Design by Prototype:
Examples from the National Aeronautics and Space Administration

Gerald M. Mulenburg and Daniel P. Gundo,
National Aeronautics and Space Administration, Ames Research Center
MS 213-14 Moffett Field CA 94035

Abstract:
This paper describes and provides examples of a technique called *Design-by-Prototype* used in the development of research hardware at the National Aeronautics and Space Administration's (NASA) Ames Research Center. This is not a new idea. Artisans and great masters have used prototyping as a design technique for centuries. They created prototypes to try out their ideas before making the primary artifact they were planning. This abstract is itself a prototype for others to use in determining the value of the paper it describes. At the Ames Research Center *Design-by-Prototype* is used for developing unique, one-of-a-kind hardware for small, high-risk projects. The need for this new/old process is the proliferation of computer "design tools" that can result in both excessive time expended in design, and a lack of imbedded reality in the final product. Despite creating beautiful three-dimensional models and detailed computer drawings that can consume hundreds of engineering hours, the resulting designs can be extremely difficult to make, requiring many changes that add to the cost and schedule. Much design time can be saved and expensive rework eliminated using *Design-by-Prototype.*

Key Words: Prototype, prototyping, rapid-prototyping, design-by-prototype, prototype-as-design, product development, new product development, project management, project design, project cycle-time.

Introduction

Is there anything new about project management as it relates to new product development? Project management is changing, but in this author's view, not fast enough and, according to Frame (2002),"...traditional project management is broken." The rationale for this bold statement is that *times* have changed and project management must change to meet new situations. As noted by Whitney (1989), "In many large companies, design has become a bureaucratic tangle, a process confounded by fragmentation, overspecialization, power struggles, and delays." Modern project management over-focuses on what is often called the *iron-triangle* or the *triple-constraints*: meeting the cost, time, and technical requirements of a project. Frame (2002) says, "This traditional outlook is undergoing rapid adjustment." With global commerce supported by technology and communication made possible by the internet, time is now 7/24 and cost and technical challenges are addressed on a global basis using team members in different countries, with different cultures and time zones, languages, and methods. This paper addresses a technique called Design-by-Prototype still in its infancy in use at the National Aeronautics and Space Administration's Ames Research Center, but which shows significant success in simplifying and speeding up the development of research hardware with large cost savings. Design-by-Prototype is a means to use the old artisan's technique of prototyping as a modern design tool.

The Project Front-End

The project front-end plays a key role in project success or failure. The Project Management Institute's, A Guide to the Project Management Book of Knowledge (PMBOK, 1996, p29, Fig3-2), provides an excellent example of the project cycle, shown in Figure I, with the early initiating and planning processes overlapping and peaking long before controlling and executing processes become drivers.

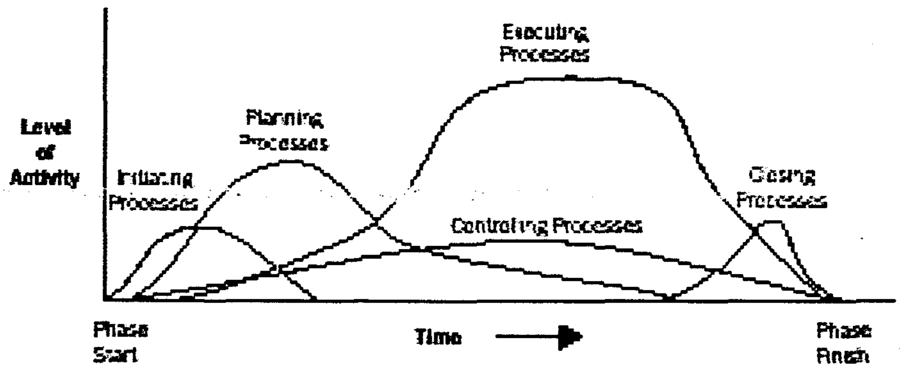


Figure 1. The PMBOK Project Cycle

More often than not, the technical requirements are unknown or *fuzzy* at best at the outset of a modern research and development project. Even those requirements that are known can change rapidly as development progresses. The importance of this *fuzzy-front-end* period of product development is well known and often described in the literature (Kim & Wilemon, 2002; Montoya-Weiss & Driscoll, 2000; Smith, et.al. 1999). During this earliest portion of the project only vague end results are known, and the pathway to achieve these results is still an open network (the really *fuzzy* part). The reality is that major improvements become visible too late in a regular development cycle to make the changes that need to be incorporated and, at that point, drive the cost up too high for the project to succeed as initially formed. This is often due to initial overconfidence that what is wanted or needed is clearly understood. This situation is further exacerbated by under-attention from management during early concept exploration. A major problem in this early part of the development cycle is caused by a lack of management attention when most needed, and provided when too late, as eloquently shown from Wheelwright and Clark (1992, p33) in Figure 2.

