A TOOL FOR MULTIDISCIPLINARY DESIGN CONCEPTION OF SPACECRAFT EQUIPMENT LAYOUT

Fabiano L. de Sousa
INPE/DSE – Av. Dos Astronautas 1758, S.J.Campos, SP, 12227-010
fabiano.sousa@inpe.br

Roberto Luiz Galski
INPE/CCS – Av. Dos Astronautas 1758, S.J.Campos, SP, 12227-010
galski@ccs.inpe.br

Evandro Marconi Rocco
INPE/DMC – Av. Dos Astronautas 1758, S.J.Campos, SP, 12227-010
evandro@dem.inpe.br

José Carlos Becceneri
INPE/LAC – Av. Dos Astronautas 1758, S.J.Campos, SP, 12227-010
becce@lac.inpe.br

Walter Abrahão dos Santos
INPE/LAC – Av. Dos Astronautas 1758, S.J.Campos, SP, 12227-010
walter.abrahao@lac.inpe.br

Sandra Aparecida Sandri
INPE/LAC – Av. Dos Astronautas 1758, S.J.Campos, SP, 12227-010
sandra.sandri@inpe.br

Abstract. *In the process of building a new spacecraft, one of the earliest issues the design team has to face is to define its mechanical and electrical architecture. In this context, the choice of where to place the spacecraft´s electronic equipment is probably one of the most complex task to be addressed, since it involves taking into account simultaneously many factors, such as the spacecraft´s required position of mass center, moments of inertia, equipment heat dissipation, electromagnetic interference and integration and servicing issues before launch, among others. Since this is a multidisciplinary task, the early positioning of the spacecraft´s equipment is usually done "manually" by a group of system engineers, heavily based on the their experience. Coupled to an analysis stage, where the system´s performance and constraints are verified, the spacecraft´s equipment layout definition is an interactive process that takes time and hence, as soon as a good feasible design is found, it becomes the baseline. This precludes a broader exploration of the conceptual design space, which may lead to a suboptimal solution, or worse than that, to a design that will have to be modified later on in the development process, impacting in schedule and costs. Recently, it has been shown the potential benefits of process automating the spacecraft´s equipment layout conception, using optimization techniques. In this paper it is shown the concept and early results of an Excel®-based tool for multidisciplinary spacecraft equipment layout conception. This approach provides the system engineering team an efficient and easy to use way to explore the layout conceptual design space. A particular case study is run where results are shown for the positioning of equipment considering three objectives: i) position of system´s mass center ii) equipment heat dissipation density and iii) proximity of equipment by similarity of sub-system, in a multiobjective approach. After the Pareto set is found, the problem of decision making is also addressed for choosing a suitable solution to be implemented.*

Keywords: layout optimization, spacecraft, conceptual design, electronic equipment

1. INTRODUCTION

The development process of a new spacecraft is composed of phases, which goes from conceptual studies to disposal (NASA, 2007). In the conceptual phase of the development of a new spacecraft, different candidate solutions for its electrical and mechanical architectures are assessed, in a search for one which would fit the spacecraft mission, within the constraints of cost and schedule. It is in this phase where the main features of its subsystems are defined, and where the systemic and multidisciplinary character of design process becomes more relevant to the definition of its cost and performance.

The assessment of different solutions for the mechanical and electrical architecture includes the positioning of the spacecraft´s equipment over its structure panels, aiming at satisfying mechanical and electrical requirements or constraints. A target position for the system´s mass center, preference of moment of inertia in a given direction,

minimization of electromagnetic interference, avoidance of high heat dissipation equipment being positioned close to another, and minimization of cabling are examples of such concerns. The early positioning of the spacecraft´s equipment is usually done "manually" by a group of system engineers, heavily based on their experience. Coupled to an analysis stage, where the system´s performance and constraints are verified, the spacecraft´s equipment layout definition is an interactive process that takes time and hence, as soon as a good feasible design is found, it becomes the baseline. This reduces the exploration of the design space, and hence increases the probability that better designs are missed. Hence, increasing the creation of candidate solutions by numeric automatization of the search through the conceptual design space, would increase the possibilities that better designs are found.

The works of Ferebbe Jr. and Powers (1987) and Ferebbe Jr. and Allen (1991) are probably the firsts to propose numerical optimization methods for automating the process of determining the layout of equipment during the conceptual phase of spacecraft design. In a series of works, Teng et al. (2001), Sun and Teng (2003), Zhang et al. (2008) and Teng et al. (2010), studied the efficacy of the approach when applied to a spinning telecommunication satellite, considering also the influence of the application of different optimization methods. These works have in common the focus on placing the equipment driven by the system´s mass properties (position of mass center and magnitude and direction of principal axis of inertia) requirements, subject to geometric constraints. In Jackson and Norgard (2002) thermal issues and minimization of wiring between equipment were introduced as objectives to be considered in the search for candidate solutions in the design space. Thermal requirements are in fact one of the main drivers of the spacecraft layout design, and in the context of conceptual layout optimization they have been treated either by trying to meet requirements of equipment heat dissipation uniformity over the spacecraft´s structural panels (Jackson and Norgard, 2002; Hengeveld et al., 2011) or target temperatures on them (De Sousa et al., 2007). In the later work the problem was treated as fully multi-objective, that is, opposed to the usual approach of transforming it in mono-objective before optimization is performed, a set of trade-off solutions is the objective of the search. This provides more information about the design space, leaving for a posteriori analysis the choice of which solution will be implemented.

Coupling optimization algorithms with CAD and engineering analysis packages, provides an efficient way to tackle the spacecraft equipment layout problem, as highlighted in the works of Baier and Pühlhofer (2003), Pühlhofer et al. (2004) and Cuco (2011). In the later one, a new methodology proposed to address the problem. Cuco´s methodology (Cuco, 2011) considers the main drivers commonly used to define the equipment layout during the spacecraft´s conceptual design: i) the position of the system center of mass; ii) the alignment and strength of the system principal axis of inertia; iii) avoidance of concentration of high heat dissipation equipment over the satellite panels; and iv) equipment functional requirements.

