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HEURISTICS-BASED PROTOTYPING STRATEGY FORMATION: DEVELOPMENT AND TESTING OF A NEW PROTOTYPING PLANNING TOOL

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ABSTRACT
This work seeks to introduce and evaluate effects of a novel method for designing prototyping strategies. This newly developed heuristics-based tool guides designers in planning a prototyping strategy based on answers to Likert-scale questions that embody empirically validated heuristics. We created this tool to augment prior work in the development of prototyping planning methods. The new tool guides designers through six critical prototype strategy choices: *(1) How many concepts should be prototyped? (2) How many iterations of a concept should be built? (3) Should the prototype be virtual or physical? (4) Should subsystems be isolated? (5) Should the prototype be scaled? (6) Should the design requirements be temporarily relaxed?*

We assessed the new planning tool in two environments: (1) a controlled experiment in which volunteers completed a prototyping design challenge, and (2) a capstone design class with a diverse range of open-ended sponsored design projects. In both cases, students received training for the method and then employed it in their own efforts.

In our study the new tool caused student teams to employ significantly more efficient and effective prototyping strategies, such as prototyping early and often. The results indicate a higher functional performance of prototypes from groups using the new planning tool compared to control groups. This paper describes the new prototyping strategy planning tool, details both sets of experiments, and discusses results.

1. BACKGROUND
Prototyping is a promising frontier for design methodology research advances. Research shows that prototyping decisions are often based on practical knowledge and management approaches rather than experimentally tested methods [1,2,3,4,5,6,7,8]. Simultaneously it has been shown that perhaps the greatest portion of sunken costs in new product development occurs during the prototyping process [9]. Therefore, a methodical tool to help teams direct their prototyping efforts could be a great asset to mitigating improper use of time, money, and other resources.

1.1 HEURISTICS FOR PROTOTYPING STRATEGIES
A number of projects have explored heuristic observations of better practices in prototyping. Viswanathan, *et al*. conducted an in-depth tracking study of graduate design students to determine beneficial practices of prototyping [10]. Their experiment involved data collection over three semesters of a graduate design course. These results include foundational open-ended heuristics such as “use standardized parts” and “support building with analytical calculations.” An in-depth DoD study makes the following observations on best practices over forty years of prototyping: [11]: 1. Make sure the (final) prototype meets the minimum design requirements; 2. The goal of a prototype is to prove that the final product is viable in the real world; 3. Prototypes are intended to be focused on determining unknown quantities; therefore, avoid adding non-critical features; 4. During prototyping there should be no commitment to production; 5. Once the design process is

underway, do not add design requirements or performance expectations.

Another set of research efforts explored modeling techniques to hypothesize the number of prototypes to increase profit and decrease risk. Dahan and Mendelson find that sequential designs succeed in cost-constrained environments while parallel designs succeed in time-constrained environments [12]. Thomke [13] and Thomke and Bell [14] add that significant savings can be achieved through multiple low fidelity prototypes. Dahan's [12] equations leverage basic assumptions for the uncertainty of success of a prototyping effort and the marginal increase in profit that results from that effort.

An additional set of empirical studies evaluates the effects of controlling these strategy variables one at a time and measuring design outcomes. Haggman, *et al*. [15] tracked the activities of mid-career professional graduate students during the preliminary design phase, examining various correlations between 'throwaway' rapid prototyping and performance metrics. They found that building prototypes early in the design process correlated positively with success, while the total amount of time spent did not. Similarly, the lower performing teams prototyped later in the process. Kershaw, *et al*. [16] found that teams which developed prototypes earlier identified and positively reacted to flaws in their designs, and developed countermeasures or improvements compared to teams that prototyped later in the process or did not develop multiple prototypes. Yang 2004, furthermore, shows that time spent testing is positively correlated with outcome and conversely, time spent fabricating is negatively correlated with outcome [17]. Jang confirms in another, independent empirical study that more successful teams prototype earlier and more often throughout the entire process [18]. Dow [19] conducted a controlled study requiring half the participants to iterate and requiring the other half to focus all available time on one prototype without iteration. This study empirically confirms that, in the circumstances tested, pursuing at least three additional iterations beyond development of a single prototype significantly improved final design performance.

