Rock Impact

- Peak Filtered Deceleration 980g (Target <70g)
- Peak Airbag Material Stresses 281MPa (Target <533MPa)
- Deceleration Constraint Exceeded Due to 'Dive Through'



Baseline Response : Inclined Rock Impact 'Dive Through'

- Critical to prevent 'direct' payload to Rock/Ground Impact
- This type of impact guarantees violation of deceleration constraint



Baseline Response : Vent Triggering

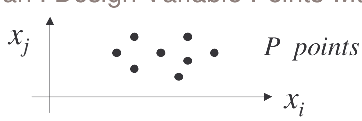
- Wang Nefske Airbag definition uses raw rigid body deceleration to trigger airbag venting (no filtering)
- Cumulative time above trigger is used as filter

Response Surface Methodology

- Non-linear systems are solved using response surface techniques
- Unique unifying approach
  - Both optimisation and reliability utilise response surface
  - Different design variables with different limits used to create response surfaces
- Accuracy of Response Surface
  - Optimisation and reliability studies based on response surface
  - Quality approximation is required
  - Error in surface assessed using checking plan

Response Surface Generation : Four Steps

1. Select Test Plan : Design Variable Points within the Design Space



2. Run LS-DYNA Analysis for each Test Plan Point
   - LS-DYNA Outputs Responses
   - Extracted using HyperStudy
3. Use Advanced Curve Fitting to Approximate Response Anywhere in Design Space
4. Use Response Surface to Determine the Global Optimum or Assess the Design Reliability

Optimisation: Set-up

Design Objective - Minimise System Mass (Airbag + Payload + Gas + System)

Design Constraints
- Payload Acceleration (<70g)
- Global Bag Von Mises Stress (<533MPa)
- Re-bound and "roll over" inversion kinematics

Design Objective and Constraint Responses Evaluated for each Load Case

Design Variables
- Airbag Base Diameter (HyperMorph)
- Airbag Height (HyperMorph)
- Airbag Venting Area
- Airbag Steady-State Pressure (Mass of Gas)

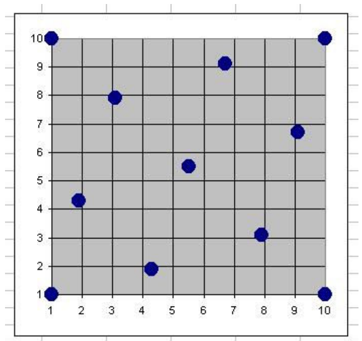
▲ Minimise Design Objective by varying the Design Variables whilst satisfying the Design Constraints

Specified Airbag Design Variable Limits

Variable	Baseline	Lower Limit	Upper Limit
Airbag Diameter (m)	3.2	3.0	5.0
Airbag Height (m)	1.0	0.8	1.2
Inflation Pressure (kPa)	35	15	55
Vent Area (m^2)	0.25	0.15	0.40

Response Surface Generation : Step 1 Test Plan

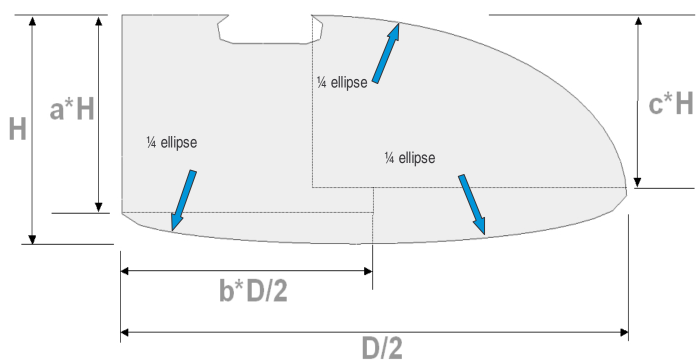
- Uniform Latin HyperCube Test Plan
  - Latin Hypercube had Good Space Filling Qualities
  - Enhancement Allows Inclusion of Boundary Points
  - HyperStudy Allows Inclusion of 2nd 'Check' Test Plan