The methodology of Cuco (2011), or different versions of it, may be implemented in different ways using commercial or custom made software. Cuco (2011) used modeFrontier® to couple Solidworks®, Matlab®, Excel® and an executable written in C, for such purpose. The advantage of using a software such as modeFrontier® as the core tool to implement the methodology, is that since it was specially developed to tackle optimization problems and act as an integrator of other CAD or CAE tools, it has readily available on its internal features different optimization algorithms and techniques to be used on the problem, and provides a user-friendly interface to integrate other tools and analyze the results. On the other hand, the user has limited or no access to changes on the workings of these tools, what may affect his/her ability to explore new ways of addressing the problem. In the context of a research tool for the exploration of different concepts and algorithms to address the spacecraft equipment layout optimization problem, Excel would® provide a convenient alternative, since it can be used as a platform where new optimization algorithms can be embodied, a calculator for engineering analysis, data storage, visualization of results, as well as an integrator of CAD and CAE tools. It also has the advantage of being known and be available by large in the engineering community.

In the present work Cuco´s methodology (2011) is used as the main framework from where a prototype of an Excel® based tool for spacecraft equipment layout is developed. Adding to Cuco´s work, the tool also will incorporate decision making criteria to help the design team choose one or more candidate solutions for further evaluation, after the Pareto set and Pareto frontier is returned.

In the Sections that follow, a prototype of the layout tool is presented and a simplified example of application are shown in Sections 3 and 4, respectively, while in Section 5 final remarks and future work is highlighted.

2. SPACECRAFT EQUIPMENT LAYOUT AS AN OPTIMIZATION PROBLEM

The spacecraft´s layout problem can be tackled as a multidisciplinary multiobjective optimization problem and can be generally stated as:

$$\textbf{Min } f_i(x_j) \; ; \; i = 1 \text{ to } I \; , \; j = 1 \text{ to } J \tag{1}$$

Subject to:

$$g_k(x_j) \leq 0 \; ; \; k = 1 \text{ to } K, \tag{2}$$

$$h_l(\mathrm{x_j}) = 0 \; ; \mathrm{l} = 1 \text{ to L}, \tag{3}$$

$$x_{jmin} \leq x_j \leq x_{jmax} \tag{4}$$

where f_i is a vector of I objective functions, x_j is a vector of J design variables, g_k and h_l are vectors of K and L inequality and equality constraints, respectively, and x_{jmin} and x_{jmax} are the bottom and upper boundary constraints on the design variables.

The objective functions encode the design requirements for the spacecraft, such as a target position for its mass center, whereas the constraints define the viable design space. For example, there must be no mechanical interference among the equipment. In the simplified case study showed in Section 4, these points will be made clear.

The approach for the spacecraft equipment layout problem proposed by Cuco (2011) is used here as the general framework in which the tool presented in this work is built. In Cuco´s methodology the design variables are defined considering the panels where the equipment would be positioned and, over a given panel, the local coordinate position of the equipment mass center being positioned on that panel. Hence, for example, if there are 10 equipment to be positioned and 2 panels available for positioning, there are 22 design variables for optimization. Design requirements for the position of the system´s mass center, the alignment of the principal axis of inertia and avoidance of "hot spots" over the panels are tackled by three objective functions, while geometric and functional requirements are take into account as constraints. In Cuco´s methodology the result of the optimization is a set of candidate non-dominated solutions for the layout and its respective Pareto frontier. The decision of which solution, or solutions, would be subject to a further analysis to become the baseline layout is left for the engineering team responsible for the layout design. Cuco´s methodology framework is depicted in Figure 1.
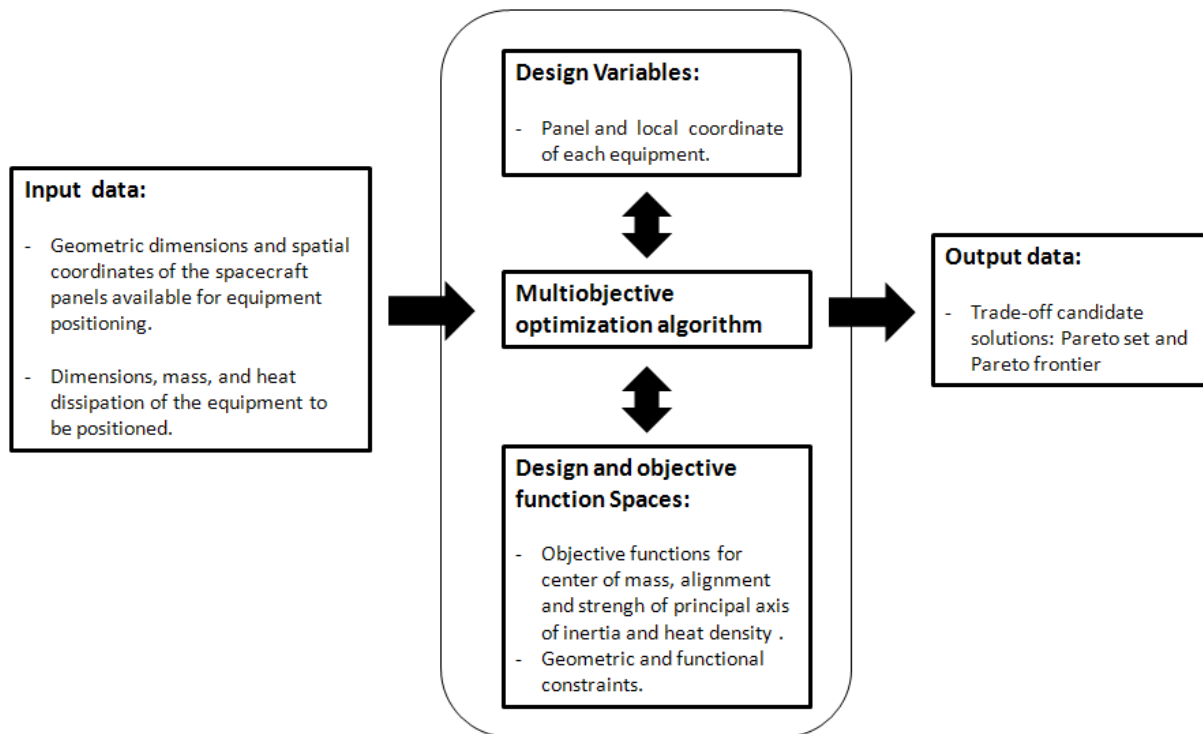

Figure 1 – Simplified representation of Cuco´s (2011) methodology for spacecraft´s equipment layout.

The general framework depicted in Figure 1 highlights the basic aspects to be considered by any computational environment aimed at providing the system´s engineering team, a tool for the spacecraft´s equipment layout, during its conceptual design phase. It is flexible enough to accommodate design goals being treated either as objective functions or constraints.

