DEBRIS PROTECTION OPTIMISATION OF A REALISTIC UNMANNED SPACECRAFT USING SHIELD

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ABSTRACT

Previous investigations by the authors have applied genetic algorithms to the problem of optimising debris protection on very simple, idealised spacecraft. This paper summarises an ESA funded study into the potential for genetic algorithms to optimise protection on a realistic unmanned spacecraft. The software tool SHIELD is used for this purpose. Results show that optimal protection solutions can be found. Consideration of the spacecraft structure in conjunction with the arrangement of internal equipment appears to be the best strategy.

1. INTRODUCTION

The SHIELD software model performs two distinct functions: first, it provides a capability to assess the through-mission survivability of an unmanned spacecraft against debris impact; second, it provides a means to optimise the debris protection strategy of an unmanned spacecraft. In this paper we concentrate on the latter of these two functions by applying SHIELD to the protection optimisation of a 'realistic' satellite.

The satellite chosen for this purpose is MetOp. MetOp is a meteorological satellite that will be launched into low Earth orbit in 2005. It will operate in an 800 - 850 km altitude, 98.7° inclination orbit. The satellite is 3-axis stabilised and has a total mass of ~4.2 tonnes. Its size, attitude orientation, and operation in a relatively high debris density region make it an attractive candidate for assessment.

We start by constructing a 3D representation of the baseline MetOp design in SHIELD using data as defined in Turner, et al. (1999). MetOp comprises a Payload Module (PLM) and a Service Module (SVM). In the study we focus on the SVM as this contains all of the usual subsystem support functions that one finds on a typical satellite.

Next, we assess the survivability of this baseline design by performing the following sequence of evaluations:

- Determine the distributions of impactors and penetrators
- Evaluate the penetrative damage on the internal equipment
- Calculate the impact-induced failure probability

To optimise the baseline SVM protection strategy, three possibilities can be considered. First, varying the properties of the external aluminium honeycomb sandwich panels; second, varying the arrangement of equipment (including harnesses) inside the SVM; or third varying both of these options simultaneously.

The optimisation process in SHIELD begins with the specification of an extensive and detailed set of variables, which defines the scope of the problem. SHIELD employs a genetic algorithm (GA) to search through this 'variable space' for the global optimum solution. It does so by generating a series of populations of competing design solutions, where each solution has a unique combination of values for its variables. To distinguish between 'good' and 'bad' solutions, and hence guide the GA towards the optimum, an objective function is employed. This combines the probability of failure of a design with its cost. The function also permits the inclusion of terms that allow consideration of other competing engineering drivers, such as the retention of mass balance, thermal balance, and radiation protection.

In the paper, it is shown that the baseline SVM protection design can be improved by considering a combined strategy of SVM panel enhancement and equipment rearrangement.

This study has been performed by the University of Southampton under an ESA contract entitled 'Genetic Algorithms for Optimisation of Spacecraft Equipment Location for Protection against Space Debris and Meteoroids' (Stokes, 2005).

1. SURVIVABILITY ASSESSMENT

1.1. Spacecraft definition

The following criteria were considered relevant in choosing a satellite as the basis for the optimisations in this study:

1. The design of the spacecraft and onboard equipment must be typical of many LEO satellites (i.e. in terms of size, configuration, subsystem designs, and functionality).
1. Adequate data on the spacecraft must be available in the literature.
1. The assessed spacecraft should be an ongoing or proposed programme, rather than a past one.

After reviewing several possible candidates, MetOp was selected as a baseline design. MetOp is a series of three satellites to be launched sequentially over 14 years, starting in 2005, and forms the space segment of EUMETSAT's Polar System (EPS). It will carry a set of 12 complementary instruments dedicated to operational meteorology. The satellite's overall design is based on a modular approach, which relies upon two largely independent modules, the Payload Module (PLM) and the Service Module (SVM), as shown in Fig. 1.