Two design variables both range between 1 & 10
Eleven Test Plan Points Selected

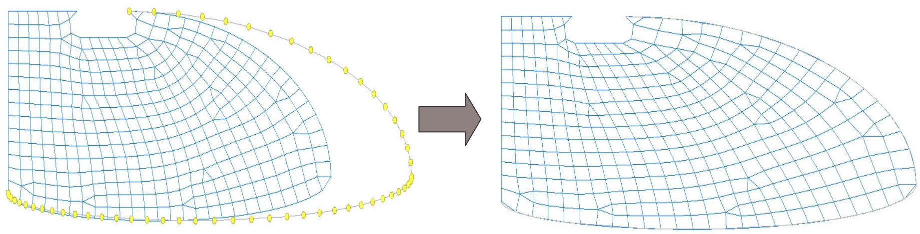
Design Variables : Airbag Height and Diameter

- Airbag geometry defined by dimensional relationships between height (H) and diameter (D) of cross-section, curves are elliptical sections
- Geometric factors a, b, c are constant



Airbag Geometry Parameterised using HyperMorph

- Automatic Morphing of an Internal partition to comply with external shape
- HyperMorph enables the same mesh to be used for all bag geometries



Response Surface Generation : Test Plan (Step 1)

- Four Design Variables – 40 Test Plan Points (EULH) / Load Case

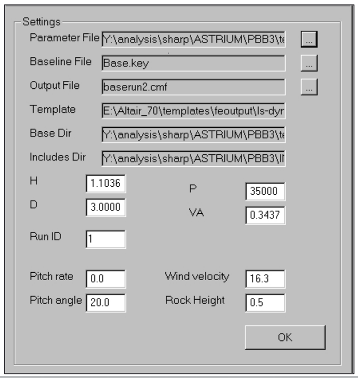
DOE Run Table | DOE Run Plot

Run	Diameter	Height	Pressure	VA
1	3.0000000	0.8000000	15000.000	0.1500000
2	5.0000000	0.8000000	15000.000	0.1500000
3	3.0000000	1.3000000	15000.000	0.1500000
4	5.0000000	1.3000000	15000.000	0.1500000
5	3.0000000	0.8000000	55000.000	0.1500000
6	5.0000000	0.8000000	55000.000	0.1500000
7	3.0000000	1.3000000	55000.000	0.1500000
8	5.0000000	1.3000000	55000.000	0.1500000
9	3.0000000	0.8000000	15000.000	0.4000000
10	5.0000000	0.8000000	15000.000	0.4000000
11	3.0000000	1.3000000	15000.000	0.4000000
12	5.0000000	1.3000000	15000.000	0.4000000
13	3.0000000	0.8000000	55000.000	0.4000000
14	5.0000000	0.8000000	55000.000	0.4000000
15	3.0000000	1.3000000	55000.000	0.4000000
16	5.0000000	1.3000000	55000.000	0.4000000
17	3.0000000	0.9956500	44565.220	0.2043500
18	3.0869600	1.2347800	41086.960	0.2260900
19	3.1739100	0.9739100	27173.910	0.3456500
20	3.2608700	1.0391300	53260.870	0.3347800
21	3.3478300	0.8000000	39347.830	0.2913000
22	3.4347800	1.1913000	34130.430	0.3782600
23	3.5217400	1.0826100	21956.520	0.1717400

Response Surface Generation : Evaluate Response (Step 2)

Automated Input Deck Generation

- Process Required to generate models for run parameter matrix
- Input decks for all runs auto created from parameter matrix
- Run generator fired from HyperStudy
- Uses HyperMesh and HyperMorph in batch mode



Automated Input Deck Generation Movie

Response Surface Generation : Evaluate Response (Step 2)