3. **DESCRIPTION OF A PROTOTYPE FOR AN EXCEL BASED MULTIDISCIPLINARY CONCEPTUAL DESIGN TOOL FOR SPACECRAFT EQUIPMENT LAYOUT**

The main components of the optimal layout tool are presented in Figure 2.
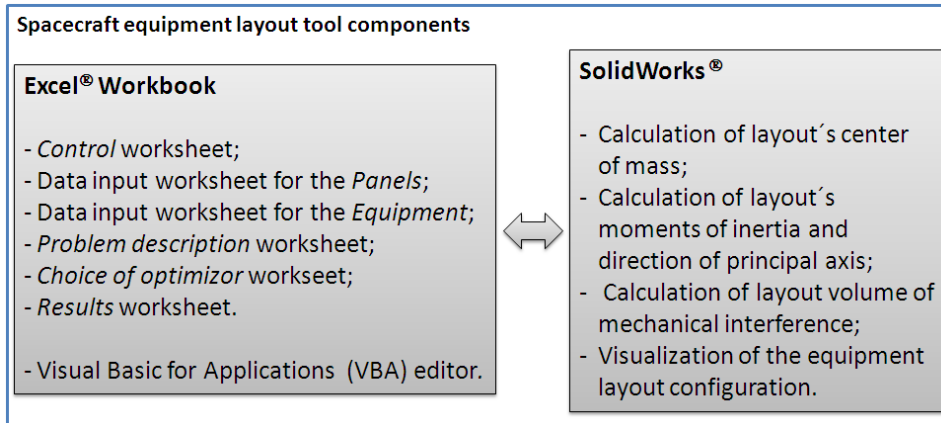

Figure 2 – Main components of the spacecraft equipment layout tool.

The Excel workbook consists presently of 6 worksheets and 8 macros. From the *control worksheet*, a specific geometric configuration defined in the *Panels* and *Equipment* worksheets is built in SolidWorks®, which is invoked by clicking a button inside the *control* worksheet. All design parameters calculated inside SolidWorks®, are returned to the *control* worksheet. In the *Panels* worksheet the geometric characteristics of each panel available for equipment positioning is entered. In the present version of the layout tool only rectangular panels are modeled. In the *Equipment* worksheet, the mechanical and thermal characteristics of the equipment are entered, together with the information of what subsystem they belong. In the present version of the layout tool, rectangular, cylinder and sphere solids can be used to simulate the equipment. The solids may be assigned with different colors. In this worksheet can also be entered values for the design variables. In the *Problem Description* worksheet, a brief description of the objective functions, constraints and design variables being considered in the optimization problem is provided. In the *Choice of Optimizor* worksheet, the optimization algorithm to be used is chosen and information concerning its operational parameters and stopping criteria is entered. The optimization process is initialized from this worksheet, by clicking a button representing an available optimization algorithm. This calls a macro that embodies the algorithm and links it to the ones that invoke the SolidWorks®. Finally, in the *Results* worksheet, the Pareto set and Pareto frontier obtained during the search is presented. Different types of graphs available in Excel may be used to show the Pareto frontier. For example, for problems with three objective functions, bubble or surface graphs may be used. In Figure 3, from top right, clockwise direction, screen prints of the six worksheets are presented.

The macros for the optimization algorithms, objective functions and routines that link Excel® to SolidWorks® are built using the VBA editor, in a modular approach, such that new optimization algorithms or objective functions can be added or removed from the tool, as desired. In its present version, only the M-GEO optimization algorithm (REF Galski) was incorporated to the layout tool. In Figure 4 screen prints of the VBA editor, with the macro that encodes the M-GEO algorithm showed upfront in the screen (left) and the *Equipment* worksheet together with the Solidworks® environment in the same view (right), are shown.

The layout optimization process embodied in the layout tool just described is fully automatic. That is, once the "button" linked to an optimization algorithm is clicked in the *Choice of Optimizor* worksheet (for example, Play M-GEO in Figure 3), the information on the *Panels* and *Equipment* worksheets are accessed, the SolidWorks® is invoked and linked to the Excel, the optimization performed and the results sent to the *Results* worksheet. The graph that plots the Pareto frontier is also automatically updated. After the Pareto frontier is retrieved a particular layout solution may be visualized in SolidWorks® by copying the values of the design variables that represent it to the appropriate cells in the *Equipment* worksheet and invoking the SolidWorks® from the *Control* worksheet.