Most of the studies reviewed above are of one of two types, either observation of designers' practice without external control or evaluation of strictly enforced single strategy variable studies. This first type is critical to identify best practices. The second type is critical to determine if the practices and their results are repeatable. We developed an experimental approach to explore (1) if designers will actually apply these heuristics in their own practice when provided with a method at the outset of prototyping; and (2) if these teams will in fact outperform control groups that do not employ the method.

1.2 PRIOR HEURISTICS-BASED PROTOTYPING STRATEGY PLANNING

A previously demonstrated prototyping strategy planning method [20] embodied heuristics such as those described above into equations to assist a designer answer questions such as "*How many concepts should be prototyped? How many iterations of a concept should be built? Should the prototype be scaled?*" This method involved using context variables with a half-dozen equations to calculate quantitative values used to guide decisions.

This previously reported prototyping strategy methodology [20] used the independent context variables of a design problem in order to determine values for dependent prototyping strategy variables (e.g. number of prototypes to build, prototype scaling, and subsystem isolation). These dependent strategy variables were amalgamated from heuristics for prototyping best practices outlined by Moe [21], Christie [22], and Viswanathan [10]. These best practices are summarized as follows:

- Successful teams often initially prototype three or more different concepts.
- Prototype early and often. Consider low-resolution prototypes to explore many concepts quickly and economically.
- Keep prototypes as simple as possible while yielding the needed information, thereby saving time and money.
- Allocate adequate time to the engineering process for building and testing.
- Prototyping and engineering analysis need to work together for maximum effectiveness.

This prototyping strategy formation methodology provides a framework that addresses key prototyping decisions designers face by employing a hierarchical structure of generalized decision variables extracted from the heuristics referenced above.

The experimental results published by Camburn, *et al*. [20] indicate using this prototyping strategy formation method is positively correlated with early-stage design success. Accordingly, employing this method can potentially improve design performance while increasing the likelihood of staying within budget and time constraints. Camburn's research on an engineering approach to prototyping strategy implementation and the need for more comprehensive prototyping planning form the foundation for the advances reported here. However, this method proved not as straight-forward, time-efficient, and intuitive as desired. Efforts to significantly improve upon this published method led to the significantly simplified and streamlined approach presented here.

2. NEW HEURISTICS-BASED PROTOTYPING STRATEGY PLANNING METHOD

The process of transforming a design concept into a prototype, either physical or virtual, is highly dependent upon the specific circumstances of a design problem. Since every design problem (and design team) is unique, a generally applicable methodology for prototyping is needed. This paper presents a prototyping strategy utilizing a heuristics-based approach that is relatively easy to implement and is applicable across multiple design problems. Here we define a prototyping strategy as a planned set of actions the design team will take in the upcoming prototyping effort. This novel method enables a more flexible approach to developing a strategy on behalf of the designer and takes significantly less time to implement than the strategy described above. The next section also shows that the method increases efficiency and effectiveness of the prototyping process. It is therefore applicable to a broader range of design problems. Additionally, this study also provides a much more detailed investigation of quantified effects of the strategy formation method on prototyping efforts. Specifically, this tool contributes a Likert-scale assessment of context to guide designers in translating context variables into prototyping strategy variables. The method guides a strategy that covers a broad range of concerns a designer may have when prototyping. These 'strategy variables' are described below:

1. **Number of design concepts simultaneously prototyped** - Parallel prototyping occurs when multiple concepts are built at the same time, unlike serial prototyping in which one prototype is followed by another (e.g. competitive prototyping by sub-groups at a design firm).
2. **Number of iterations for each concept** - Building a prototype, testing and evaluating the prototype, refining the design concept, and re-building another prototype of that same concept is called "iterating" (e.g. the progression from initial to final form models for a car body design).
3. **Scaling** - Prototype size can be either larger or smaller than the planned final design size; however, the prototype retains relative characteristics of the full-size form (e.g. a Navy ship built 1/100 scale for initial water-tunnel testing).
4. **Subsystem isolation** - Often a subsystem of a design concept can be prototyped and evaluated in isolation (e.g. testing of LCD components, without casing, for a monitor design project).
5. **Relaxation of design requirements** - Prototypes may be built with "relaxed" design requirements to simplify the process (e.g. an engine that runs at partial torque values to initially reduce major damping modes in engine block design).
6. **Physical vs. virtual models** – A physical prototype is a tangible, material model of a product or subsystem, whereas a virtual prototype is a computer-based model (CAD model, motion analysis, FEA, CFD, etc.) of a product (e.g. architectural CAD models of skyscrappers).