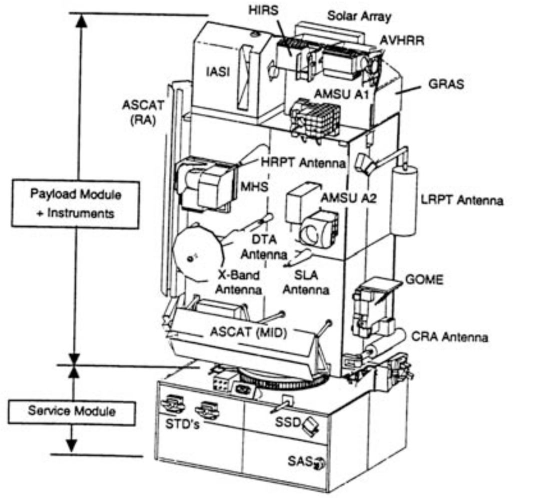

Figure 1. MetOp spacecraft configuration (solar array not shown)

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Of particular interest to this study is the Service Module (SVM) which carries all of the main satellite support functions such as attitude control, data handling, power generation and distribution, etc. This is the focus of the optimisation investigations, as its functions are common to most spacecraft. A diagram of the internal layout of the Service Module is shown in Fig. 2, and the individual units are defined in Tab. 1. The structure of the SVM comprises:

- A central cylindrical/cone structure made from a CFRP sandwich.
- A rectangular box structure comprising standard aluminium alloy honeycomb sandwich panels (upper and lower floors and external walls) which surround the cylinder. The skins are made from 0.4 mm thick aluminium alloy 2024-T81. The aluminium alloy core has a depth of 35mm and a density of 0.0705 g/cm^3.
- Aluminium alloy sandwich panel shear walls that link the cylinder to the external box structure.
- An aluminium propulsion module ring to support the four propellant tanks and to interface with both the Payload Module and the Service Module central structure.
- A battery compartment comprising a battery support plate and five equispaced radial stiffeners.
- A Solar Array Drive Mechanism (SADM) mounting structure (brackets and panels) for Attitude and Orbit Control Subsystem (AOCS) sensors and actuators, harness and antennas.

Table 1. List of main SVM equipment items

Acronym	Equipment name
CCU	Central Command Unit
BSP	Boitier de Servitude Pyrotechnique
OBA	On-board Adapter
EDR	Electronique de Decodage et de Reconfiguration
TRSP	Transponder
EAIM	Electronique de controle des Actuateurs Inertiels et Magnetiques
RW Y	Reaction Wheel: Y Axis
RW X	Reaction Wheel: X Axis
MAC Y	Magnetorquer
MAC X	Magnetorquer
EPRM	Electronique de controle de Propulsion et MEGS
EIU	Electronic Interface Unit
RSJD	Regulateur Shunt Jonction et Distribution
MEGS-E	Mecanisme Entrainement du Generateur Solaire - Electronique
RW Z	Reaction Wheel: Z Axis
BMG	Boitier Mecanique Gyro
T4S	Terminal Senseur Survie et Surveillance SCAO
BEG	Boitier Electronique Gyro

The configuration of the Service Module and location of equipment is driven by many factors, a selection of which is listed below:

- Units that are part of the same subsystem are located in the same quadrant (if possible).
- High priority is given to accessibility and ease of integration. Consequently, some panels do not have units mounted on them.
- To avoid acoustic loading problems, the location of a single light unit on any panel (except shear walls or horizontal floors) has been avoided.
- Due to the high magnetic fields generated by the magnetorquers, they are separated from other units by at least 300 mm.
- To mitigate thermal problems, the accommodation of highly dissipative units in the same quadrant has been avoided.

When considering equipment arrangement as part of the protection optimisation it is important to include as many of these factors as possible if the solutions are to be credible.

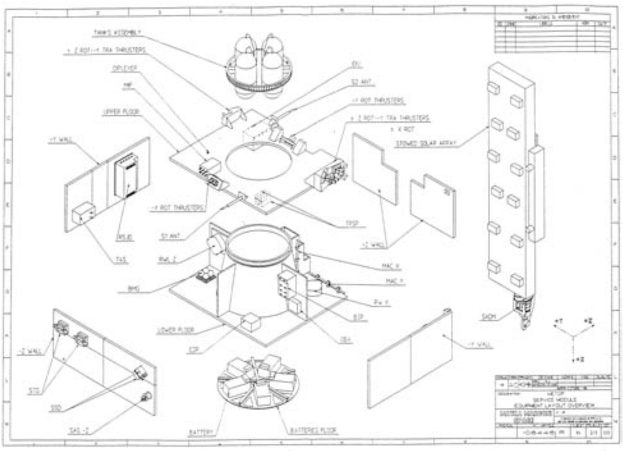


Figure 2. Exploded view of SVM interior (click to magnify)

1.2. Representation of spacecraft in SHIELD

To represent a spacecraft design in SHIELD, a 3D geometry is constructed by selecting from a library of pre-defined geometrical shapes. Alternatively, the user can construct a more complex, irregular geometry by entering specific coordinate data for the individual surfaces. Thus, a satellite geometry is represented in the software as a composite of many planes. Non-geometrical data are then associated with each surface, i.e.:

- Material properties, such as density, speed of sound, brinell hardness, and thickness or areal density.
- Shield properties, such as type (e.g. Whipple), spacing, and thickness or areal density.