- Extract LS-DYNA Responses Extracted at Test Plan Points

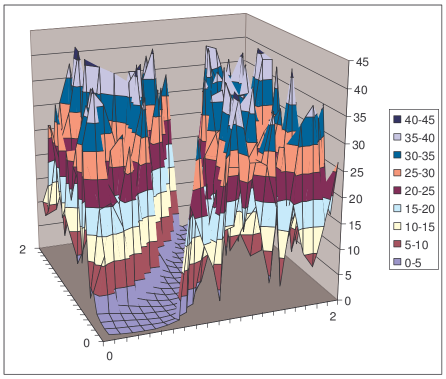
Post process

mass	accel	vm_stress	rock_accel	rock_vm_stress
582.07600	1301.0600	85.169400	10075.300	263.98400
594.26700	694.64900	117.67900	5302.7200	130.87800
585.36200	562.14300	185.26400	4134.0000	151.04600
599.94000	581.23300	104.25200	752.78400	115.06000
585.29800	750.02100	145.71900	8653.4300	222.39400
602.83300	1097.8000	174.32500	692.50600	179.05000
590.66400	768.79000	213.84500	1421.1900	344.84000
613.92600	1101.7100	95.816300	839.19700	150.45800
582.07600	1981.0600	85.169400	9878.7500	199.09700
594.26700	658.52400	117.67900	5305.9100	130.87800
585.36200	562.14300	185.26400	5543.8000	151.04600
599.94000	582.35100	104.25200	717.41800	115.06000
585.29800	1448.9300	124.26600	8614.1200	222.39400
602.83300	919.97200	157.09700	613.40100	189.67100
590.66400	708.27000	209.31500	1111.3800	344.84000
613.92600	985.78500	86.389300	735.00900	191.05900
586.32800	681.75400	169.45700	2037.6200	304.75500
588.89000	662.09300	203.47500	1446.7100	276.43300
585.45100	607.52400	124.81800	2107.1000	238.19500
589.77200	683.25100	120.62300	2358.2800	231.59100
586.23100	630.34900	148.80000	8993.2200	274.51900
590.20000	581.40000	130.43400	1717.4900	213.51600
587.94000	615.30400	92.051400	1995.4600	162.84600

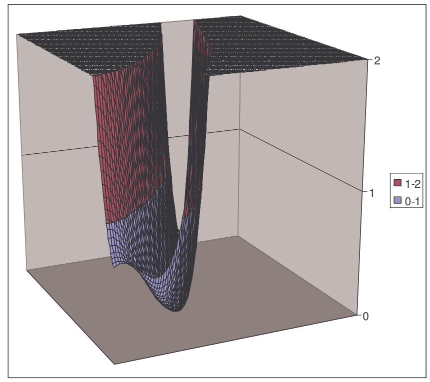
Response Surface Generation : Step 3 Curve Fitting

- Moving Least Squares Method (MLSM) is a generalisation of a weighted least squares method where weights do not remain constant
- MLSM provides a high quality response surface to accurately approximate a highly nonlinear system.
- Important feature of MLSM is efficient handling of numerical noise by adjusting “closeness of fit” parameter to provide close fit to a low noise situation or loose fit when the response exhibits a larger amount of noise
- Direct Payload to Rock/Ground Impact Resulting in High Payload Accelerations (>100g) occurred at high percentage of Test Plan Points
- These high results ‘swamp’ the responses of interest in the approximation

MLSM Test Example : Rosenbrock's Banana Valley Function



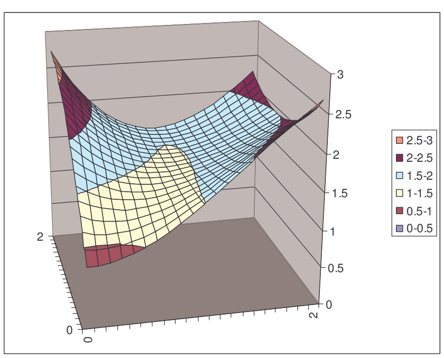
Noise Outside Area of Interest



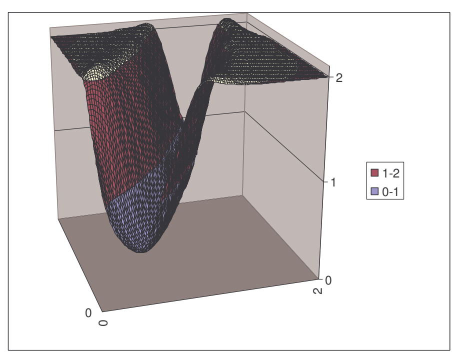
Function Capped

- To minimise this function, a good quality approximation of the valley should be obtained whilst ignoring numerical noise outside the valley