The heuristics for each strategy variable in this methodology are based on synthesis of the empirical and theoretical research findings that were discussed in the literature review section.

Number of concepts in parallel
Empirical research has shown that pursuit of multiple design concepts in parallel can increase performance of the final prototype [19, 15]**.** Beyond this, Dahan and Mendelson [12] investigate a more analytical approach to the prototyping process based on an assumption of profit from the design solution. This research investigated the trade-offs of parallel concept testing based on the roles of profit distribution (uncertainty), cost of testing, and total budget. Parallel concepts permit more rapid breadth exploration of the design space and may be explored when cost permits. These findings are reflected in the Likert scale prompts of the method in a format that retains the analytical findings and still allows consideration of the designer's experiential knowledge.

Number of iterations
Empirical studies have determined that pursuing iteration [19] correlates with increased performance outcome in the final prototype. We also adapt the theoretical findings of Thomke & Bell, [13, 14] who use an uncertainty minimization approach to determine the number of iterations to develop. Thomke and Bell conclude that savings could be achieved through multiple low fidelity prototypes, which is also supported by the empirical research [13, 14]. Finally Dahan and Mendelson conclude that iterations succeed when cost is constrained as iteration is lower cost that parallel testing [12]. The strategy encourages the designer to explore multiple iterations when feasible.

Scaled or full system prototyping
Previous empirical research studies found that when a full-system model is very costly, time consuming or impractical to build for verification purposes as a prototype, a scaled prototype can be very useful for testing the system [11]. This may also be true when a full-size system is feasible, but a scaled model is much lower in cost and allows rapid iterations.

Subsystem isolation or integration
The empirical research identifies that a prototype may embody a subsystem or the full system [11]. The indications for pursuing a subsystem are similar to those for scaling. When it is relatively difficult to construct the full system and a designer is confident that sufficient information is obtainable from building and testing an isolated subsystem, a subsystem prototype can be used. Particularly, subsystem isolation is useful when it allows rapid cycles of build and test for a complex subsystem.

Requirement relaxation or full requirement testing
Prototypes may or may not meet the final design requirements [11]. By carefully constructing a test that may not meet full system requirements, but does in fact capture some critical aspects of system function, the designer can determine potential benefits or drawbacks of a design without investing an unnecessary amount of effort or resources to the build.

Virtual versus physical prototyping
Finally, previous studies [10, 11] also identify that a prototype may be either physical or virtual. In a recent publication, [23] we also find that virtual prototypes are beneficial when the cost of a virtual prototype is lower and allows for more rapid iteration.

Figure 1 below contains the six multi-point prompts of the design tool. Each strategy variable is determined by averaging the Likert response to the multi-point prompts. Completing this process can drastically alter a designer's proposed prototyping strategy. For example, one of the teams in the in-class study (discussed below) was designing a material corrosion prevention system and used the planning tool to formulate their prototyping strategy. Prior to using the tool they identified two concepts that appeared to be promising: (1) an impressed current and sacrificial anode monitoring system, and (2) a four-point anode monitoring system. As they reviewed the matrix in Figure 1, question 1, they found that there was enough material to build multiple design concepts, two concepts showed promise, and each would be quick to build. Therefore they decided to pursue construction of both of these design concepts, an idea that previously was not considered.

As can be seen in Figure 1, the method is designed to allow consideration of the designer's experience with strategic research-based heuristics. This addresses the fact that material and time allotments are not always explicit or pre-determined and thus allow for human discretion in these choices, while at the same time providing a guide based on known best practices.

Figure 1. LIKERT-SCALE MATRICES FOR DETERMINING THE SIX PROTOTYPING STRATEGY VARIABLES.

