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Design Validation using Axiomatic Design in Spacecraft Mechanism

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***Abstract*— Unfurlable antenna (UFA) mechanism is a foldable antenna reflector which is used for the purpose of receiving and transmitting signals in space. UFA contains number of mechanism subassemblies and components which should function properly for the success of the mission. The process of validating the UFA design ensures that all functional requirements are met in the design. In this paper an axiomatic design methodology is used for the design validation of UFA. Level of robustness of the design can be evaluated by assessing the design against the axioms stated in the axiomatic design methodology. A good design satisfies both axioms.**

I. INTRODUCTION

This paper deals with the design validation of a large UFA using axiomatic design methodology. Since the late 1960’s, the use of mesh reflectors has been favoured for their potential to fill large apertures with extremely lightweight hardware. In order to have a multimedia S-band satellite with a large aperture diameter and 1-2k bus an unfurlable antenna is used with frequencies that range from 2 to 4 GHZ. The meaning of the word unfurl-able is to opening or spread.

The axiomatic design (AD) method implements a process where engineers, designers and managers think functionally first, followed by the innovative creation of physical embodiment. AD provides means of decomposing higher-level functional requirements (FRs) and physical embodiments (called design parameters, DPs) until the creation of leaf-level FRs and DPs that can be implemented to construct the system according to the resulting design decision architecture [2].

The rest of the paper is organised as follows: Section 2 provides an introduction on axiomatic design, section 3 has the methodology followed to perform the design validation. Section 4 describes how axiom 1 can be used on a functional requirement. In section 5 concluding remarks are stated, followed by scope and reference at section 6 & 7.

II. AXIOMATIC DESIGN

Axiomatic design is a design theory that was created and popularized by Professor Suh of the Massachusetts Institute of Technology. Actually, it is a general design framework, rather than a design theory. As the word “framework” indicates, it can be applied to all design activities. It makes human designers more creative and reduces random search process, trial and error process, design selection process etc. Axiomatic design principles are initially used for synthesis of design. The principles which axiomatic design is based on are universal in nature and can be used for design validation. This can be done by checking whether the given design satisfies the axioms described in axiomatic design. It consists of two axioms. One is the independence axiom and the other is the information axiom [6].

Axiom1: The independence axiom: Maintain the independence of the functional requirements. It states that when there are two or more functional requirements, the design solution must be such that each one of the functional requirement can be satisfied without affecting the other one.

Axiom2:
The information axiom: Minimize the information content of the design. The information axiom provides a quantitative measure of the merits of a given design among the acceptable designs in terms of independence axiom.

According to Suh [11] a good design should satisfy the two axioms while a bad design does not. The word “axiom” originates from geometry. An axiom cannot be proved and becomes obsolete when a counter example is validated. So far, a counter example has not been found in axiomatic design. Instead, many useful design examples with axioms are validated. Design is the interplay between “what we want to achieve” and “how we achieve it.” Axiomatic design demands the clear formulation of design objectives through the establishment of functional requirement (FRs) and constraints (Cs). It provides criteria for validating a design and categorizes a design into good or a bad design, enabling designers to concentrate on promising ideas. It also formulates the decomposition process that enables a systematic flow from creation of concept to detailed design. Understanding the structure of the design is a prerequisite for creating a design that complies with the axioms. The structure allows designers to create and communicate designs more effectively and completely. The structure also allows the designer to understand the consequences of changes on the design. The structure is made up laterally of design domains and vertically of hierarchies of detail in the domains as shown in figure 1.

The design domains essentially are just different ways of describing the design [3]. The customer domain describes what the customer wants. The elements of the customer domain drive the elements of the functional domain, although one-to-one correspondence is not required. The elements of the functional domain are the functional requirements, or FRs. The FRs are formulated based on consideration of the customer needs, or CNs. The FRs describe what the design does, the functions. The FRs need to be formulated or developed so that they are the minimum list of functions that satisfy the CNs. Formulating the best FRs to satisfy the CNs is essential. No design can be better than its FRs. Functional domain should directly drive an element of the physical domain so that there is a one-to-one correspondence. The elements of the physical domain are the design parameters, or DPs. The DPs describe what the design looks like and include bills of materials and blue prints. The DPs are the physical attributes that fulfill the FRs. In order to comply with axiom one, the independence axiom, there must be only one DP corresponding to each FR. Ideally that DP should only influence the FR that it is intended to fulfill. The individual elements of the physical domain can drive individual elements of the process domain, although rarely are designs completed to this degree. The process domain describes how the elements of the physical domain will be created, acquired, or manufactured [11].