The National Aeronautics and Space Administration documented the impact of attention during the front-end of many projects, in terms of cost as shown by Hooks (1994) in Figure 3. The apparent causal relationship between cost overruns and expenditures made during the front-end of projects indicates that major cost savings can be obtained by investing from 5-15% of the project's resources in the early portion of the project. The corollary of course is that not spending enough up-front contributes to major cost overruns. With the problem as outlined, what is the solution? How can project management change to meet the demands of new product development? One solution is to go back to earlier ways of developing one-of-a-kind products.

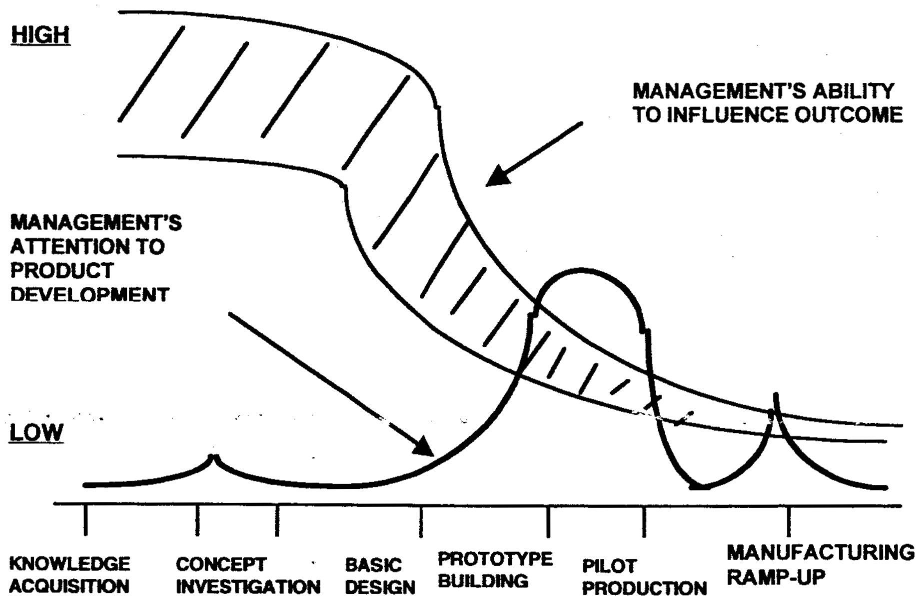


Figure 2. Management Attention During the Project Cycle

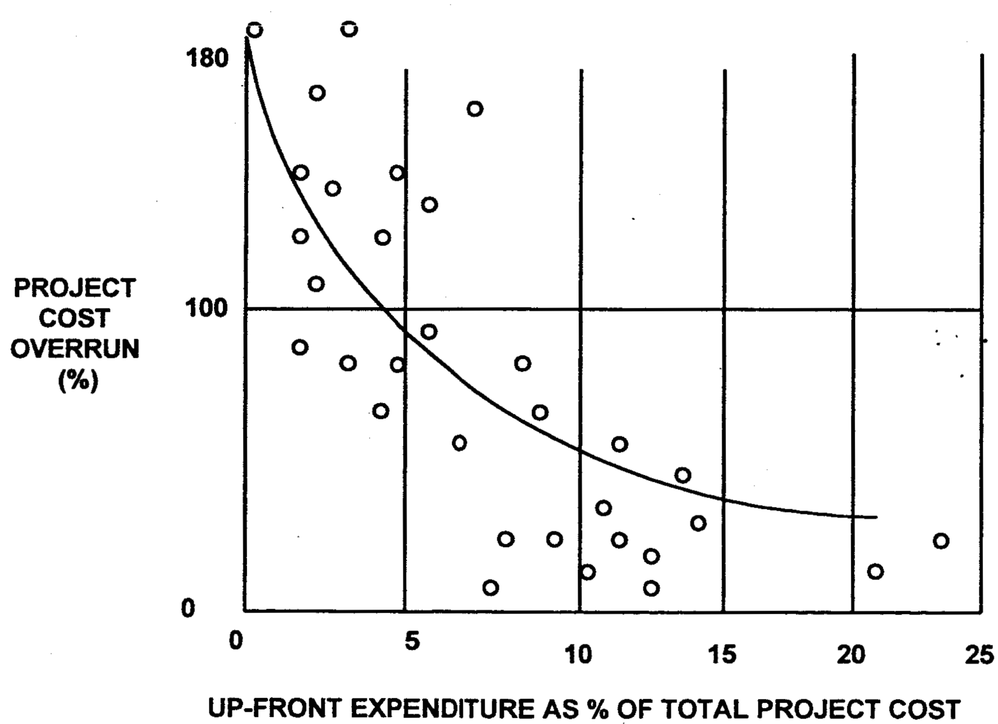


Figure 3. Impact of Project Front-end Expenditure

Design-by-Prototype

Prototyping is an ancient technique used by artisans and great masters for centuries. They created prototypes of their ideas before making the primary artifact they were planning. Design-by-Prototype is used in developing research hardware at the National Aeronautics and Space Administration's (NASA) Ames Research Center. Design-by-Prototype at Ames aids in creating unique, one-of-a-kind research hardware for small, high-risk projects by eliminating much of the formal engineering design process. The need for Design-by-Prototype is critical to many projects because, as Frame (2002) states, "...it is often impossible to prespecify requirements precisely. Even when possible, it may be undesirable to do so." Design-by-Prototype is a highly interactive, integrated process that allows multiple iterations of complex aspects of a desired R&D product to be quickly evaluated and adapted into a properly functioning whole. The whole, by default, meets the users' needs due to their active participation and agreement of the design as it evolves during development, through ever more improved prototypes.

The need for using this new/old process in a high-technology research organization such as NASA is largely based on the proliferation of highly functional and easy to use computer-aided-design (CAD) design tools to highly skilled, computer using engineers. A review of 72 development projects in the global computer industry (Eisenhardt and Tabrizi, 1995) supports using an, "... experiential strategy of iterations, testing, milestones, and powerful leaders...