	Compute the average response to the prompts under each category to determine strategy.	Strongly Disagree. -2	Disagree. -1	Neutral. 0	Agree. 1	Strongly Agree. 2
1	**For high avg, develop multiple concepts; else, build one only.**	**One concept**				**Multiple concepts**
a	There are sufficient materials to prototype multiple concepts.					
b	There is sufficient time to prototype multiple concepts.					
c	Rankings of several concepts are very close (e.g. from Pugh chart).					
2	**For a high avg, iterate; else, build once.**	**No not iterate**				**Iterate**
a	The difficulty of meeting the requirements will necessitate iteration.					
b	The difficulty of manufacturing will necessitate iterative prototyping.					
c	My team has minimal prototyping experience.					
3	**For a high avg, use a virtual prototype; else, use physical models.**	**Physical**				**Virtual**
a	Virtual prototype(s) will require less time than a physical one(s).					
b	Virtual modeling will validate: physics, interfaces and/or requirements.					
c	A CAD model is needed for analysis (FEA, CFD, etc.) or manufacture.					
d	Time & budget allow pursuit of both virtual and physical prototypes.					
4	**For a high avg, isolate subsystems.; else, integrate the system.**	**Integrate Subsystems**				**Isolate Subsystems**
a	Interfaces between subsystems are predictable and/or are NOT critical.					
b	1 or 2 subsystems embody critical design requirements & need iteration.					
c	A subsystem build would significantly reduce time, cost or complexity.					
d	An isolated subsystem can be properly tested.					
5	**For a high avg, use a scaled model; else, use a full size model.**	**Do not scale**				**Scale**
a	Scaling law(s) will permit accurate system modeling via a scaled build.					
b	Scaling will significantly simplify the prototype.					
6	**For a high avg, relax requirements.; else, pursue full requirements.**	**Do not relax**				**Relax design requirements**
a	Requirement flexibility allows significant results from a relaxed model.					
b	Requirement relaxation will significantly simplify the prototype.					

3. EXPERIMENTAL ASSESSMENT OF THE METHOD

We assessed the new tool in two environments: (1) a controlled experiment in which volunteers completed a prototyping design challenge, and (2) an open-ended capstone design class with a variety of sponsored design projects. In both cases students received training and employed the newly created prototyping strategy formation tool.

3.1. CONTROLLED STUDY EXPERIMENT

In this experiment 64 students from a senior level mechanical engineering design class at The University of Texas at Austin were divided into 32 two-person teams. The teams were split equally into control and experimental groups. Our previous research has indicated that many designers do not consciously consider the prototyping strategy variables we introduce; therefore, the control is defined as the group solving the same design problem in the same allotment of time and resources, but without access to the strategy decision matrices.

The design problem prompted teams to build a freestanding triggered device to propel an 8.5x11 inch sheet of paper the farthest distance with the greatest amount of repeatability. Students were instructed to maximize the objective function:

$$Score = Dist_{AVG} - 2 * (Dist_{MAX} - Dist_{MIN}) \quad \text{(EQ. 1)}$$

Although our analysis weights distance and repeatability in various ways, this objective equation clearly guided teams to maximize distance while minimizing variance. The design criteria also specified a minimum score of 25 feet to successfully complete the design challenge. This design problem was chosen because it can be solved in two hours of prototyping time, prototyping efforts are tractable, and there are multiple design solutions.

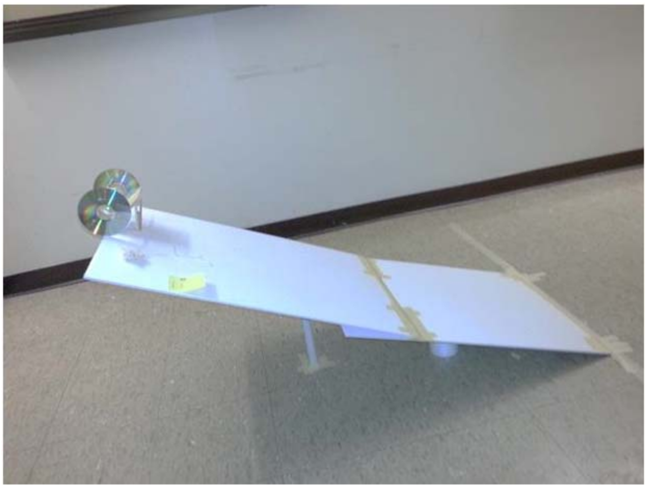

Figure 2. EXAMPLE SOLUTION TO THE GIVEN DESIGN PROBLEM.