The automatic selection of particular solutions from the Pareto frontier, based on dedicated decision making criteria, will be added in the next version of the tool. For the present work, this is done in a separate procedure, highlighted in the simplified example of the application of the layout tool shown in the next Section.
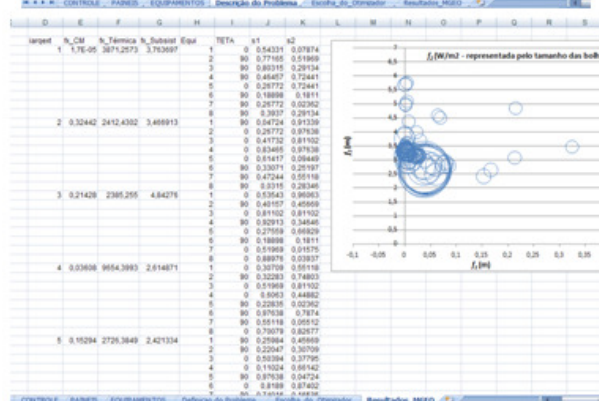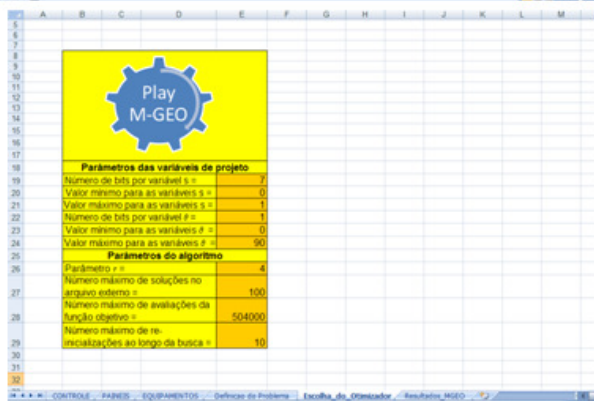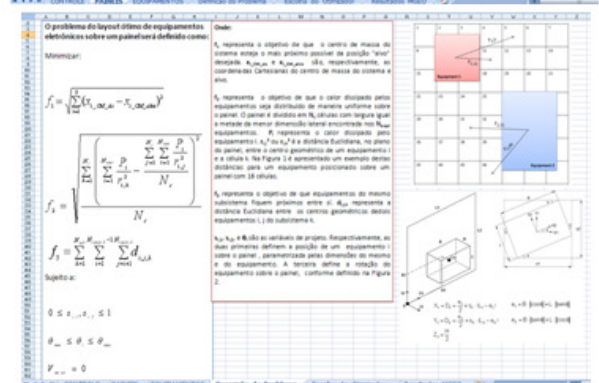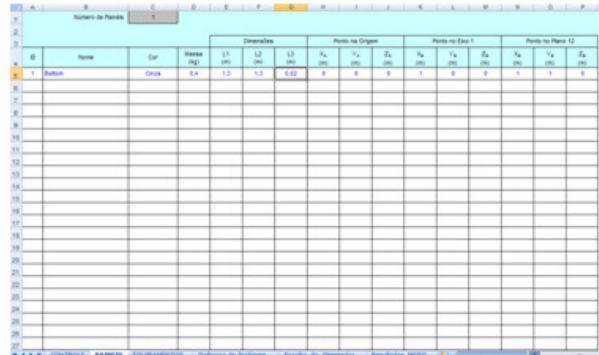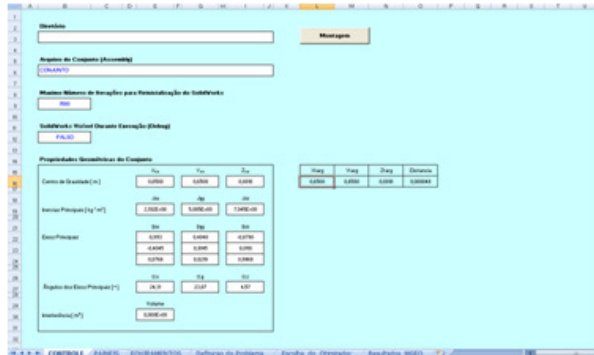
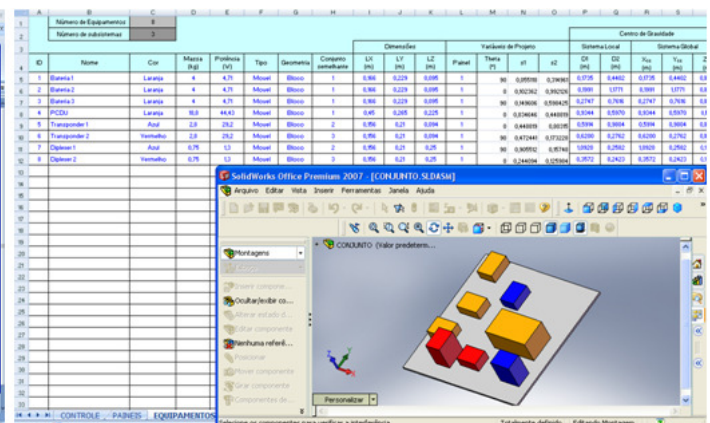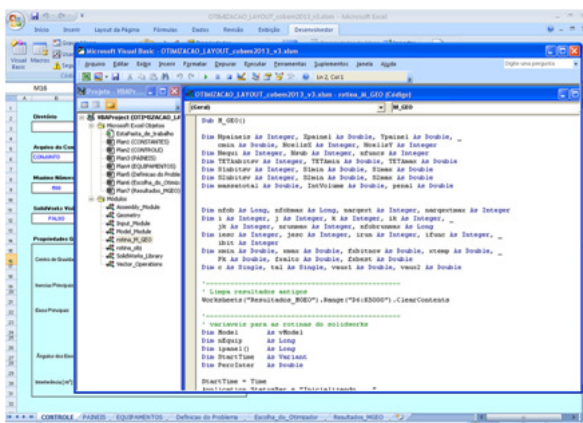Figure 3 – Screen prints of the layout tool Excel® worksheets.

Figure 4 – Screen shots of the VBA editor showing in evidence the M-GEO macro (left) and *Equipment* worksheet with Solidworks® environment in the same view (right).

4. SIMPLIFIED EXAMPLE OF APPLICATION

To illustrate the use of the layout tool, a simplified example was devised. It consists of placing 8 typical spacecraft equipment belonging to three different "common sets", over a squared panel with side dimension of 1.3 m. The objective is to place the equipment such that the resulting configuration has a center of mass as close as possible to a target position, hot spots are avoided and equipment belonging to the same "common set" is placed as close as possible.

4.1 Statement of the Layout Optimization Problem

The problem is a multi-objective optimization problem that can be posed as:

Minimize:

$$f_1 = \sqrt{\sum_{i=1}^{3} (x_{i\_CM\_sis} - x_{i\_CM\_alvo})^2} \quad , \tag{5}$$

$$f_2 = \sqrt{\frac{\sum_{k=1}^{N_c} \left(\sum_{i=1}^{N_{equi}} \frac{P_i}{r_{i,k}^2} - \frac{\sum_{j=1}^{N_c} \sum_{i=1}^{N_{equi}} \frac{P_i}{r_{i,j}^2}}{N_c} \right)^2}{N_c}} \quad , \tag{6}$$

$$f_3 = \sum_{k=1}^{N_{sub}} \sum_{i=1}^{N_{equip,k}-1} \sum_{j=i+1}^{N_{equip,k}} d_{i,j,k} \quad , \tag{7}$$

Subject to:

$$0 \le s_{i,1}, s_{i,2} \le 1 \quad , \tag{8}$$

$$\theta_{min} \le \theta_i \le \theta_{max} \quad , \tag{9}$$

$$and$$

$$V_{inter} = 0 \quad . \tag{10}$$

f_1 represents the goal of having the center of mass of the system, $x_{i\_CM\_sys}$, as close as possible to a given target center of mass, $x_{i\_CM\_target}$.

