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Creating your Own Tools: Prototyping Environments for Prototype Testing

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Abstract

Evaluating prototypes through prototype experiments is an essential part of most early stage, exploratory, product development processes. The rate at which prototypes are tested is often high and even incremental improvements in test outcomes, such as learnings and iteration speed, can be of great influence for the outcome of projects. Based on observations from a highly exploratory product development project and use existing classifications from literature to study how test environments can be prototyped in parallel with the main prototyping activities, and how fundamental trade-offs in test environment characteristics can be flexibly changed to fit each test in doing so. By getting a better understanding of how test environments can be used as tools, a higher momentum might be achieved in iterative prototyping.

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Keywords: Prototyping; Wayfaring; Prototype Testing; Experimentation

1. Introduction

Methodologies for development of new products are plentiful and highly diverse, but although the concrete practices through which we develop products varies between different fields and methods, few development processes nowadays are without prototyping of any form. Prototyping has become an essential element of the product development process [1]. As such, quantifying and recognizing success factors that lead to good use of prototyping is a popular theme of research.

Prototypes are often associated with physical representations of one or more functionalities that is to be investigated, but anything has the potential to be a prototype, as long as it serves some purpose in representing an artifact of the final product [2]. By extension, this means that for prototypes where functionalities are to be tested, a prototype is only as valuable as its ability to be tested.

While *Design of Experiments* (DOE) has grown to become a substantial field of well recognized research, prototype testing in new product development lacks similar clear frameworks for well-designed experiment setups. As a result, the way prototypes are tested to conclude their validity becomes yet another design decision that is left to the individual designers. With multiple uncertainties, the outcomes of a prototype test might not reflect the actual functionality of the artifact that is tested, and the learnings gathered wrong. A prototype experiment is governed by both the incomplete representation of the product, through the prototype, but also of its incomplete representation of the working environment through the test environment [3]. Generating accepted practices for prototype experiments might improve the quality of tests, but it might also ultimately limit the speed of prototyping activities by inducing more requirements. Unlike in DOE, design processes generally aim for satisfactory results rather than optimal results [4]. Being able to quickly test prototypes is important for fast learnings in the early stages of product development [5]. This is especially true in practices which have integrated design-

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build-test cycles, where testing and prototyping are often plentiful. In these cases, it is often accepted that a prototype experiment is seldom a perfect representation of the actual solution and problem, in favor of faster learnings. While technical knowledge and know-how among designers is often sufficient to come up with and create prototypes, this knowledge is often not utilized to also create good prototype experiments. Encouraging the use of technical know-how to also evaluate and improve testing practices in prototype experiments might increase the quality of such tests and might be favorable to stricter regulations. This could allow designers to use test environments as a tool for efficient prototyping in projects with a high rate of exploratory prototyping. To investigate this, an example of a self-made test environment developed in parallel with the main prototyping activities is presented and used to highlight some key insights into how prototypes and test environments effects each other throughout the prototyping process.

2. Testing and experiments in prototyping

The way prototype tests are performed is of critical importance to the learning outcomes of prototypes [2,3,6]. While not all prototypes are meant to test whether a physical and mechanical attribute will work in a final product, they all aim to clarify whether an artifact of the final product is up to its task. In order to show this, we device tests for our prototypes. Efficient use of testing can be a key contributor to success. A notable example of the importance of efficient tools for testing prototypes is the Wright brothers use of a self-developed wind tunnel to iteratively test wing profile which they often credited a lot of their success to. Later research shows that the wright brothers had fundamental misunderstandings in their wind tunnel tests, that would render their experiments of little quantitative value [7], yet they were able to use the tunnel for fast enough prototyping to generate a qualitative understanding of lift. This enabled them to engineer the first successful manned aircraft. Understanding how we test prototypes, and how we can make prototype testing adequately purpose-built, is clearly of great importance for success in product development.

