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Prototyping in Design of a Lunar Wheel - Comparative Case Study of Industry, Government, and Academia

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ABSTRACT

This paper explores the application of prototyping in the design process through a case study analysis using structured interviews to determine what factors and practices result in successful prototyping. Five interviews are conducted focusing on engineers and collaborators at Michelin, Jet Propulsion Laboratory, and Clemson University. Interviewees are chosen to represent all institutions within the primary case and various levels of involvement within those institutes. These three groups are collaborating to develop a non-pneumatic tire for extra-terrestrial manned exploration systems, such as NASA's ATHLETE. The findings suggest that the role of prototyping in the different organizations is a direct result of the maturity of technology, the speed of development, and the type of commercialization of product typical of the organization.

MOTIVATION

Prototyping, the creation of fit, form, or functional design representations which enable designers to communicate, test, or validate design ideas, is almost universally employed as a primary and essential component of the design process [1,2,3]. Prototypes can significantly benefit a design process, but they are often used ineffectively which can lead to adverse consequences [1,3,4,5,6]. This occurs because the relationships between specific project needs and prototyping options available are not clearly understood [4,7]. This is in part due to the fact that the interaction with the rest of the design process itself is complex and it is not trivial to define and delineate those interactions [8,9,10,11]. This means that explicit and well defined relationships in generalized design applications are not available. Yet, it is possible to scrutinize the process and draw conclusions in a more specialized way via case studies [12,13].

Within design, the communication of ideas is imperative. Implementation of a new design requires testing and validation. Various components of the design process address these needs separately while others, such as prototyping, enable designers to communicate, test and validate their ideas in an efficient yet practical way. Physical or non-physical prototypes inform others about the overall appearance of a design while detailing how each of the components fit together and function. The majority of physical and non-physical prototypes can be tested in a simplified or virtual manner. The expected reaction of a device can be demonstrated by both CAD Models and physical testing. Both physical and non-physical testing can provide pertinent information about the design components. Though a non-physical prototype provides information about a design it may not accurately demonstrate the physical behavior of a design, its components, or complications of its assembly. The testing phase of prototyping produces knowledge about the overall design functionality which aids in determining if requirements can be met by a final version of the concept/design. Analytical assessments of the prototype testing can indicate which requirements are not being met effectively. This enables the designer to make necessary adjustments to the prototype instead of the final product.

Though prototypes provide many benefits, improper use of this design tool can be a costly mistake. Concentrating resources on an unnecessary prototype can result in a waste of time, money, and effort. Prototypes which fulfill no design needs, do not address design goals, and/or supply no useful information can harm the integrity of the project design. The inability to properly test a design will also result in a loss of resources.

WHAT IS PROTOTYPING

A prototype can be defined using classification. To make this useful, the definition should not restrict the ease of use to extract as much information as possible. Variety, complexity and fidelity can be used to describe a prototype. These characteristics distinguish the prototype from similar counterparts. Variety is the generic type of the prototype, either physical or non-physical, while complexity describes the relative complexity compared to the entire design system. For example, prototypes can represent an entire system, the smallest component within that system, and anything in between. Finally, fidelity is the level of realism the prototype represents, from representations that serve as an idea communication tool to realistic components which are built to replicate and test a final design. A taxonomic hierarchy is created using discrete interpretations, or descriptors, of these characteristics and it is demonstrated in Figure 1 [14]. Other classifications can be found in [15,16]