MLSM Test Example : Rosenbrock's Banana Valley Function



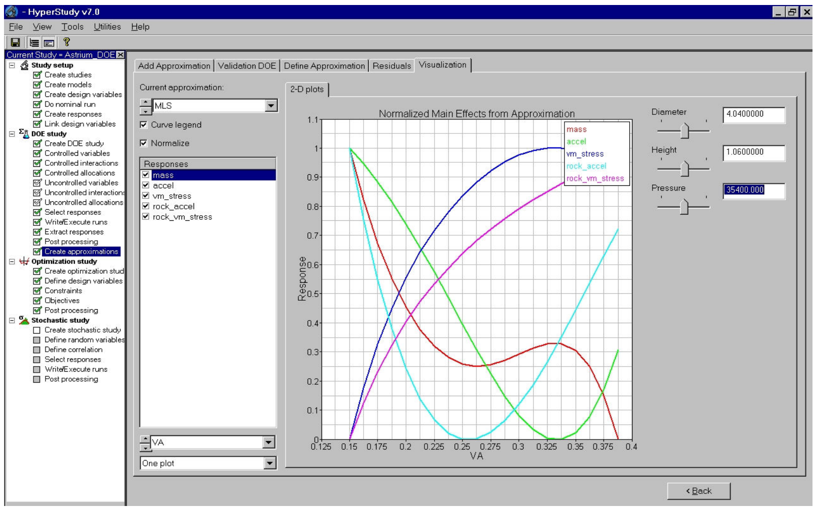
Least Squares approximation of capped function, 100 Sampling points still gives poor approximation of function



MLSM approximation of capped function, 100 sampling points gives good approximation of function

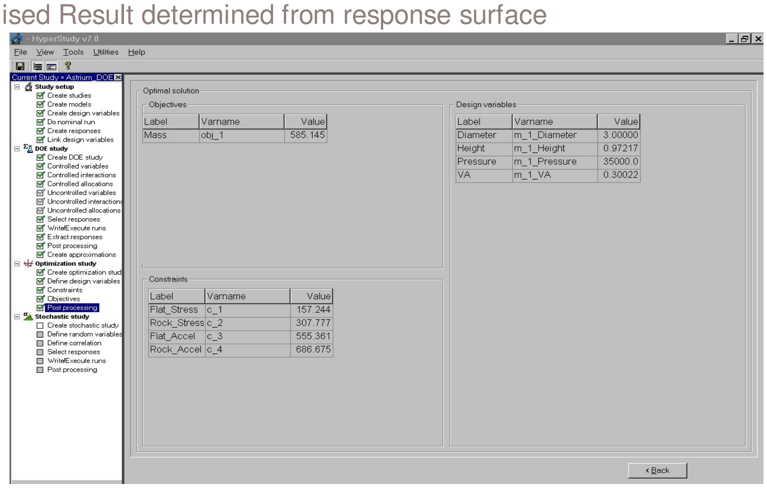
Response Surface Generation : MLSM Curve Fitting (Step 3)

- HyperStudy has visualisation tools for assessment of curve fitting



Response Surface Generation : Optimisation (Step 4)

- Optimised Result determined from response surface



- Satisfies all constraints with a small increase in System Mass

Optimisation Results

- On review of the response data set obtained from the Test Plan points it was observed that there was a high percentage of runs that failed to meet the constraints
- This was reflected in the approximations and resulted in a very small 'sweet spot' on the response surface where the constraints could be met
- Model mass varied very little (<0.25%) within this area (all runs in this area had more mass than baseline run)
- Because of the minimal mass penalty, instead of optimising for mass it was decided at this stage to optimise for payload deceleration and residual energy in order to achieve the best model to carry forward to the reliability analysis