2.1. Iterative development in wayfaring

Iterative prototyping through design-build-test cycles in product development is hardly new [4], and multiple methodologies exist that package the concept with slight variations. Among them is the wayfaring method [8] which in a product development context relies on rapid iterations in order to learn from prototypes [9]. The method addresses the ambiguity of the process in which we find and perform the design-build-test cycles, by introducing the concept of probing [10]. It utilizies the high ambiguity in the fuzzy front end of a project by encouraging multiple probing prototypes to decide on the direction of the project by uncovering unknown-unknowns. While the learning outcomes can be great by frontloading the prototyping [11], it also creates a need for high flexibility in performing prototype experiments as consecutive prototypes will not necessarily require the same type of testing in divergent phases. Prototyping activities can be exploratory, with high variations as compared to other product development methods. The high variations pose a challenge that needs to be addressed not only in the making of prototype artifacts but also in making good decisions for testing the prototypes.

2.2. Prototype test environments

With few restrictions as to what that can constitute a prototype, it follows that prototype experiments and testing is also a wide term. As most of the learnings of design-build-test cycles are in the testing phase an influential part of any prototype test is the environment in which the tests are performed. The prototype itself is only one of the input classes into such a test. The other classes which are of importance are: human interaction, product system into which the prototype will fit, the physical environment, and the prototype itself [3]. The interaction between and within the classes in any test environment is high, and may contribute to unexpected results in increasingly complex test environments with previously proven solutions in simpler test environments [12]. To replicate these classes in prototype testing one would typically either make a physical representation of the model, an analytical estimation such as computer models or finite element analysis, or a reflective estimation based on common sense, previous experience, or rules of thumb. In Thomke's work [12] he describes how managing to switch between these methods efficiently reduces development time and cost. By practicing high flexibility and a broad skillset one can choose the best fitting method for the given problem in the development process. With increasing computer power, many problems can be solved through analysis that were previously impossible, but still physical models are typically used to confirm analytical results. This is especially true in hydro- and aerodynamics. With analysis tools, it is possible to inflict high control of the test parameters and environment, reducing potential production errors and unforeseen problems. But as part of the prototyping process is often to uncover these problems, physical prototyping and test environments should still be an important tool for designers and will be the further focus of this paper.

3. Prototyping physical environment representations

In the wayfaring method we tend to favor prototypes with physical dimensions when feasible. While some problems most certainly are best solved through analytical modeling or reflective estimation to reduce extensive construction work, adding physical representation to your prototypes can greatly aid understanding the problem in the real circumstances and aid in uncovering unknown-unknowns. As part of an academic master's thesis, a problem prompt was given that asked for using biomimicry to discover potential for improving propulsion methods in marine technology. With little prior experience in marine propulsion and biology, a wide divergent and exploratory approach using the wayfaring method was employed to quickly explore the problem and solution space. To enable multiple design-build-test probes to be tested, an environment in which water could be moved around prototypes had to be used. We postulated that using in-house resources and equipment to make the test environment along with the prototype artifacts might lead to higher flexibility and iteration speed in probing, than by using out of house facilities. We have collected some observations of the effects of this parallel prototyping work, to form an explanatory case study. Where the goal is to generate ideas for further studies and not conclude a study [13].

3.1. Water Tunnel Construction

Water tunnels are used in fluid dynamics to simplify tests of physical prototype behaviours when moving through fluids. Care is usually taken when constructing such tunnels to enable low turbulence and Reynolds numbers, either through inducing little turbulence in the movement of the fluid, settling the flows in the structure or conditioning the flow before entering the testing area of the tunnel [14]. In this project there was little initial knowledge as to the degree of control needed over the flow for adequate results in the prototype testing, so a simple approach to the water tunnel was chosen. The tunnel had to be small enough to fit in the lab, and simple enough to be made and altered in the lab. It was made by laser cutting acrylic sheets to a rectangular shape, long enough that the flow would be able to completely develop from one end to the other [15]. Some room was made on either end to allow the flows to settle before and after pumping, while the main section of the tunnel was enclosed by honeycomb flow straighteners made from drinking straws to condition the turbulent flows from the settling reservoirs [16]. Focusing on conditioning rather than more advanced tank structure and water movement, allowed a smaller footprint of the tank, where the returning water could be run through flexible tubes outside of the tank setup. The pump could be easily switched to accommodate different flow speeds, and the tank structure could be made using fast methods such as laser cutting.