f_2 is a heuristic devised to represent the goal that the N_{equi} equipment are distributed over the panel in such a way that the heat dissipated by them is, as best as it is possible with discrete heat sources, uniformly distributed over the panel´s surface. The panel is divided in N_c rectangular cells, each side of them with half the size the smallest side dimension of all equipment. P_i represents the heat dissipated by equipment i, and $r^2_{i,j}$ the distance between the center of the ith equipment to the center of jth cell, as seen in Figure 5.
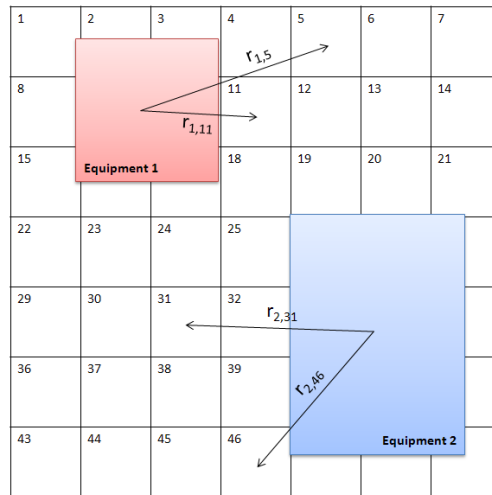
Figure 5 – Representation of how the distance between the equipment and the panel´s cells is considered in the heuristic used to calculate f_2. Example with two equipment and 49 cells. Only distance for cells 5, 11, 31 and 46 are shown in the example, but all cells are considered when calculating the value of f_2.

Minimizing f_2 means that the standard deviation of the quantity $\displaystyle\sum_{i=1}^{N_{equi}} \frac{P_i}{r_{i,j}^2}$ is minimized, that is, the combined influence of all equipment over each panel cell would be the same. This would avoid "hot spots" over the panel.

The third objective function, f_3, represents the goal of minimizing the distance between equipment belonging to the same subsystem, where $d_{i,j,k}$ is the distance between the geometric centers of equipments i and j belonging to the subsystem k.

$s_{i,1}$, $s_{i,2}$ and θ_i are the design variables. Respectively, the two first define the parameterized position of the geometric center of an equipment i over the panel, while θ_i is the rotation of the equipment, as shown in Figure 6. The values of the parametric variables $s_{i,1}$ and $s_{i,2}$ can vary in the range [0, 1]. This parameterization guaranties that the boundaries of the equipment always lies inside the area of the panel.

$$X_1 = D_1 = \frac{e_1}{2} + s_1 \cdot (L_1 - e_1)$$

$$Y_1 = D_2 = \frac{e_2}{2} + s_2 \cdot (L_2 - e_2)$$

$$Z_1 = \frac{H}{2}$$

$$e_1 = B \cdot \|\cos\theta\| + L \cdot \|\text{sen}\theta\|$$

$$e_2 = B \cdot \|\text{sen}\theta\| + L \cdot \|\cos\theta\|$$
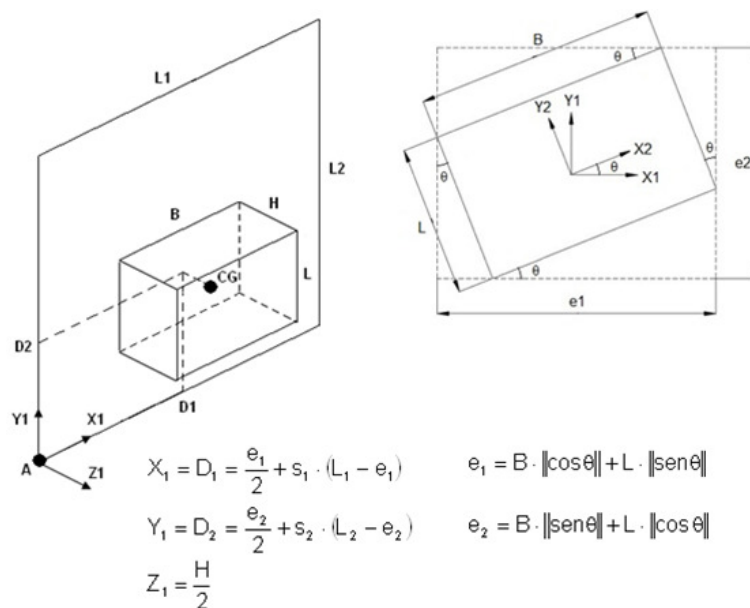
Figure 6 – Parameterization of equipment position over the panel.

The bound constraints on the design variables (Eqs. 8 and 9) are automatically considered when they are codified in into the binary strings, while the equality constraint (Eq. 10) is treated as a penalty for the objective functions when it is violated, using a exterior penalty method (Vanderplaats, 2007) approach.

4.2 M-GEO algorithm

The M-GEO algorithm (Galski, 2011) is a multi-objective version of the GEO evolutionary algorithm (De Sousa, 2002, De Sousa et al., 2003). In essence, the multi-objective strategy of M-GEO is the strategy of an M-to-one tournament, where, at each algorithm iteration (generation), all the M objective functions compete for the privilege of being used as the fitness assignment function and just one is chosen. As the choice is totally random, theoretically, along several generations, any sequence of choices is possible, even those where only one objective function is used as the fitness assignment function during the entire search. M-GEO does not work with sub-populations, hence, at a given iteration, only one of the objective functions is used for the fitness assignment of all species. As in the canonical GEO, in M-GEO the initial population is created from a single point in the design space. This could lead to an initial population close to one of the edges of the Pareto front in the objective space, then delaying the spread of the population over the entire frontier. To avoid this, the algorithm is restarted some times during a run. The main steps of M-GEO are shown in Figure 7.
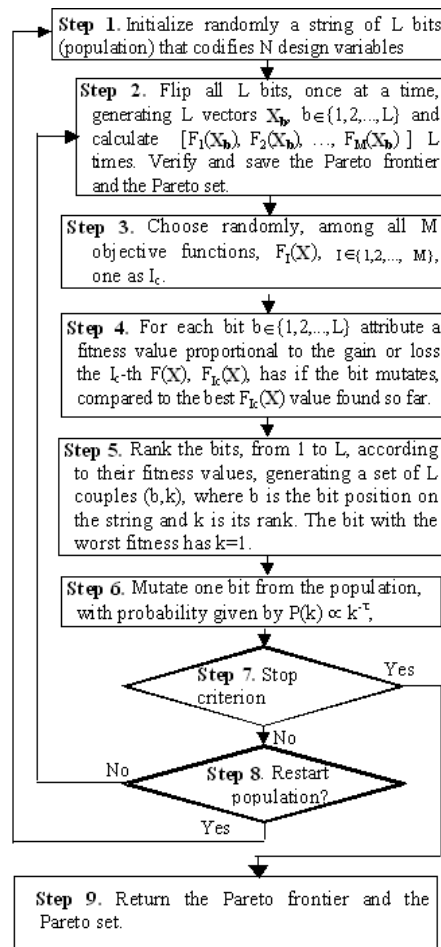

Figure 7 – Main steps of M-GEO multiobjective optimization algorithm.