Shelves and walls are constructed in almost exactly the same fashion as a satellite body surface, i.e. a plane with material properties assigned to it. Fig. 3 shows a rendered image of MetOp (excluding solar array) constructed in SHIELD.

Each equipment unit on the SVM is constructed in almost exactly the same manner as the main satellite body. However, there are some notable differences:

- A component can be attached to any point on a body face, shelf, wall, or any user defined point in the satellite. To do this, an attachment point on the component has to be specified. This is usually the centre of one of the component's surfaces.
- Each component is defined in terms of its own coordinate system. Therefore, to attach a component to a point somewhere inside the satellite body, the software performs a set of matrix transformations on the coordinates of each of the component's points.

Fig. 4 illustrates the internal arrangement of equipment on the SVM.

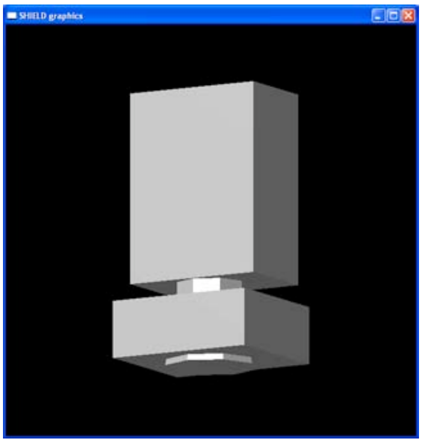


Figure 3. Rendered image of MetOp in SHIELD

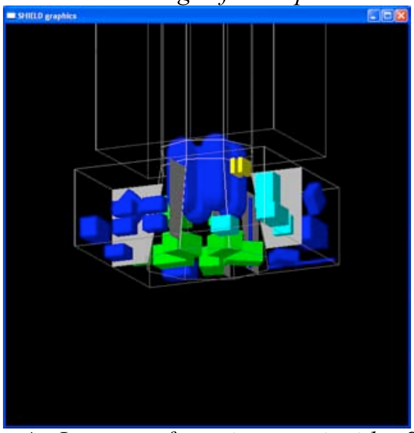


Figure 4. Layout of equipment inside SVM (view through Earth, RAM, & port faces)

1.3. Impact distribution on spacecraft

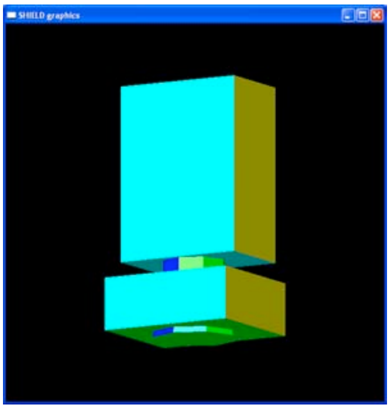
To determine the distribution of debris impacts on a spacecraft, SHIELD extracts target-centred flux data generated by QinetiQ's IDES debris environment evolution model. Specifically, the IDES output file contains relative flux over encounter velocity, azimuth, elevation, and target true anomaly for debris larger than a user-defined threshold. Test particles are generated using the Poisson probability density distribution from $x = 0$ to X event probabilities, P_x, where

$$P_x = \frac{\lambda^x}{x!} e^{-\lambda} \quad (1)$$

and

$$\lambda = F\,A\,\Delta t \quad (2)$$

and F = flux, A = area, Δt = time interval.
Each of the generated test particles is then evaluated to determine whether it will impact the target satellite geometry, and if so where. A ray-trace method establishes the point of intersection on the spacecraft geometry. Thus, repeating this process for all test particles at each time interval will produce the desired through-life impact distribution on the spacecraft. Finally, in the case of MetOp, the entire lifetime simulation is repeated 30,000 times to derive a statistically large enough distribution of particles that might penetrate. Fig. 5 shows the distribution of number of impacts/m^2/year on MetOp for particles larger than 0.5 mm. Not surprisingly, the RAM face (coloured yellow) experiences the highest number of impacts.