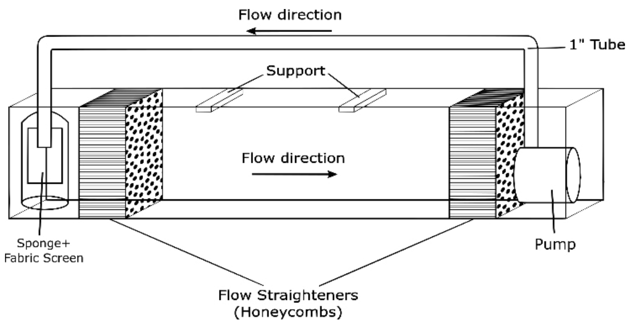

Figure 1: Sketch of water tunnel construction.

4. Iterative development of prototypes and test environment

The main structure of the water tunnel was constructed, and able to run simple prototype tests, within a weekly sprint. The initial simple construction matched the low resolution of the initial exploratory prototypes and small alterations could be made to accommodate the prototype tests, rather than needing to alter the prototypes to fit the test environment.

4.1. Meeting changing requirements

Throughout the process of using the testing environment the requirements of the water tunnel continuously changed. While in initial phases, high flexibility and low iteration time was important; in later stages more explicit presentation of results and a closer approximation of environment characteristics became increasingly important. To facilitate high flexibility in the beginning the setup was kept simple and alterations non-permanent and rough. Metal pipes and new pumps were introduced for changes in flow, and simple static fixtures used to hold prototypes stationary in the water. As an example, in an attempt to achieve mechanical Kármán gaiting behaviors [17] in rubber silicone fish, metal tubes were introduced with increasing size in front of a rubber fish prototype held stationary by metal wire in the water tunnel. This was done until an alternating vortex street was achieved and movement of the rubber fish observed. Different prototypes for achieving passive Kármán gait could then be tested to better understand how one could benefit from it in a final product, and knowledge into how to generate controlled alternating vortex flows in the test environment was gained.

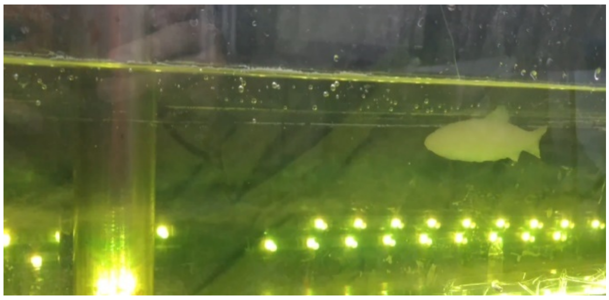

Figure 2: Rubber silicone fish suspended behind metal tube to replicate Kármán like swimming motions.

In the later development phases, more refined alterations were made to meet the testing needs of the setup. Dampening vibrations, adjustable speed control, and calculated obstacles were introduced to achieve the right conditions for prototype testing when the results of a test revealed that the existing environment was not able to achieve satisfactory conditions for the prototype. Among these later prototypes was a prototype for a self-developed flexible sensor skin. The skin, Figure 3, aimed to detect small pressure changes in the water to measure the flow along hydrofoils. By staying flexible, the hydrofoil in turn could be able to adapt to the flow conditions. As the sensor prototype was highly susceptible to noise, alterations had to be made to reduce noise in the prototype tests. Some of the concepts that were prototyped and used to achieve this were; testing during weekends and evenings when the lab saw less activity, dampen tank and prototype holding racks, and reduce flow speeds. Furthermore, a half-cylinder was made with a known shedding frequency to clearly link frequencies in the sensor data with those of vortices along the foil. As can be seen in Figure 4.

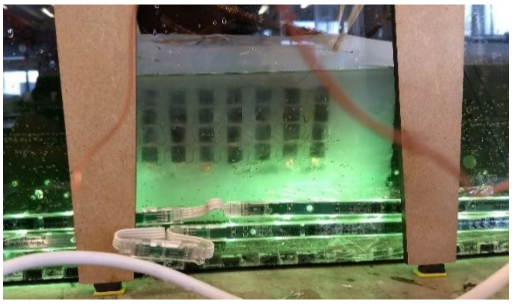

Figure 3: Dampened sensor skin suspended in water tunnel.