The non-dominated solutions found during the search are stored in the computer memory and returned at the end of the search (Step 9). Because the number of points contained in the Pareto frontier may become very large (even infinite if the frontier is continuous), in the layout tool presented in this work the user can set the maximum number of non-dominated solutions desired to be stored in the memory and retrieved at the end of the search. If during the search a new created non-dominated solution makes that number be exceeded, the "crowded distance" strategy proposed by (Deb et al., 2000) is used to identify the point in the Pareto frontier that is on the most crowded region of the frontier, and this point is removed. This procedure not only keeps the maximum number of non-dominated solutions to be retrieved fixed, but also helps to spread them over the frontier, what leads to a better covering of the objective design space.

4.3 Decision criteria for selecting candidate solutions on the Pareto frontier

Decision making criteria may be used to help the designer to choose which solutions on the Pareto frontier would be further investigated. The Smallest Loss Criterion could be adopted: when the goal is to optimize equally and

simultaneously the objectives, the solution for a problem with n conflicting objectives must be the one that results on the smallest loss for each of the objectives, since there is no solution capable to optimize the n objectives simultaneously individually (Rocco et al., 2013). Therefore, this solution could be obtained by the barycenter of a n-dimensional figure (the Pareto frontier) where each vertex would be the optimal solution of each objective (extreme solutions). However, the barycenter may be outside the Pareto frontier. In this case, considering only the set of solutions in the Pareto frontier, the closest solution to the barycenter is selected. A variation of this method would be to calculate the barycenter considering all solutions in the frontier instead of just the extreme solutions. Another possibility would be to consider the utopian solution, where the coordinates represent the optimal solution of each objective isolated. But the utopian solution is not practicable, thus the closest solution in the Pareto frontier could be selected (Venditti et al., 2010). These six criteria are used in the present work to select solutions on the Pareto frontier.

4.4 Results of simplified case study

The values used for the geometric dimensions, mass, heat dissipation and common set for each equipment is shown in Table 1.

Table 1 – Geometric, mass, power and common set data of the equipment.

Equipment	Mass (kg)	Heat dissipation (W)	Dimensions			Common set
			LX (m)	LY (m)	LZ (m)	
Battery 1	4.000	4.71	0.166	0.229	0.095	1
Battery 2	4.000	4.71	0.166	0.229	0.095	1
Battery 3	4.000	4.71	0.166	0.229	0.095	1
PCDU	18.800	44.43	0.450	0.265	0.225	1
Transponder 1	2.800	29.20	0.156	0.210	0.094	2
Transponder 2	2.800	29.20	0.156	0.210	0.094	3
Diplexer 1	0.750	1.30	0.156	0.210	0.250	2
Diplexer 2	0.750	1.30	0.156	0.210	0.250	3

The design variables s_1 and s_2 where encoded in strings of 7 bits each, what gives a spatial resolution for the movement of the equipment of approximately 0.010 m over the panel. Preliminary studies on the performance of M-GEO to this problem indicated that the best value for the τ parameter is 4. The value for re-initializations was set to 10 and the maximum number of non-dominated solutions to be stored set to 100. The Pareto frontier found for a run of M-GEO, initializing the equipment from a random position over the panel, with 504000 function evaluations as the algorithm stopping criterion, is presented in the "bubble" graph shown in Figure 8. The simulations were done in a PC with Pentium CPU running at 3 GHz and 2 GB of RAM memory.
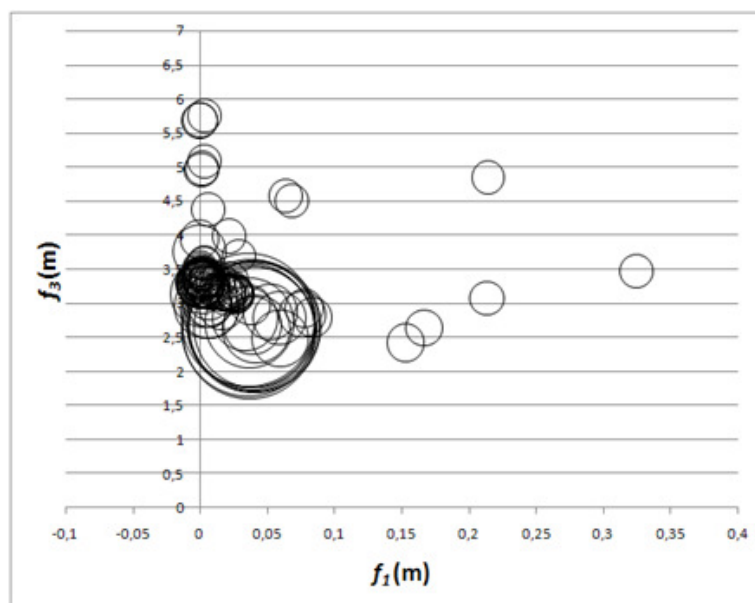

Figure 8 – Pareto frontier found in one execution of M-GEO. The relative value of f_2 is represented by the size of the bubbles.

Ninety seven non-dominated feasible solutions were retrieved at the end of the search. The large number of non-dominated solutions makes evident the convenience of using decision making techniques to help the design team select candidate solutions for further analysis. Applying the criteria presented in Sub-section 4.3, six non-dominated solutions were picked from the frontier. They are presented in Table 2 and Figure 9. In Figure 10 the layout configuration of each of these solutions is presented.