(Yellow = 1-10,….., Dark blue < 0.01)
Figure 5. Number of impacts/m^2/year on MetOp

1.4. Penetration distribution on spacecraft

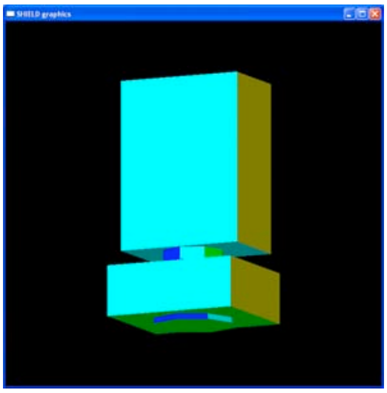
The impact distribution is now assessed to see which particles penetrate into the spacecraft interior. For each particle / spacecraft structure interaction, the use of an appropriate ballistic limit equation is required to ascertain whether penetration has occurred. In SHIELD, the ballistic limit equations are categorised according to the following two types – single wall and multiple wall. Both types are provided in a parametric form. The following equation represents the multiple wall type:

$$d_{p_{crit}} = \left[\frac{t_B + K_2 t_s^{\mu} \rho_s^{\upsilon 2}}{K_1 \rho_p^{\beta} v^{\gamma} (\cos\alpha)^{\xi} \rho_B^{\kappa} S^{\delta} \rho_s^{\upsilon 1}} \right]^{\frac{1}{\lambda}} \quad (3)$$

where

- d_p = Particle (impactor) diameter
- t_B, t_s = Thickness of rear wall, shield
- v = Impact velocity
- K = Characteristic factor. K_1, K_2 are equation specific factors
- S = Space between shielding and rear wall
- α = Impact angle (with respect to surface normal)
- ρ_p, ρ_s, ρ_B = Density of particle, shield, rear wall

For the MetOp analysis, the parameter values derived in Turner, et al. (1999) are used. The resulting distribution of penetrating particles is shown in Fig. 6.



(Yellow = 0.01-0.1,….., Dark blue < 0.0001)
Figure 6. Number of penetrations/m^2/year on MetOp

SHIELD predicts that, overall, MetOp has a probability of penetration of ~0.45. It is clear that any internal equipment located near the RAM faces will experience the highest risk of a penetrative impact.

1.5. Failure assessment of spacecraft

For each of the particles that penetrate the spacecraft structure, a ray-trace is used to identify which internal equipment units are vulnerable. SHIELD then determines whether the units will be penetrated. To do this, the software follows an assessment procedure that essentially approximates the spacecraft structure as the bumper element of a multiple wall ballistic limit equation, and the impacted face of the equipment as the back-wall (see Fig. 7).

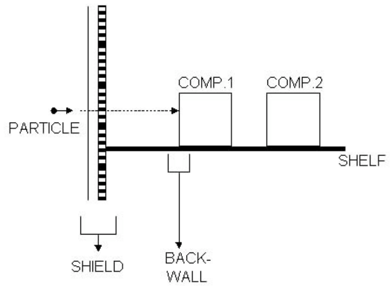


Figure 7. Penetration of an equipment unit

Currently, in SHIELD it is assumed that a penetrated unit always fails, whereas one that experiences a non-penetrative impact survives. This assumption is the focus of investigations in another ongoing ESA contract (ESA, 2002), the output of which may provide more realistic equipment failure probability density functions that can be coded into SHIELD.

In the event that a given penetrator causes an equipment to fail, this does not necessarily mean that the spacecraft will fail. For example, if the equipment is not critical to the mission or has a redundant unit, then it is conceivable that the mission may still be able to continue (at least partially). In SHIELD, one method to assess the high-level consequences of an equipment loss is Fault Tree Analysis (FTA). A spacecraft is represented as a set of 'function' block diagrams, where each diagram describes a specific spacecraft function of a given level of importance. An example of such a diagram is shown in Fig. 8.