To simplify the experiment and reduce the noise induced by concept generation, we provided the teams with four rudimentary design concept sketches to base their prototyping upon: (A) sling shot, (B) wheeled vehicle, (C) rolling cylinder, (D) catapult. Figure 2 depicts an example of one solution a team designed, using concept C, to successfully complete the challenge. All teams kept a running log of time spent testing, concept tested, design change made since previous test, and distance reached. At the end of the two-hour prototyping period, each team made five launches and was evaluated by the researchers according to the three launches that gave the best performance score according to EQ. 1.

3.2. CONTROLLED STUDY RESULTS

Using EQ. 1 as the performance objective, the three best final launches from each team were averaged into a team score. A statistical analysis was performed using a two-tailed t-test. Figure 3 depicts the average overall performance rating for the 16 experimental and 16 control teams. The experimental group shows a higher average performance score, but not to a level of statistical significance (p=0.43, t-test).

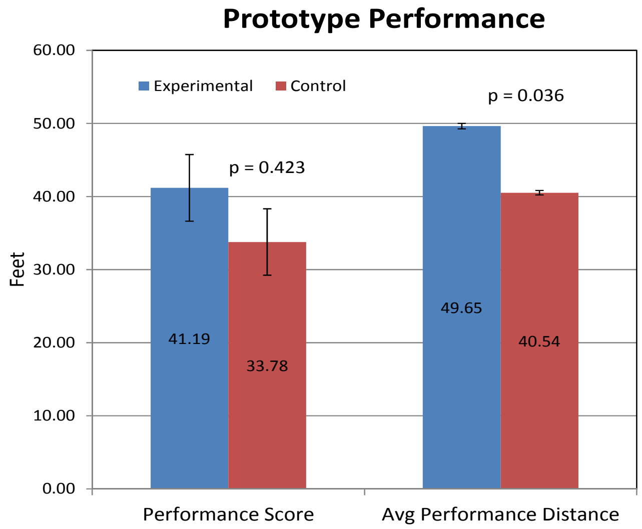

Figure 3. COMPARISON OF EXPERIMENTAL AND CONTROL GROUPS OVERALL PERFORMANCE.

One possible explanation for this result is that this performance measure overly penalizes design variance and inherently amplifies the standard deviation. Therefore, a second metric considers only distance. In this case the performance metric was calculated by averaging all five tries from each team within the experimental and control groups respectively (Figure 3) This distance-only assessment yielded similar results to our previous evaluation, indicating the higher average of the experimental group but also proved to be statistically significant (p = .036, t-test).

This analysis indicates there is a performance advantage gained from the prototyping strategy formation method for this experiment. Furthermore, the data also justifies the increased performance by showing a remarkable increase in prototyping best practices such as prototyping earlier and iterating more as can be seen below. Figure 4 shows the experimental group time-to-first-prototype is dramatically lower (*p*=0.03, t-test), and Figure 5 shows the experimental group outperformed the control group at the end of one hour (p=0.00, t-test) by averaging distances nearly 10 feet more than the control.