Table 2 – Objective function values for selected solutions on the Pareto frontier.

| Selection Criterion	Index of solution on the Pareto frontier	f_1 (m)	f_2 (W/m²)	f_3 (m)
Best value for f_1.	1	0.000	3871.257	3.764
Best value for f_2.	3	0.214	2385.255	4.843
Best value for f_3.	5	0.153	2726.385	2.421
Solution on the Pareto frontier closest to the barycenter obtained only considering the extreme solutions.	33	0.078	2780.563	2.925
Solution on the Pareto frontier closest to the barycenter obtained considering all non-dominated solutions.	23	0.007	3140.317	2.959
Solution on the Pareto frontier closest to the utopian solution.	81	0.001	2904.060	3.360
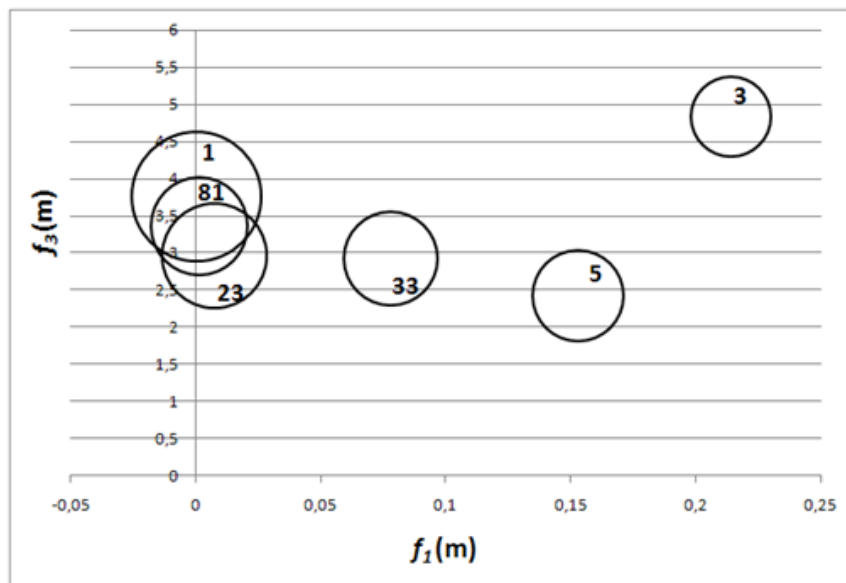
Figure 9 – Selected non-dominated solutions shown in Table 2 in the objective function space. The relative value of f_2 is represented by the size of the "bubbles".

From the results shown in Figures 8, 9, 10 and Table 2, it can be said that the prototype tool presented here worked very well, being capable of generating a great number of feasible non-dominated solutions, from a completely random initial layout configuration. Looking closely at the six selected layout configurations shown in Table 2 and Figures 9 and 10, it can be seen clearly how different layout trade-off possibilities can be generated. The extreme solutions (1, 3, 5) represent trade-off solutions privileging one of the objective functions, and they are very different layout designs. On the other hand, selecting non-dominated solutions using different implementations of the Smallest Loss Criterion approach (solutions 23, 33 and 81), results in less dissimilar designs but still providing plenty of information on alternative design solutions for the designer. Although applied here in a simple 2D example, it is noteworthy how the tool can provided potentially significant design gains. For example, a 21 % reduction on the value of f_3 is obtained if solution 23 is chosen instead of solution 1. This would mean a significant reduction on the cabling connecting the equipment, that usually is treated as a less important parameter in the conceptual design phase, in contrast with the requirements for center of mass (better addressed by solution 1), but that can become a big issue later on the spacecraft development cycle.
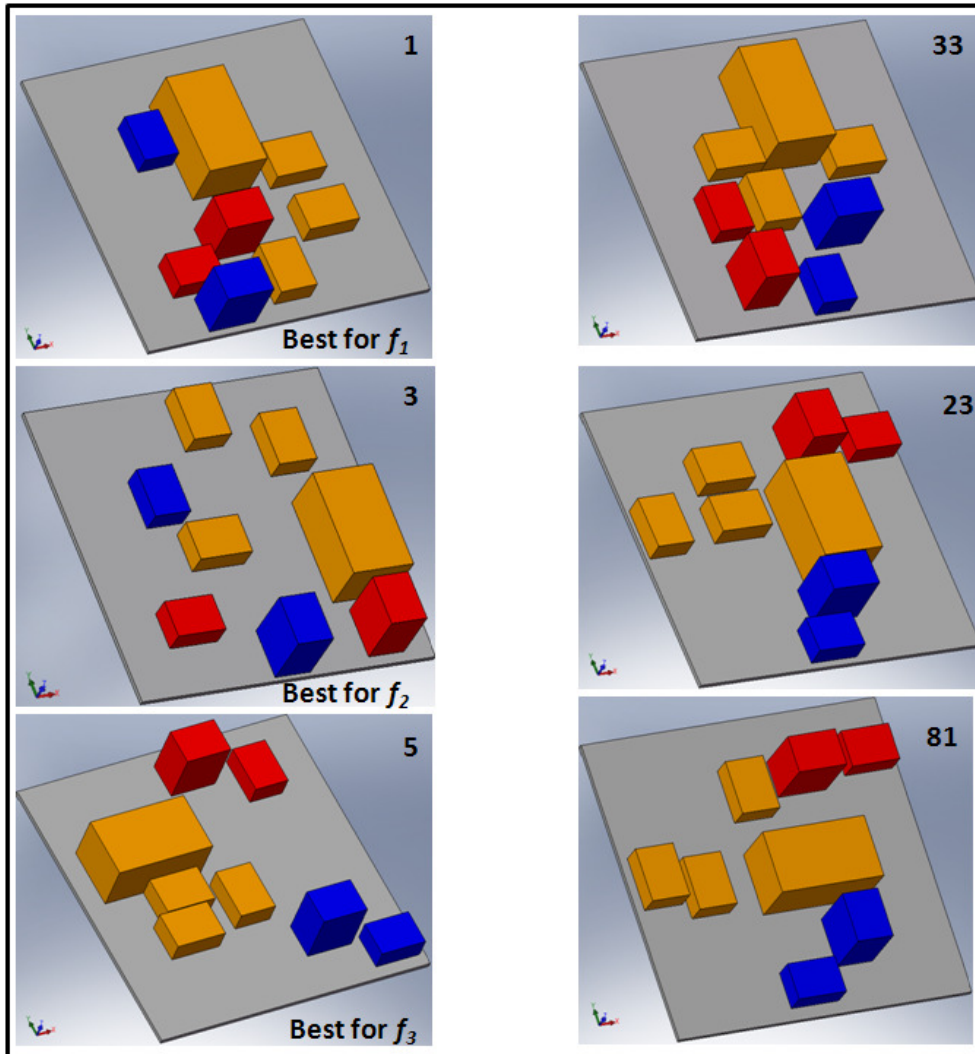
Figure 10 – Layout configurations for the selected solutions shown in Table 3.