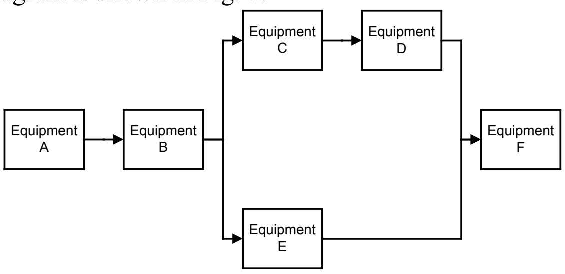


Figure 8. Example of a 'function' block diagram

The blocks are the equipment units used to perform the function and the paths are connections between the units. If one or more blocks or paths fail (due to a penetrative impact) so that there is no unbroken route between both ends of the diagram then this particular function will cease. If the function has a high level of importance associated with it, then the mission will terminate.

When all spacecraft penetrators have been analysed in this fashion, it is then a straightforward matter to count up all those that cause mission termination. Knowing the number of failures, N_{deb}, the through-life debris-induced probability of failure of the spacecraft can be readily determined using:

$$P_{deb} = 1 - e^{-N_{deb}} \qquad (4)$$

For the MetOp SVM, SHIELD predicts a value of ~2%.

1.6. Objective function assessment of spacecraft

The final step in the survivability assessment is to calculate an objective function that is a measure of the 'fitness' of a particular satellite design to survive the space debris environment. This enables the distinction between so-called 'good' and 'bad' solutions and is the core element of an optimisation. The function combines the total failure risk of a spacecraft with its life cycle cost. In SHIELD, it takes the following basic form:

$$S = \frac{1}{\left(N_{deb} + N_{equip}\right)C_{lcc}} \qquad (5)$$

where, N_{equip}, is the number of failures experienced by the equipment units as a result of random or wear-out effects, i.e. not debris-induced. This value is derived from standard reliability analysis techniques. C_{lcc} is the life cycle cost of the mission (which comprises spacecraft launch and manufacturing costs, including the costs of implementing protection). The life cycle cost is derived from a parametric cost model comprising Cost Estimating Relationships.

The goal is therefore to maximise S by finding the optimum balance between risk and cost. This enables the cost-effectiveness of radically different protection and configuration strategies to be determined and compared in a completely objective manner.

Finally, it should be noted that the function, S, is normalised against a notional 'ideal' satellite (i.e. one where N_{deb} = 0 and the cost of protection is zero). For the MetOp SVM, S = 0.984.

3. PROTECTION OPTIMISATION

The question that the study must now address is this: is it possible to improve the survivability of the baseline design in a cost-effective manner by (a) adding shielding mass to the structure and (b) rearranging the internal equipment? The complexity of the problem necessitates the use of a modern stochastic search method, such as a genetic algorithm, to generate and evaluate sets of competing design solutions, and converge on the 'best' solution. Each competing solution (i.e. spacecraft design) will be unique, and differ from the other solutions according to the values of certain variables, e.g. the location of equipment units.

3.1. Multidisciplinary design optimisation setup

The protection optimisation problem is in fact one of Multidisciplinary Design Optimisation. Structural enhancement and equipment layout is driven by a number of competing, and potentially contradictory, engineering requirements, as illustrated in Fig. 9.

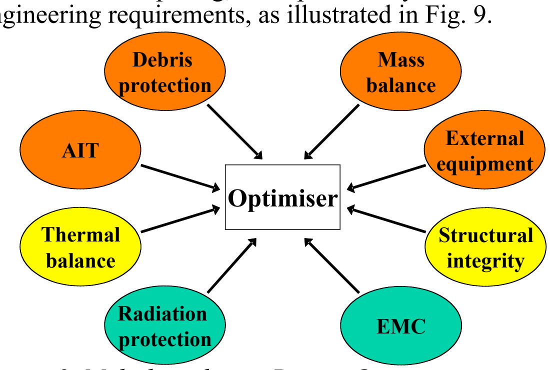


Figure 9. Multidisciplinary Design Optimisation

For example, besides debris protection, the layout of equipment must take into account factors such as:

- The need to retain overall mass balance within certain limits.
- Allowing easy access to equipment during Assembly, Integration and Testing (AIT).
- Locating high power units on surfaces that radiate heat to space.
- Locating sensitive electronics close to the centre of the spacecraft to minimise radiation dose.
- Avoiding Electromagnetic Compatibility (EMC) problems by sufficient separation of equipment.
- Locating equipment so that structural loading limits are not exceeded.
- Minimising harnesses to externally mounted equipment.