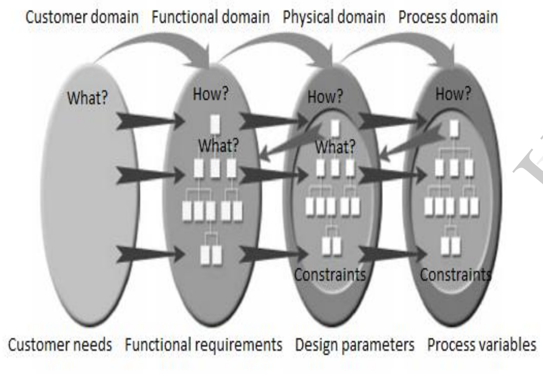

Figure 1 Domains [6]

III. METHODOLOGY

The methodology used to validate the UFA design is depicted in the figure 2.

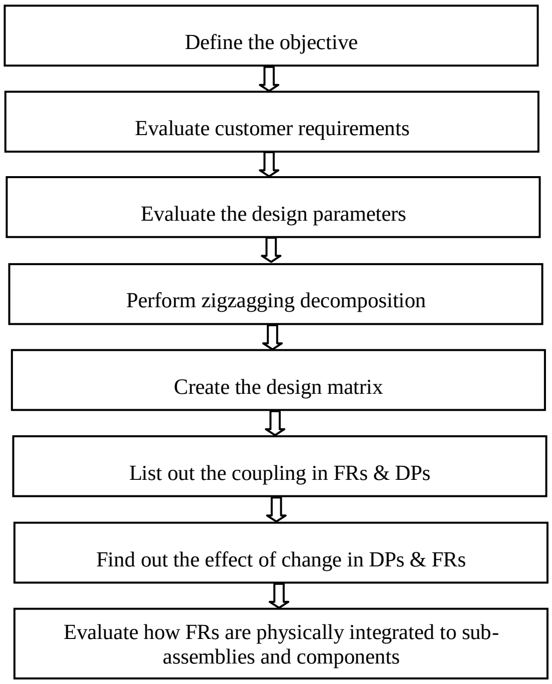

Figure 2 Methodology

The process of ensuring that the final product conforms to user is called design validation. The function of the AD tool starts from customer requirements and mapping it through FRs & DPs. This process helps in the creation of a design matrix for visualizing the interaction and coupling within the design. The result of the validation process shows whether the customer requirements are fulfilled by the design and how they are mapped from functional requirements to design parameters. It also helps to show how each FRs and DPs are physically integrated to sub-assemblies and components. The listed coupling helps to find out the effect of change in DPs and FRs. Till this step the first axiom in axiomatic design is followed. The second axiom is not followed because there is only one design to validate and it is an existing design, not a new design. The information axiom is useful when there is more than one design that satisfies the independence axiom equally and the best design is the one with the least information.

IV. DESIGN VALIDATION USING AD

The initial step is to obtain the requirements of the customer.
The requirements obtained from the customer are
1. Multimedia s- band communication.
2. Reduce the receiver size.
3. Satellite based communication
4. Should survive launch and space environment.

The customer domain as shown in figure 3 holds the information obtained from the customer. The obtained information is evaluated and transferred to a minimum set of independent requirements (FRs) that characterizes the design goal. The required functions are made possible by key physical variables known as design parameters. According to AD methodology, the elements of the primary functional requirements have been evaluated to produce its corresponding design parameters. The interactions between FRs and DPs are shown in figure 4.

At the present condition according to AD methodology, the three domains have been initialized as shown in figure 3. The figure shows how information from customer domain are transferred to functional domain and then into the physical domain by lateral decomposition. After the domains are defined appropriately, the next step in AD is to perform a functionally based decomposition of the obtained top level FRs. This type of decomposition is called zigzagging decomposition. Decomposition helps to convert the elements of the design into hierarchy until a complete detailed design is obtained. The design of the UFA is large therefore in order to decompose the functional requirements and design parameters, a mind mapping software called free mind was used. The use of the software helps to visualize the relation of each function to its design parameters more clearly.

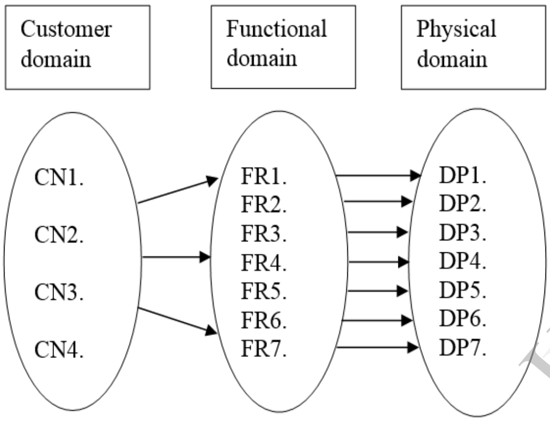

Figure 3 Mapping from domains

A. Decomposing FR1 to levels and sublevels.

The antenna which reflects the RF signal is held within the deployable truss. The molybdenum mesh which is stitched on the cable net forms the reflecting surface of the antenna. The antenna is designed for an aperture size of 6m, which is bigger than the available space in the heat shield. In order to accommodate the antenna into the rocket envelop, the antenna has to be folded and should have a dynamic clearance when placed inside the spacecraft envelop. The clearance provided helps to prevent any damage to the stowed deployable truss due to vibration.