Optimisation Results

Design Variable	Baseline	Optimised
Airbag Diameter (m)	3.20	4.41
Airbag Height (m)	1.00	1.16
Inflation Pressure (kPa)	35.0	30.3
Vent Area (m^2)	0.25	0.40

- Optimised mass selected was 403.5kg (baseline 392.8kg)
- Flat Bottom Impact Payload Acceleration increased from 65.5g to 67.7g
- Rock Impact Payload Acceleration decreased from 980.3g to 69.1g
- Maximum Material Stresses were reduced from 281MPa to 157MPa
- While 3 variables are in middle of range, Vent Area pushes limit

Reliability: How reliable is the product?

- Reliability using Monte Carlo sampling is well understood in industry
  - safety risk assessments
  - warranty / insurance issues
  - Investment decisions
- Sigma Level design is often used in manufacturing to define the reliability of processes or the probability of failure of components
- Directly performing Monte Carlo sampling not practical on LS-DYNA model (+100,000 sample points often required to convergence on % probability)
- Instead utilise response surface to assess Monte Carlo variation

Procedure for Calculating Reliability

- Response Surface Generation
  - Select environmental variables, establish pdf for each (mean, standard deviation, distribution)
  - Select Test Plan in range of design variables (often mean $\pm 3\ \sigma$)
  - Run LS-DYNA model to evaluate responses at test plan points
  - Use curve fitting to determine response surface
- Evaluate the Probability of Failure
  - Define level of response that constitutes a failure
  - Perform Monte Carlo sampling on response surface according to pdf
  - Count events when response level exceeds failure threshold
  - Calculate probability of failure F or reliability index 1- F.

Value of Reliability Figure For Mars Lander Design

- Ultimately, the reliability figure gives the probability of a successful landing for a given design under a range of conditions
- Alternatively it can be used to establish an envelope of conditions for a given success probability
- For this project, the limited number of design variables (4) considered, results in a reliability index 'figure of merit', rather than an overall probability of success
- Establishing this 'figure of merit', index for the reliability of a design gives a useful comparison with alternative designs

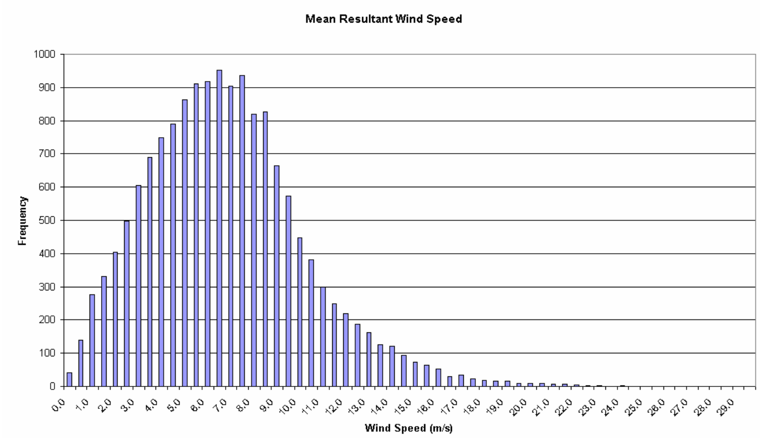
Reliability: Model Definitions

- Adopt airbag design variables determined by optimisation study
- Consider only rock impact loadcase (though rock height may be zero, i.e. flat surface)
- Failure defined by exceeding similar constraints to optimisation study
  - Resultant deceleration < 80g
  - Kinematic metrics, re-bound, roll-over
  - No bag tearing
- Environment Variables

Design Variable#	Description	Lower Bound	Upper Bound
DV1	Lateral Wind Velocity	0 m/s	20 m/s
DV2	Rock Height	0 m	0.8 m
DV3	Lander Pitch Attitude	-20 º	20 º
DV4	Lander Pitch Rate	-30 º/s	30 º/s