[however] the common perception that Computer Aided Design (CAD) greatly enhanced product development time, was often not the reality." Anecdotal experience also shows that the extensive use of computer design tools can result in both excessive time expended in design, and a lack of imbedded reality in the final product. A design may look *pretty* on the computer screen and from a color printer, but will it meet the users' needs and can it be efficiently made as designed? Unfortunately many design changes occur during the manufacture of these pretty designs that increase both schedule and cost to the project without a commensurate increase in product usability or quality. Beautiful three-dimensional computer models and detailed CAD/CAM drawings can result in difficult to manufacture hardware that requires expensive fabrication processes that add cost and/or increase schedule. Barkan & Insanti (1992) advocate prototyping as a core development process for a way out of this dilemma. In this author's viewpoint, this is a major contributing factor in the 70-80% of projects that never make it through complete development, or fail in the marketplace because of compromises made during development that reduce content to save cost and schedule.

One of the major contributors to problems during the traditional linear design process is an attempt to make every part as effective as possible. Trained in design, many engineers try to optimize every portion of a product in trying to create an optimized whole, which is exactly the opposite needed for both speed and parsimony in design. The result is sub-optimization adding time and cost to the design process without optimizing the final product. An old Zen proverb captures well the need to oppose this; *Perfection comes not when there is nothing more to add, but when there is nothing more to subtract.*

The desired product *must* of course meet the basic needs of the intended user, and those needs must be agreed to and defined as early and as clearly into the project as possible. Often however, because things can be optimized they are. As an example, when only one or a few units will be built, does a lengthy comparison of which fasteners to use need to optimize the highest quality with the lowest cost when only a minimum order quantity will be purchased anyway? If the functional requirements can be properly met by an adequate early choice, it is much more important to make the selection and move on to more complex aspects of the design that may need extra time to ensure they meet the desired needs. The following examples help to explain the use and value of Design-by-Prototype.