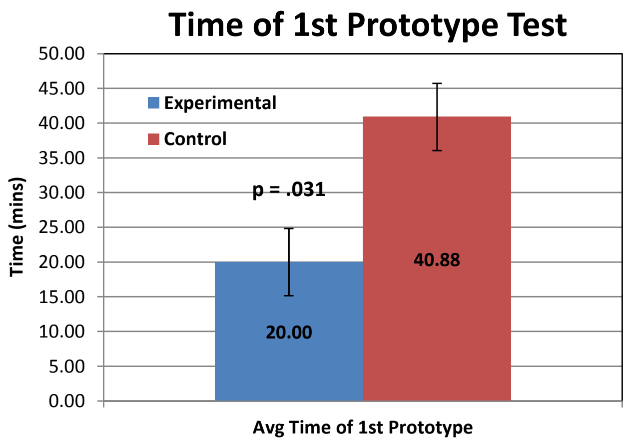

Figure 4. AVERAGE TIME OF FIRST PROTOTYPE TEST FOR EXPERIMENTAL AND CONTROL GROUPS

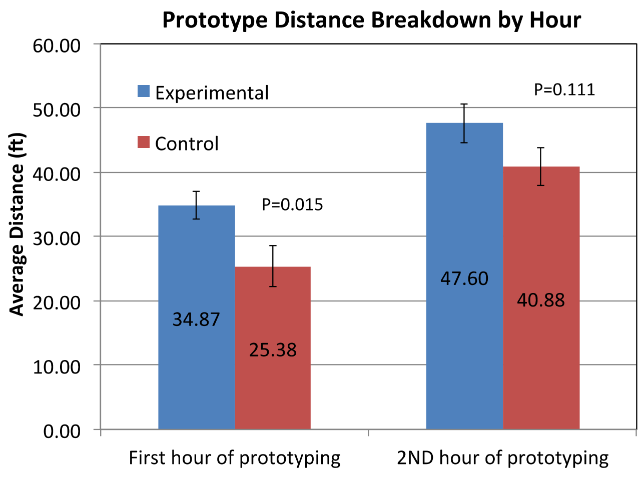

Figure 5. AVERAGE DISTANCE REACHED BY EXPERIMENTAL AND CONTROL GROUPS' PROTOTYPES FOR FIRST AND SECOND HOUR.

Figure 6 further demonstrates that the experimental group achieves performance more rapidly. It can also be seen that performance for both conditions starts to level out after about an hour and a half. This indicates that the problem lent itself to a certain level of design performance saturation, and that for complex problems the strategy may be even more applicable.

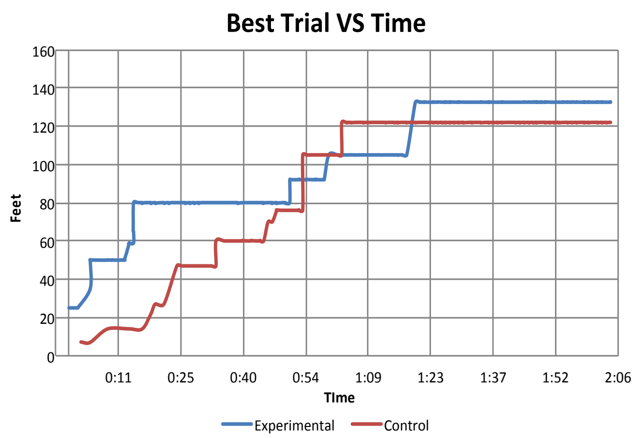

Figure 6. BEST PROTOTYPE TEST VS TIME FOR EXPERIMENTAL AND CONTROL GROUPS.

Figure 7 graphically depicts how each group tested over time, and shows the experimental teams prototyped and tested at a consistent rate throughout the allotted time, suggesting better time management and better prototyping practices. The control teams were slow to begin prototyping and had to dramatically increase their efforts towards the end to finish.

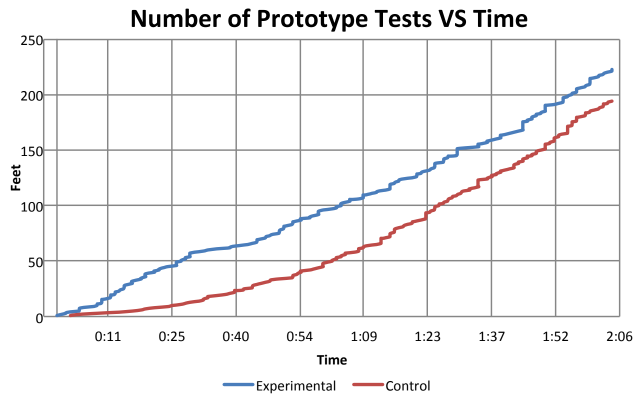

Figure 7. CUMULATIVE NUMBER OF PROTOTYPE TESTS FOR ALL EXPERIMENTAL AND CONTROL GROUPS.

Figure 8 adds further insight to the observation of testing over time by depicting only tests that were prototype iterations. Here a prototype iteration is defined as a fundamental change to the physical model. The graph again shows that the control group was slow to start in the first half hour. This relatively slow progress may represent intuitive minor adjustments to their designs, rather than explicit iteration. In contrast, the experimental group was quick to start and consistently iterated throughout the experiment.