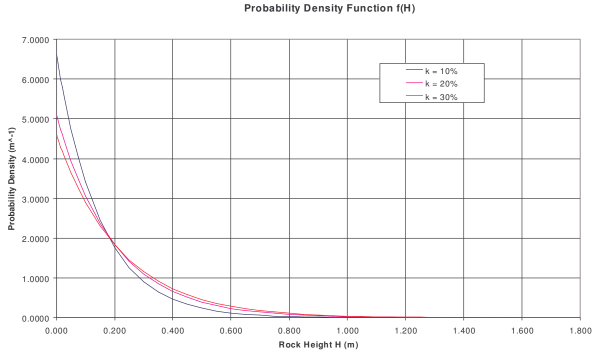
Design Variables & PDFs

- Wind Velocity - Weibull distribution, Determined from European Mars Environmental Model Project



Design Variables & PDFs

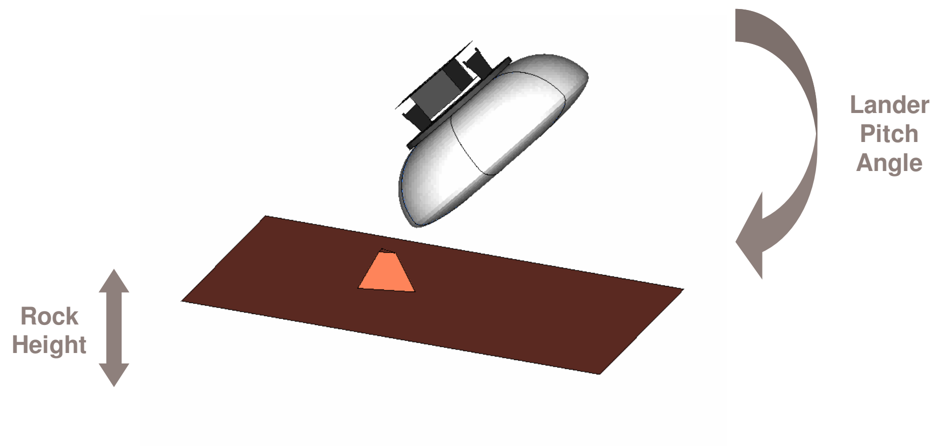
- Rock Height -Exponential distribution, Determined from past mission data



- Pitch Attitude – Normal distribution - Variation from mean at ±3σ is ±30°
- Pitch Rate – Normal distribution - Variation from mean at ±3σ is ±20°/sec

HyperMorph : Parameterised Geometry

- Pitch attitude and rock height model build using HyperMorph

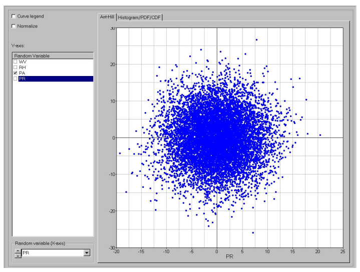


Response Surface Generation

- Test Plan – Uniform Latin HyperCube with Extremities Extension
- Eighty Test Points – 80 LS-DYNA runs executed (single load case)
- Responses extracted
- Advanced Curve Fitting using moving least squares method
- Process is the same as for the approximations used to generate optimisation response surface, but with different variables

Determining the Probability of Failure

- Perform Monte Carlo Sampling on Response Surface
  - •Counting events which result in failure
  - •Calculating probability of failure *F* or reliability index 1- *F*



Monte Carlo Sampling Size	No of Failed Landings	Failure Index (%)	Reliability Index (%)
100	33	33	67
1000	317	31.7	68.3
10000	3141	31.41	68.59

$\pm 3\sigma$	99.73	$\pm 2\sigma$	95.46	$\pm 1\sigma$	68.26

Exploring Sensitivity of Variables PDFs

- What happens for different PDFs for design variables?
  - •Landing Site Constrained to a smaller latitude range and solar time (corresponds to a lower wind speed range spread)
  - •Rock Coverage assumed at 10% instead of 20%
  - •Pitch Angle Range considered reduced from ± 30º to ± 20º
  - •Pitch Rate Considered reduced from ± 20º/s to ± 15º/s
- Effects of new PDF distributions and ranges can be evaluated without further analysis