The optimum solution is therefore the one that is the best compromise between these different requirements. In Fig. 9, the orange coloured requirements represent ones that are already addressed in SHIELD; yellow ones are partially considered; and green ones are not yet included. For the study, we keep the problem relatively simple by activating just the mass balance requirement in conjunction with debris protection.

3.2. Genetic algorithm setup

There is extensive material on the design and operation of genetic algorithms in the literature, so no description will be included here. The genetic algorithm in SHIELD is standard in its functionality and comprises the following features:

- Roulette wheel or rank selection
- Two-point crossover
- Bit mutation
- Elitism

In the study, a sensitivity analysis was performed which identified the best set of parameters for the genetic algorithm, as follows:

- # generations = 1500 – 2000
- Population size = 30
- Probability of crossover = 0.9
- Probability of mutation = 0.01

Thus, the optimisation has to create and evaluate ~50,000 competing design solutions.

3.3. Variables setup

The input data shown in Tab. 2, which were fixed for the baseline MetOp design survivability analysis (in Section 2), are now reassigned as variables for the optimisation.

Table 2. Variables for the optimisation

Variable type	Variable options
Face panels: inner skin	0.4 mm – 1.4 mm
Face panels: outer skin	0.4 mm – 1.4 mm
Face panels: core depth	30 mm – 40 mm
Equipment casing	1.0 mm – 3.0 mm
Equipment orientation on a surface	4 positions (90º apart)
Equipment attachment	one or more face panels
Equipment attachment	one or more walls

In particular, it should be noted that there are differing amounts of variability for locating the equipment in the MetOp SVM depending upon its functionality. For example, the three reaction wheels must be positioned so that they are orthogonal to each other.

3.4. Optimisation #1

A typical genetic algorithm optimisation in SHIELD takes of the order of 2 days to complete on a dual 3GHz Pentium PC. The performance of the GA in reaching the optimal MetOp SVM solution can be seen in Fig. 10. This shows a plot of the objective function (i.e. survivability, *S*) of the best design in each generation. There is a rapid increase in survivability within the first 500 generations, followed by a long period during the remainder of the simulation where improvements are much harder to achieve. This is characteristic of genetic algorithms, which are very good at exploring a large multivariate design space and focusing on the general region where the global optimum lies. However, the long period of limited improvement illustrates the difficulty that GAs have in reaching the absolute global optimum.

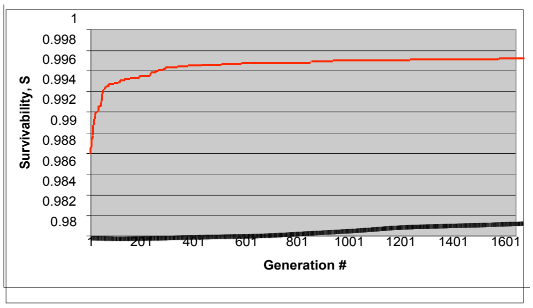


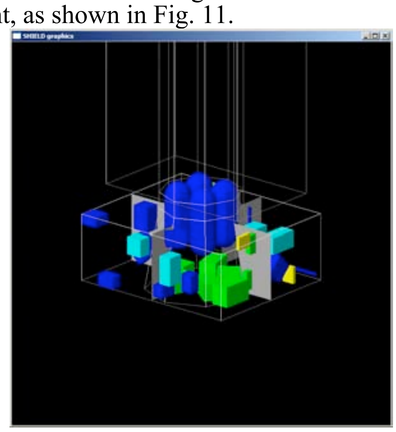
Figure 10. Survivability of best design in each generation

Comparing the best solution in the final generation with the baseline SVM design, we have the result shown in Tab. 3. The best solution provides a fourfold reduction in through-life debris-induced failure probability. From the increase in mission cost it is clear that this is explained, at least in part, by the addition of shielding mass to the structure. One can conclude, therefore, that the benefit obtained from the shielding outweighs its cost, and contributes to some of the improvement in survivability.

Table 3. Comparison of best solution with baseline

Parameter	Baseline SVM	Opt. #1
Prob. fails due to debris	0.0201	0.0045
Mission cost (Euro)	245,605,767	246,438,369
Survivability, S	0.984	0.996

The remainder of the survivability enhancement is derived from a rearrangement of the layout of equipment, as shown in Fig. 11.