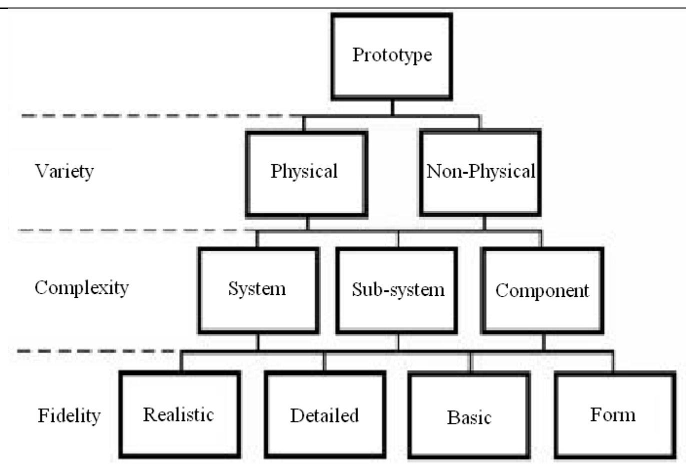

Figure 1. Hierarchical Morphological Prototyping Options

The classification hierarchy of Figure 1 represents a generic taxonomy with twenty-four degrees of freedom in a morphological configuration. Additionally, the morphological configuration inherently creates a distinction between the variety, complexity, and fidelity characteristics. This means that the taxonomy is also, by definition, completely orthogonal.

LUNAR TWEEL DEVELOPMENT

In 2006, Michelin and JPL confronted Clemson Faculty with the task of creating a functional extra-terrestrial wheel. This challenge was passed along to the students who were tasked with creating a non-pneumatic structure composed of three main components shown in Figure 2. The Tweel™ is defined as two side by side membranes encase a low modulus elastic material creating a shear beam. The shear beam is connected to the rigid hub by thin deformable spokes. This amalgamated tire/wheel is appropriately named a Tweel™.

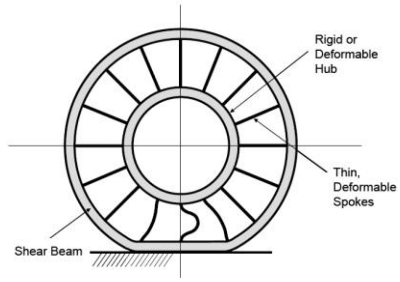

Figure 2. Main Components of the Tweel™

Both the Apollo mission wheels and those of the Mar's rover are insufficient to fulfill the needs of the current ATHLETE system. The TweelTM shown above only dictates the three components of the design. Each of the components can be varied to create the functionality desired by JPL. The capstone design class was tasked with developing a space capable Tweel™ (based on the Tweel design of Michelin) that is constructed from flight acceptable materials providing the desired functionality as demonstrated in the commercial earth-based Tweel system. According to Bart Thompson, an Innovation Engineer in MARC's Tire Development group, the goal of the project was to develop a TweelTM concept which used materials for the lunar environment such as textiles and metallic components while maintaining the TweelTM structure. This course resulted in sample physical prototypes (Figure 3).

Figure 3. Conceptual Design System Prototypes [17]

CASE STUDY ANALYSIS

A comprehensive case study analysis has been done on the design and development of the lunar Tweel™ from the perspective of the role that prototyping played in its development [14]. This paper presents results from the extensive interviewing process that was used for this analysis. Five individuals (one professor, one graduate student, one undergraduate student, one engineer from industry, and one engineer from NASA) were interviewed in a structured manner with a transcript review used to ensure correct collection of data. The interviews were triangulated internally through redundant questioning and multiple participants and externally through additional document analysis and an ethnographic study.

PROTOTYPING IN INDUSTRY

Prototyping in industry at Michelin North America revolves around two main focuses: product and concept development. Their high reliance on prototyping stems from the need to efficiently communicate their designs amongst their team as well as test potential designs. "In making Tweels, we first do some virtual prototyping and do some FEA. The FEA includes in-house code as well as ABAQUS commercial software. We try to do as much optimization as we can in terms of software before we build physical prototypes. We gain a lot in physical prototyping," says Bart Thompson an Innovation Engineer at Michelin. Physical Prototyping provides an opportunity to discover glitches within a design. This information allows for corrections to be made to the design before major production. In other instances in which Michelin already has a prototype protocol, most of the designing and prototyping will be done internally. These prototypes will be produced for testing and then manufactured once the issues are addressed.