PDF Change Made	No of Failed Landings	Failure Index (%)	Reliability Index (%)
Baseline	3141	31.41	68.59

$\pm 3\sigma$	99.73	$\pm 2\sigma$	95.46	$\pm 1\sigma$	68.26

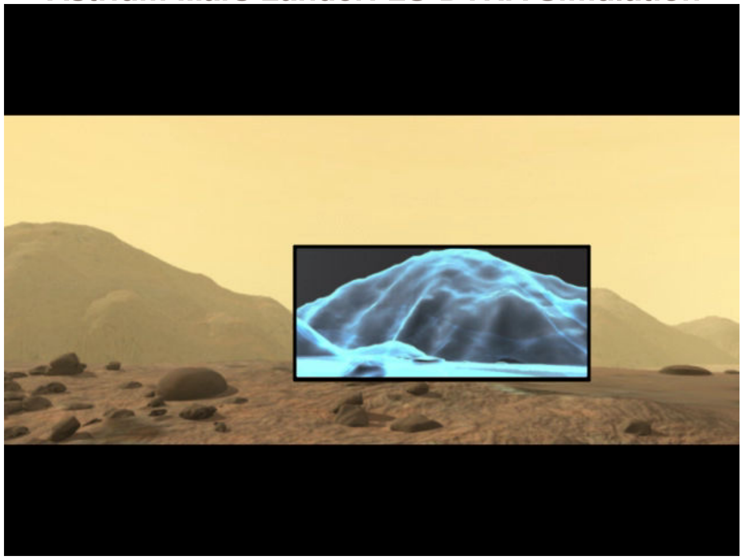
Conclusions

- Response surface generation methodology successfully used to perform optimisation and assess reliability in HyperStudy
- The optimisation study successfully demonstrated an efficient process for quickly arriving at an optimum design
- A methodology has been proven for setting up and automatically running large number of impact cases
- Automated 'morphing' of airbag geometry, in particular, greatly reduces time over the previous 'semi-manual' process
- Design can be improved by increasing vent area (upper limit on optimisation found to be too constraining)
- Reliability analysis uncovered failure modes that had not previously been considered

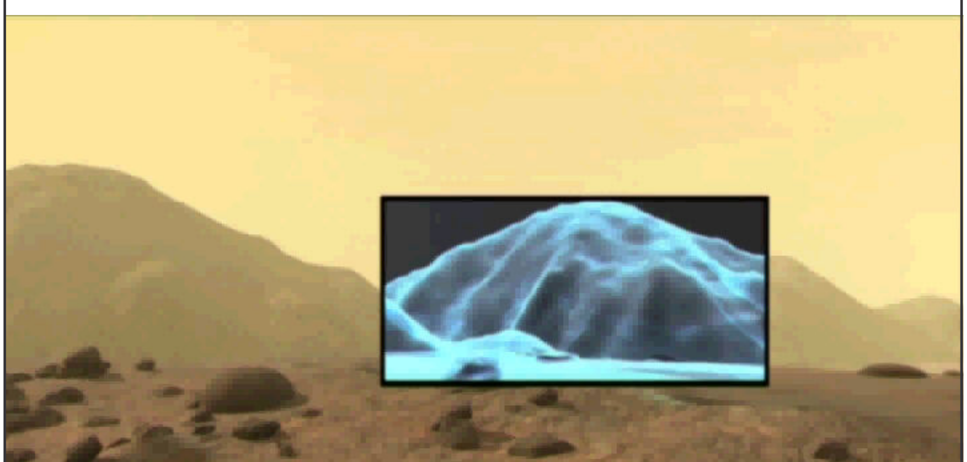
Conclusions

- The proven airbag optimisation & robustness process can be employed in future phases of the ExoMars project, with:
  - Further design improvements by increasing design variable space (vent areas, trigger accelerations, more complex differential venting strategies etc.)
  - More comprehensive robustness analyses, with aim of determining overall airbag reliability

Astrium Mars Lander: LS-DYNA Simulation



Astrium Mars Lander: LS-DYNA Simulation



Astrium Mars Lander: LS-DYNA Simulation