5. FINAL REMARKS AND FUTURE WORK

In this paper a new tool for multidisciplinary design conception of spacecraft equipment layout was presented. The tool is aimed at both being a research instrument where different methodologies and optimization algorithms can be tested, as well as an operational tool to be used for engineering design. The tool uses Excel[®] as interface for input and output data, repository of the optimization algorithms and integrator of CAD or CAE software. In the prototype developed so far, Cuco´s (2011) multiobjective methodology coupled to M-GEO optimization algorithm are used to find a set of feasible non-dominated solutions, from an initial random layout configuration. Decision making criteria is used to select solutions from the Pareto frontier. SolidWorks[®] is fully coupled to the optimization loop using Excel macros, and is used to calculate design parameters as well as present candidate layout configurations.

From the exercising of the tool in a simplified example of application, many potential benefits of its utilization for the spacecraft layout design became evident, such as: i) input data for the panels and equipment is easily done; ii) visualization of either a given layout configuration or a selected solution from the Pareto frontier is easy and fast; iii) a great number of feasible non-dominated solutions can be generated, from a completing random initial configuration; iv) results data from the optimization is automatically retrieved to a dedicated Excel[®] worksheet from where it can be analyzed using different internal Excel[®] features.

Ongoing work is aimed at including new optimization algorithms to the tool, couple the decision making criteria into the optimization automate process, and apply the tool in a real spacecraft application.

6. ACKNOWLEDGEMNTS

The authors would like to acknowledge the significant contribution to this work made by engineer Valentino Lao in the integration of SolidWorks® to Excel®.

7. REFERENCES

NASA, 2007. *System Engineering Handbook*. NASA SP-2007-6105, Rev 1.

Baier, H. and Pühlhofer, T., 2003. "Approaches for further rationalization in mechanical architecture and structural design of satellites". In *Proceedings of 54th International Astronautical Congress*, Bremen, Germany, 2003.

Cuco, A.P.C. Development of a Multiobjective methodology for layout optimization of equipment in artificial satellites (in Portuguese), 2011. *Master degree dissertation*, Postgraduate Course in Space Technology and Engineering, National Institute for Space Research (INPE).

De Sousa, F.L., Muraoka, I. and Galski, R.L., 2007. "On the optimal positioning of electronic equipment in space platforms". In *Proceedings of the 19th International Congress of MechanicalEngineering*, Brasilia, Brasil.

De Sousa, F. L., 2002. Otimização extrema generalizada: um novo algoritmo estocástico para o projeto ótimo. 2002. 142 p. (INPE-9564-TDI/836). Tese (Doutorado em Computação Aplicada) - Instituto Nacional de Pesquisas Espaciais.

De Sousa, F.L.; Ramos, F.M.; P. Paglione, R. M. Girardi. New stochastic algorithm for design optimization. AIAA Journal, v. 41, n. 9, p. 1808-1818, Sept. 2003.

Deb, K.; Agrawal, S.; Pratap, A.; Meyarivan, T., 2000. "A Fast Elitist Nondominated Sorting Genetic Algorithm for multi-objective optimization: NSGA-II". In: *INTERNATIONAL CONFERENCE ON PARALLEL PROBLEM SOLVING FROM NATURE*, 6., Paris, France. Proceedings… Paris, France: Springer, p. 849–858.

Galski, R. L., 2006. *Desenvolvimento de versões aprimoradas híbridas, paralela e multiobjetivo do método da otimização extrema generalizada e sua aplicação no projeto de sistemas espaciais*. 279 p. (INPE-14795-TDI/1238). Tese (Doutorado em Computação Aplicada) - Instituto Nacional de Pesquisas Espaciais, São José dos Campos, 2006.

Hengeveld, D.W., Braun, J.E., Eckhard, A.G. and Williams, A.D., 2011. "Optimal placement of electronic components to mininize heat flux nonuniformities". *Journal of Spacecraft and Rockets*, Vol. 48, No. 4, pp. 556-563.

Jackson, B. and Norgard, J., 2002. "A stochastic optimization for determining spacecraft avionics box placement". IEEE *Aerospace Conference*, Vol. 5, pp. 2373-2382.

Ferebee Jr. M.J. and Powers, R.B., 1987. *Optimization of payload mass placement in a dual keel space station*. NASA Technical Memorandum 89051, March.

Ferebee Jr. M.J. and Allen C.L., 1991. "Optimization of payload placement on arbitrary spacecraft". *Journal of Spacecraft and Rockets*, Vol. 28, No. 5, pp. 612-614, Sep-Oct.

Pühlhofer, T., Langer, H., Baier, H. and Huber, M., 2004. "Multicriteria and discrete configuration and design optimization with applications for satellites". *In Proceedings of 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*; 30 Aug, 01 Sept, Albany, 2004.

Rocco, E.M.; Souza, M.L.O.; Prado, A.F.B.A., 2013. "Station Keeping of Costellations Using Multiobjective Strategies". *Mathematical Problems in Engineering*, Hindawi Publishing Corporation, Volume 2013, 15 pages. dx.doi.org/10.1155/2013/476451.

Sun, Z-G and Teng, H-F., 2003. "Optimal layout design of a satellite module". *Engineering Optimization*, Vol. 35, No. 5, pp. 513-529.

Teng, H-F, Sun, S-L, Liu, D-Q and Li, Y-Z., 2001. "Layout optimization for the objects located within a rotating vessel – a three-dimensional packing problem with behavioral constraints". *Computers and Operations Research*, Vol. 28, pp. 521-535.

Teng, H-F., Chen, Y., Zeng, W., Shi, Y-J. and Hu, Q-H., 2010. "A Dual-system variable grain cooperative coevolutionary algorithm: satellite-module layout design". *IEEE Transactions on Evolutionary Computation*. Vol. 14, No. 3, pp. 438-455.

Vanderplaats, G. 2007. *Multidiscipline Design Optimization*. Vanderplaats Research and Development Inc. ISBN 0-944956-04-1.

Venditti, F.C.F.; Rocco, E.M.; Prado, A.F.B.A.; Suhkanov,A. "Gravity-assisted maneuvers applied in the multi-objective optimization of interplanetary trajectories" *Acta Astronautica*, Elsevier Ltd., Volume 67, Issues 9–10, November–December 2010, Pages 1255–1271. dx.doi.org/10.1016/j.actaastro.2010.06.022

Zhang B., Teng H-F. and Shi Y-J., 2008. "Layout optimization of satellite module using soft computing techniques". Applied Soft Computing, Vol. 8, pp. 507-521.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.