Undersea Thermal Vent Observer

A chance to participate with the Coast Guard's Polar Sea ice-breaker ship returning from Antarctica provided an opportunity that fit the prototype as design philosophy well. This was an experiment to examine concentrations of chemicals near hydrothermal vents in an undersea volcano in the Vailulu'u Seamount required an undersea camera. The camera was to document visually the areas near where the chemical instrumentation would be exploring possible life forms living in the toxic, high-temperature areas at the mouth of these vents. The project's funds had been exhausted and any solution had to not only cheap, but also fast. There would be only one chance to board the vessel two weeks later when it docked to refuel and take on supplies at Pago Pago in American Samoa. That meant the NASA person bringing the camera would have to depart in ten days in order to "catch the boat." The process of determining what could be put together began on Monday morning when the Hardware Development staff was asked for help in developing and fabricating the needed equipment. It was quickly determined that all that could be accomplished within the available time frame and funding would be a simple light source and camera to drag over the vent area. Identifying the equipment and how to package it became the first challenge. The solution was an inexpensive, small video camera and a motorcycle headlight with a 12-volt battery. Looking at available materials to contain the equipment that could survive the tremendous pressure at ocean depths, a quick analysis showed that placing the light source and camera together was not possible. The decision Tuesday packaged the two functions separately using available thick walled cylinders and some optic quality window material that would withstand the high pressures at depths up to 1000 meters. The camera and light would be activated, a pressure cap quickly attached and the entire unit lowered over the ship's side. The challenge became how to install the optic lenses and provide a simple cap to install quickly on deck that would allow the two cylinders to focus both the light and camera on the desired location. A technologist experienced in working with researchers on challenging problems such as this, and the research engineer solved the lens attachment problem first and work immediately began to modify the cylinders and the lenses while work continued to find how to attach the caps. By the time the cylinders and lenses were complete on Wednesday, the cap concept was defined and work began to make the two caps. By Friday morning all the components were complete and assembled for pressure testing, completed on Saturday. The engineer left the following Monday with everything in his luggage and returned two weeks later with great video of the volcano rim and crater.

The success of this project was possible through the close integration allowed by the design-by-prototype process. In real time, communicating through pencil sketches and oral discussion, the resulting prototype became the final product. Figure 4. shows the technologist and research engineer with the two returned cylinders after the voyage.

Figure 4. Successful Undersea Thermal Vent Experiment

Exercise Bed

The deterioration of bone and muscle tissue due to weightlessness during space flight is a serious problem that NASA has been addressing since early space missions began. One method for evaluating different prevention and recovery treatments for this problem is to expose normally healthy individuals to long periods of bed-rest that duplicates many of the space-weightlessness symptoms. The bed-rest participants remain in a prone position for up to 30 days without sitting up or standing. A horizontal shower is used for bathing during these studies.

To evaluate the usefulness of exercise in reducing or preventing bone and muscle deterioration during these studies, a method of exercising in the prone position was needed to compare with benefits achieved from exercising in a normal one-G environment.

Using design-by-prototype, an initial concept used existing resistance devices for the bed-rest participants to perform horizontal "squats" in the prone position using a footplate to push against. Fabrication of the exercise-bed began while waiting for the arrival of the resistance devices from another location. Upon their arrival, evaluation of mounting methods quickly showed limitations in the planned approach. A major change was needed to ensure that the bed would be able to accommodate normal bending positions of the body while performing the exercises. A practical solution was quickly developed following discussion with experts in human physiology. Development of the design continued to its final conclusion shown in Figure 5. In this example, the use of design-by-prototype was combined with traditional engineering and expert consultations to meet a critical need. The total time and cost involved was significantly less than if a traditional linear engineering and fabrication process was used from beginning to end.

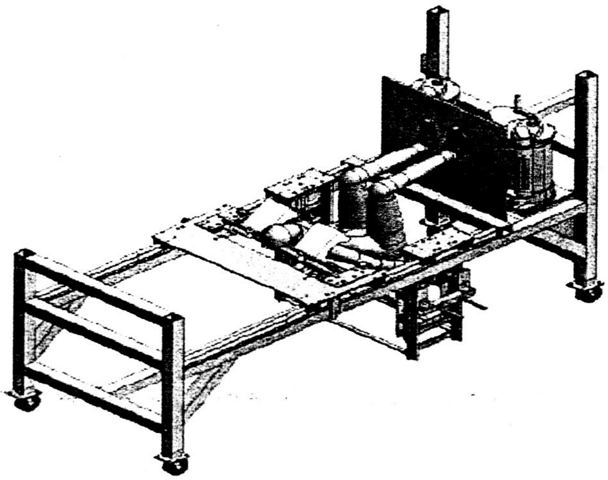
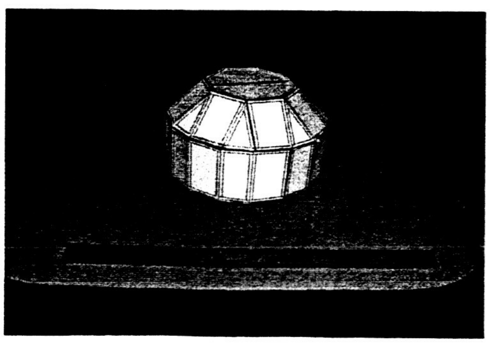