View of RAM, Earth, and right-side faces
Figure 11. Layout of equipment in best design

The first point to note is that the equipment is distributed fairly evenly throughout the SVM indicating that the mass balance requirement has been satisfied. Secondly, the most vulnerable face - the RAM face - has only three low-criticality units on it. Most of the critical units are located either on the Earth and space faces, which have low impact vulnerabilities, or on internal walls. Thus, we can see that SHIELD has identified an arrangement of equipment that is consistent with the requirements and constraints of the optimisation.

One of the biggest contributing factors to the improvement in survivability is the relocation of the critical Central Command Unit. In the baseline design this is positioned on the RAM face, whereas in the optimised solution it is placed on the Earth face.

3.5. Optimisation #2

The above optimisation simulation does not include any consideration of linkages in the spacecraft. By this we mean harnesses, cables, and pipe-work. The presence of these can play an important role in terms of impact failure risk and cost, and therefore should produce a different result. The purpose of this optimisation is to demonstrate the effect harnesses may have.

During the previous optimisation, a total of ~50,000 different equipment layouts were constructed and evaluated. In this optimisation, SHIELD has to wire up 34 harnesses in each of the 50,000 designs automatically, and do so in the most efficient manner. This means that the software must find the shortest route through a given spacecraft design for each and every link. Essentially, SHIELD is now performing an additional 1.7 million mini-optimisations within the overall optimisation. Clearly this is a large computational overhead that must be solved with a highly efficient algorithm.

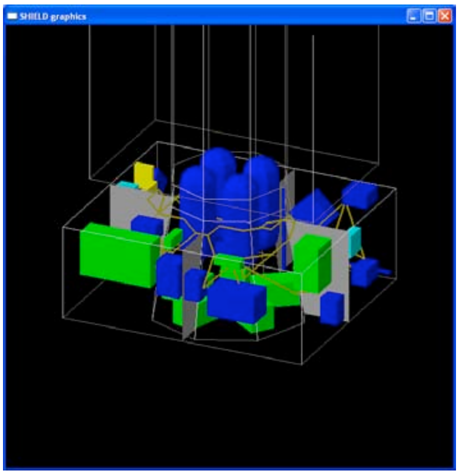
We solve the problem using an algorithm devised by a Dutch computer scientist called Edsger Dijkstra. Dijkstra's algorithm is designed to find the most efficient path from a point in a graph (the *source* node) to a destination node (NIST, 2005). For example, it can be used to find the shortest route between two points on a map (via a set of intermediate points), or it can identify the cheapest route to send traffic between two nodes of a communications network (via intermediate nodes).

The inclusion of links in the optimisation causes a significant increase in run-time from two days to two weeks. The resulting best solution has the summary characteristics listed in Tab. 4.

Table 4. Comparison of best solutions with and without harnesses included

Parameter	Opt. #1	Opt. #2
Prob. fails due to debris	0.0045	0.0063
Mission cost (Euro)	246,438,369	247,099,789
Survivability, S	0.996	0.994

Not surprisingly, the inclusion of harnessing as an additional item inside the SVM has increased the failure probability and cost. Thus, the survivability, S, is less than that in Optimisation #1. So, the presence of the harnesses can play an influential role. This is seen by examining the layout of the equipment (including harnesses) in Fig. 12. It is clear that this arrangement is radically different to that obtained in Optimisation #1.



View of RAM, Earth, and right-side faces

Figure 12. Layout of equipment (including harnesses) in best design

The even distribution of equipment, relatively short harnessing, and positioning of most critical units away from the RAM face all indicate that this is a 'good' solution.

4. SUMMARY

This paper summarises a recent ESA/ESTEC study into the potential for genetic algorithms to optimise protection on a realistic unmanned spacecraft. Using a software tool called SHIELD, results show that optimal protection solutions can be found when taking into account other competing engineering requirements such as the need to retain spacecraft mass balance. Enhancement of the spacecraft structure in conjunction with the arrangement of internal equipment appears to be the best protection strategy.

It is anticipated that the SHIELD tool will be further extended to include a more realistic penetrative debris cloud model; better characterisation of the response of equipment to cloud impact; and consideration of the remaining multidisciplinary design engineering requirements.

5. ACKNOWLEDGEMENTS

The work presented in this paper was performed as part of the ESA/ESTEC contract (no. 17552/03/NL/MRP) entitled 'Genetic Algorithms for Optimisation of Spacecraft Equipment Location for Protection against Space Debris and Meteoroids'.

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