PROTOTYPING IN GOVERNMENT LABS

Reduction of risk is a major motivation for prototyping within government laboratories such as the Jet Propulsion Laboratory of NASA. Research of a topic leads to proof-of-concept development in order to validate an initial design. Testing of the concept allows for advancement of the Technological Readiness Level (TRL) at JPL to integrate into the flight program. Many of the initial prototypes begin as a rough sketch and a search for off the shelf solutions for project problems. The sketches turn into an attempt to demonstrate that an idea is worth pursuing. This demonstration often involves a prototypes and evolution of that prototype into a final system. According to Jaret Matthews, a systems engineer in the Robotic Hardware Systems Group at JPL, prototypes are necessary at some point though "…I'm probably further on the side of the spectrum of build- it- and- try- it than a lot of my colleagues. From my perspective, you have to eventually build it and try it anyway, and I tend try to do that earlier in the process than most." Preliminary prototyping at JPL involves a design with as few dimensions as possible. This enables the designers to concentrate more on the system than on the details of each component. When developing an idea or design, working with industry is rare at JPL. Working with vendors on the flight projects is the extent to which other companies are involved in the prototyping and creation process. Often times, a JPL employee will oversee the manufacture of a parts to be used in a final system to insure the necessary quality control. Though design projects at JPL are normally done internally, JPL has a history of working with universities to accomplish a few projects. The universities provide a low cost option for research and prototype creation. Prototypes also provide more than just a demonstration of an idea. "The Clemson involvement allowed physical prototypes to be built and tested at an increased rate and get initial learning curve out of the way…That allowed us to obtain the money to develop more refined prototypes like the titanium helical Tweel and ultimately the composite Tweels," says Matthews. The prototyping done by the students led to acquiring the needed funding for more in-depth work on the final design prototypes.

PROTOTYPING IN ACADEMIA

Within academia, there are multiple forms of prototyping. For many undergraduates, prototyping links what they have learned in coursework to the actual application of those principals in design. These forms of prototyping may be only a component level or extend up to system level prototypes. "Also, what you have on paper isn't necessarily what you're capable of building… The challenge of building something and then having to validate that it works or has some level of performance introduces an interesting level of understanding for the students," comments Dr. Joshua Summers, an Associate Professor of Mechanical Engineering at Clemson University whose research focuses on Design Representation and Interpretation. Without the comparison of educational concepts to real world application, the educational process becomes more tedious and complex to comprehend for the average student.

As a graduate student, engineering design is somewhat restricted by time. Prototyping in these time constraints leaves many details to be sought out later. Beshoy Morkos, a Ph.D. student at Clemson University states, “We were more concerned developing different concepts and finding new domains you could reach into in order to create a wheel. It wasn’t so much to have a design set in stone, and say that this works and we’ve tested it in every possible manner.” Development of useful, creative design ideas takes precedence over the final overall functioning design in the upper levels of prototype design for graduate students.

Use of both virtual and physical prototypes is needed in academia. Comparison of the two allow for the design to be evaluated and to insure that both prototypes fit the design. As stated by Dr. Joshua Summers, “This exposed issues not evident in either the physical or virtual prototypes individually, so the two together were greater than the whole.” Academia provides industry and government labs with a cost effective option for design prototypes.

SUMMARY DISCUSSION

Prototyping plays a major role in all forms of design. The benefits gained from prototyping include: (1) Ease of communication of information about a design, (2) Proof-of-concept plausibility, (3) Potential cost saving in determining failures of the system before large expenditures, (4) Determination of achievement of design goals, and (5) Discovering new information about the design potential.

Industry uses prototyping to test final designs before implementing them to everyday applications. Government labs use prototyping to reduce risks among designs and to facilitate the communication of potential for varying design ideas. Component and system level prototypes are used in academia to understand the concepts learned and how to apply them in real world designs. The prototyping process provides information for many forms of engineers. Without prototyping, designs around the world would be more costly and time intensive leading to an overall more difficult world to engineer.

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