Figure 5. Exercise Bed Concept

Centrifuge Accommodation Module

A mock-up of the International Space Station Centrifuge Accommodation Module (CAM) was needed to train technical staff and astronauts in the use of experiments that will someday occur on the International Space Station. Working from photos and a verbal description of the need, a technologist spent some time thinking about the task while working on other projects. Using his experience from fabricating literally thousands of research devices, the technologist sketched out on paper what he believed would meet the need. Folding the paper sketch into a prototype paper model of his idea, shown in Figure 6., the customer quickly concurred with the technologist's concept and approved fabrication. Working from the paper model with only gross dimensions, the full-scale model was quickly completed and installed. When requested to also provide a full-scale mockup of an experiment glove box unit for the CAM mockup, the craftsman quickly repeated the earlier process. The results are shown in Figure 7.



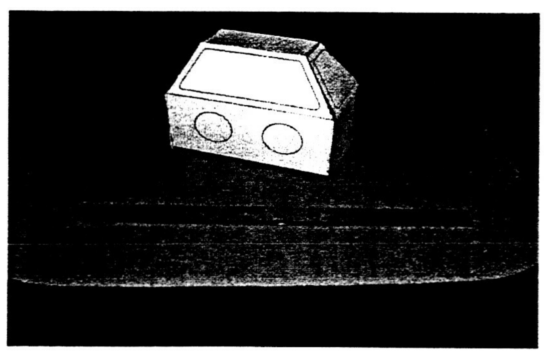


Figure 6. Centrifuge Accommodation Model Figure 7. Space Flight Glovebox Model

The training of the technologist in metal fabrication, and his extensive experience in developing research hardware, provided the resources for meeting the customer's needs. With a flexible schedule in this example, the primary factor of concern was cost. The zero cost of engineering, coupled with the ability to work on the project during lulls in other schedule-driven work, made Design-by-Prototype the preferred methodology. The completed Centrifuge Accommodation Module is shown in Figure 8.

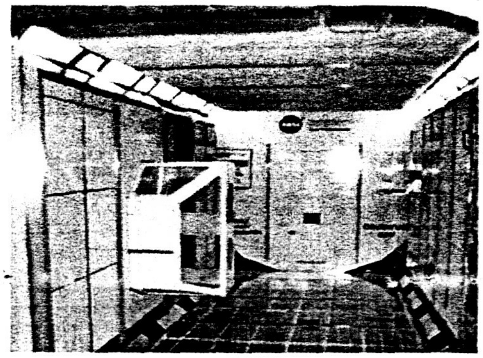


Figure 8. Space Station Centrifuge Accommodation Module & Glovebox

Summary & Conclusions

Design-by-Prototype is not a panacea for all problems that may lead to project cancellation, or for the failure of large numbers of other projects. For many large, complex projects of today it may be too simplistic. It may however, have a significant role in developing some of the subsystems or sub-subsystems of these projects. It has resulted in large cost and schedule savings, with significant improvements in a product's design and functionality, when used in the appropriate environment. Although this paper of necessity cannot cover all of the potential applications for Design-by-Prototype, it is hoped that the usefulness of this technique will be recognized, and will lead to improved results in developing hardware in research environments, and possibly even in the early phase of non-research product development.

References

Barkan, P. and Insanti, M. (1992). *Prototyping as a core development process.* Design for Manufacturing-Course Handout, Stanford University.

Frame, J.D. (2002). *The New Project Management.* Jossey-Bass, New York.

Hooks, I.F. (1994). Managing Requirements, in *Issues in NASA Program and Project Management*, NASA SP –6101 (08).

Kim, J. and Wilemon, D. (2002). Strategic issues in managing innovation's fuzzy front-end. *European Journal of Innovation Management, **5**, (1) 27-39.*

Montoya-Weiss, M.M., and O'Driscoll (2000). Applying performance support technology at the fuzzy front end. *Journal of Product Innovation Management, **17**, 143-61,*

PMI Standards Committee, (1996). *A Guide to the Project Management Body of Knowledge.* Project Management Institute. Upper Darby, PA.

Smith,G.R., Herbein,W.C., and Morris,R.C. (1999). Front-end innovation at AlliedSignal and Alcoa. *Research Technology Management, **43** (6) 15-24.*

Wheelwright, S.C. and Clark, K.B. (1992). *Revolutionizing Product Development.* The Free Press, New York.

Whitney, D.E. Manufacturing by design, in, *Managing Projects and Programs,* Harvard Business School Press, Boston MA.