5. Observations

The two examples of alterations done to the tank represent prototype-stages of very different fidelity. Yet both prototype artifacts were able to be tested in the test environment through prototyping and implementing necessary changes to the environment. The time to make the alterations was relatively short as the designer had good insights into the workings of the environment, usually within an hour, and the costs were low as simple material resources were used.

5.1. Bias towards action

In design thinking, bias toward action is one of the core principles and governing mindsets, meant to inspire new thinking and encourage productivity. While it is often used to justify prototyping activities, a similar mindset might have enabled the fast results in the making of the water tunnel example. With a humble starting point, it enabled the designer to learn the important aspects of the test environment and make necessary alterations and improvements for future tests, and not be held back by over engineering a perfect solution to a problem he had little prior knowledge of. Rather than calculating the needed geometry and flow speeds to achieve the wanted Reynolds numbers for certain flow conditions to occur, a flow visualization method was made by running electrolysis along a thin aluminum wire in the water tunnel to create a sheet of small hydrogen bubbles. The visualized flow could then be altered until the wanted flow conditions were observed in the tank. This made it possible to observe and fix unknown problems such as imperfections in the honeycomb structure that through a pure planning approach might have gone unnoticed.

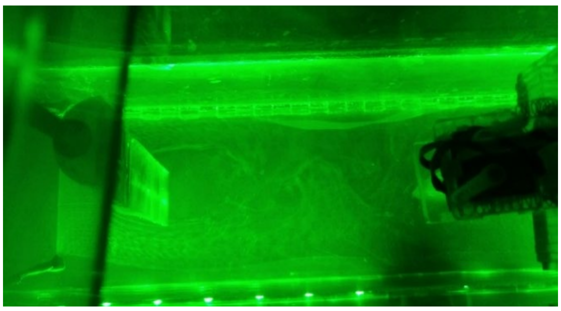

Figure 4: Kármán vortex street visualized with hydrogen bubbles behind half cylinder.

5.2. Flexibility

By using a test environment made by the prototype designer, the designer can flexibly change the environment to fit the needs of the prototype experiments. The designer can accommodate a wide range of prototypes by either making alterations to the prototype, the environment, or both as he might more fully grasps the needs and limitations of his own creations, than when using externally sourced test equipment. To the limit of the technical know-how of the designer, it is possible to alter or redesign the test environments to simulate different conditions and scenarios as the designer sees fit.

5.3. Using existing infrastructure

As opposed to creating purpose-built test environments for prototype experiments, perhaps the most common way in which we test prototypes is using existing testing facilities. We use already developed and calibrated wind tunnels, material testers as well as real world interactions. Using well established facilities is often preferred as it much more resembles DOE approaches and can offer more dependable accuracy, while also reducing the designer's bias where they are not creating both the solution and the method to test the solution. The penalties however can become high, as the use "out of house" testing facilities can increase both iteration time and cost due to relocation and rental fees. Additionally, facilities typically need to be booked beforehand in set time slots; if timeslots are even available. The flexibility of the test setup is also often predefined, and the prototypes needs to fit the test setup and not the other way around. You might also be dependent on an operator or machinist, adding to iteration cost and loss of flexibility. As prototype tests become more specific, sourcing facilities that meet the requirements of the prototype test might also be more difficult. This is especially true in extreme environments where conditions can be far from those considered normal and creating environment proxies necessary if tests are to be performed outside of the final working environment of the product [18].

6. Trade-offs in prototype testing

In existing literature, there is a high focus on the outcomes of prototyping, such as reducing cost, increasing product quality, and shortening development time [19], as well as the potential success factors. Although new product development activities that produce only incrementally improved products might be governed by lower uncertainties, prototyping is usually a highly unpredictable exercise, filled with ambiguity and unknown-unknowns [11]. We cannot know all the outcome of our prototyping activities beforehand; or we wouldn't need to prototype. Every product development process is different and requires an individual approach. Likewise, quantifying why and if parts of the process is successful can be hard to do objectively. Understanding how to balance the governing factors that make up a prototype experiment might increase the likelihood of desirable results from the protype testing. And might also be a good measure for comparing prototype test environments. In an attempt to classify fundamental tradeoffs in prototyping experiments Tronvoll et al. propose six performance measurables for test environments of prototypes in a similar case study [6]:

1. **Iteration cost:** The cost of performing a test, both in resources and labor.
2. **Iteration time:** The time between each timeslot that new iterations of prototypes can be tested. Contributors to iteration time might typically be; time to generate a prototype to fit the test environment, time to set up the test, and booking- and waiting lists.
3. **Approximation level:** How closely is the test able to represent the real challenges for its application.
4. **User level:** Typically related to the level of complexity of the setup. Can you operate it yourself, or do you need a dedicated operator for the testing?
5. **Results presentation explicit/implicit:** How well does the test show your result. Can you gather and plot data from the test, or do you need to implicitly judge the test results?
6. **Experiment flexibility:** How well is the experiment environment able to accommodate changes in prototype design and test scenarios. Is the experiment setup able to change and adapt to accommodate multiple types of prototypes, or does the setup make multiple restraints on the prototype design? Does the prototype only represent a very specific case or can you test multiple scenarios in the lifecycle of the product?

We recognize that while most prototype test environments can be classified by their ability to meet these classes, the goal is not necessarily to maximize all of them but finding a balance that is right for the given prototype experiment. While the emphasis has been that for self-made test environments the flexibility is high, it can also be recognized that such experiment environments would score high also in other classes such as low iteration time and cost and low, personal, user level. Approximation level might be limited by the designer's abilities, and result presentation can be changed to fit the need. In addition to these classes one could argue that there is an additional class layer which is in the balancing of the classes. Where as by using existing infrastructures to perform prototype tests you would choose a test environment that best fit the characteristics that you want, you are continuously able to alter which classes to emphasize when creating the environments alongside the prototyping process, thus exercising additional flexibility.

7. Concluding remarks

In this paper we have described how prototype testing is a crucial part of the prototyping process, and the test environment an influential part of the testing. Through observations from a project in the early stages of product development we have observed that a test environment made in parallel with prototyping showed a high degree of flexibility and low iteration times and cost for prototype tests.

7.1. Discussion

Using a self-made test environment fit well for the exploratory development process of this project, as it enabled flexibility to accommodate the high probing rate of the project. The flexibility was enabled through the use of own resources and equipment, so that high independence could be exercise. It does, however, not fully explain how this freedom was used to create meaningful changes to enable the prototype probing. This might have been enabled by using the designers existing technical knowledge in a meaningful way. In line with this would also be the bias towards action explanation, where the designers existing preset going into the prototyping process also transferred momentum into the development of the test environment. Similarly, as the designer digs deeper into the knowledge of the prototyped problem, some of this knowledge will naturally also cover expectations of the environment in which the final product will reside. Through this and vice-versa, spending additional time and resources on designing test environments can ultimately generate useful information for the project from a different perspective.

We have observed similar trends in other projects in our lab environment, where creating tools for testing prototypes was necessary either because good and accessible proxies were not practically available due to the extremity of the environments [18] or commercially accessible and size efficient [20] due to their industrial nature. The heuristics of prototyping test environments can be an efficient way to deal with the high uncertainties in early-stage product development projects [18], while using self-made tools for testing, even if simple, can reduce cost and iteration time in exploratory prototyping projects [20] for faster learnings.

7.2. Further work

One of the bigger drawbacks from prototype testing is the lack of impartial and dependable data as much is left to the individual designer. This bias is especially true when also the environment is made by the designer and the approximation level is hard to quantify without in dept evaluation and test of the environment itself. Much like the Wright brothers wind tunnel, prototyped test environments might be limited to fast qualitative estimates of the performance of prototypes. In convergent prototype testing this is often what we are after. Even with extensive testing in prototype test environments, ultimately tests need to be performed in real environments to uncover any discrepancies between them.

We have here merely presented some observations based on our experience in working with prototype test environments. More in-depth experiments and controlled case studies might shed further light on the influence of using prototyping of test environments as a tool in design-build-test cycles and could be of interest for further research.

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