The launch of the rocket in to the orbit causes vibration due to the g forces acting on it. The 3J and the 5J hinges to which the cable net is connected helps in folding the deployable truss. The above mentioned requirement is represented by FR1 and the corresponding design parameter is represented in DP1. Decomposition of the DP "high folding factor" in to its sublevels provides an insight into the design and will explain how the functional requirement is attained. After decomposition the results are made into a design matrix which represents the interactions between different levels of FR and DP. The matrix shown in figure 5 represents elements of the first level after decomposing FR1.

	DP1. High folding factor	DP2. West face of S/C bus	DP3. Unfurlable antenna	DP4. Antenna should meet a pointing accuracy of .02°	DP5. RMS< 2mm	DP6. Stiffnes of DT members & latching mechanism	DP7. Size of deployable truss
FR1.Dynamic clearance of DT with S/C envelop	X						
FR2. Accommodate the DT on S/C bus		X					
FR3.Deploy on orbit			X				
FR4. Pointing accuracy				X			
FR5.Surface accuracy					X		
FR6. Structural rigidity after deployment						X	
FR7. Deployed diameter.							X

Figure 4 Initial Matrix

	DP1.High folding factor	L1. Stowed and deployed diamensions of DT	SL1. Number of bays	SL2 Dimensio of bay assembly	SL3 Length of horizontal tube	SL4 length of vertical tube	SL1.4.1 Mini Clearence in between cable net(150mm)	SL4.1.1 Depth of cable net
FR1.Dynamic clearence with GSLV envelop	X							
L1. Folding factor		X						
SL1.Minimum stowed dia			X					
SL2. Deployed dia			X	X				
SL3. Stowed height			X		X			
SL4. Deployed height			X			X		
SL4.1 Fabrication & assembly feasibility of cable nets						X	X	X
SL4.2 Accommodate two cable net of 6m dia						X	X	X

Figure 5 Matrix

B. Coupling & physical integration

Coupling occurs in AD when a functional requirement cannot be easily controlled by changing its corresponding design parameters. The independence axiom helps in pointing out any coupling in the design. The size of the UFA antenna is 6m, which is stowed within the spacecraft envelop. The foldability of the antenna is critical to ensure the proper storage of the antenna. The design matrix of FR1 shown in figure 5 points out the number of coupling present. The four sub levels of folding factor are dependent on the parameter number of bays. Any change or modification to the above mentioned DP will affect all the four sub levels of FR folding factor.

Similarly all the high level functional requirements were decomposed and it was found out that another higher level FR shares the same design parameter "number of bays". Therefore a change in the design parameter "number of bays" will affect both the functional requirements. The selection of number of bays should be done in such a way that both functions are satisfied and coupling is removed.

Physical integration is the process of integrating functional requirements to components without affecting the independence of functional requirements with minimum number of components. Whenever two components can be physically integrated they should be as long as it can be done, without compromising function, controllability, introducing unintended consequences or reducing the chance of success, that is, without violating the axioms.

Consider the functional requirement "Dynamic clearance of DT with S/C envelop". The FR is supported by a design parameter "folding factor" as shown in figure 5. The matrix shows all parameters required for the functional requirement and when all these parameters are put together, they form the bay assembly. Therefore it shows that all the DPs of FR1 are physically integrated to the bay assembly.

V. CONCLUSION

AD design methodology has been applied to validate the design of an UFA. A small part of the work regarding UFA is presented by taking FR1. The rest of the work is completed by following the same procedure as FR1.The customer requirements are traced to physical integration through functional requirements and design parameters. The process ensured that each functional requirement is fulfilled by its corresponding design parameters and no requirement is left out unsatisfied. The results obtained from the analysis of UFA are used to check for incorporation of functional requirements into sub-assemblies and components. Checking for incorporations, were able to establish how physical integration is done and physical integration shows how components are put together to fulfill the customer needs.

Robustness of design and effect of change in design parameters of UFA is assessed using the first axiom in axiomatic design. The use of axiom one helps in listing all the coupling in the design. The information for listing the number of coupling present in the design is obtained from the design matrix. The obtained results will help in making design decisions in future modifications and scaling of design.

VI. SCOPE FOR FUTURE WORK

According to axiomatic design methodology one more domain can be defined, which is called the process domain. The process domain describes how the elements of the physical domain will be created, acquired, or manufactured. Tests & evaluation and quality assessment strategies can be devised for each and every FR-DP relationship. The above mentioned assurance strategy helps to reduce the time required to understand the design for future up gradation. Introduction of new design ideas for UFA can be compared with the old design by using the second axiom in axiomatic design. The second axiom will help to identify the strength and weakness of both the design when decomposed functionally. The second axiom can be used in the process domain for establishing the best process available to fulfill the design parameters.

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