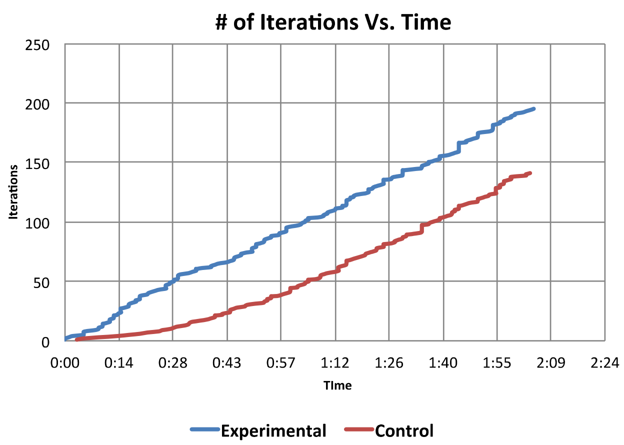

Figure 8. NUMBER OF PROTOTYPE ITERATIONS FOR EXPERIMENTAL AND CONTROL GROUPS.

A post-experiment survey was administered in which teams recorded how many iterations they completed before reaching their finished product. We found that the experimental teams reported an average of 11.5 iterations for their prototypes compared to the 7 iterations for the control teams. This result represents a confidence interval greater than 95% that experimental teams completed more iterations. The more detailed prototype tracking logs showed that the experimental group had an average consistent with what they originally reported (12.31, 6.5% difference). In contrast the control group misreported their iterations by nearly 30% (see Figure 9), suggesting the experimental group showed a marked improvement in record keeping accuracy. This likely indicates that a close attention to strategy also allows for more accurate self-assessment as choices were explicit rather than intuited.

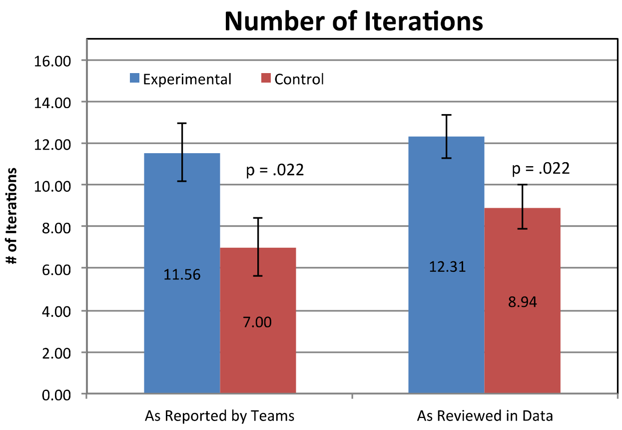

Figure 9. COMPARISON OF TOTAL NUMBER OF ITERATIONS AS REPORTED BY EACH TEAM AND AS REVIEWED IN THE DATA.

The experimental teams were informed of the research showing successful teams often initially prototype three or more different concepts, and each experimental team did initially plan to test two or more concepts. However, only seven of the sixteen teams actually attempted more than one concept. This was more than the control group, but less than expected. Many teams that did not attempt the second concept reported their first prototype proved promising enough that they did not see the need to prototype a second concept. The prototyping strategy formation method clearly prompted teams to consider multiple concepts; however, in this particular experiment it may have been likely that teams did not have sufficient materials. This result is what would be expected from Dahan and Mendelson's experimental model [12]. Further, the performance saturation curve, Figure 6, indicates that time was not the driving constraint (for which parallel prototyping is more critical). Therefore we do not expect that this observation would recur in different design problems, as it is specific to these conditions rather than indicative of the method.

3.3. CAPSTONE DESIGN CLASS EXPERIMENT

Senior engineering students at the United States Air Force Academy enroll in a two semester capstone design course and work on a wide variety of corporate sponsored projects. As a part of their curriculum we introduced the method to the design teams during the first semester of the class. Each team then planned to implement the method once they reached the prototyping phase of their project. At the beginning of the second semester all teams had begun their prototyping. We then gathered feedback from the students and instructors to assess the usefulness of the method for formulating effective prototyping strategies.

3.4. CAPSTONE DESIGN CLASS EXPERIMENT RESULTS

After implementing the new tool, one student and the instructor from each of the seven teams evaluated the method on a Likert scale of 1-5 based on the following criteria: easy to follow, useful, efficient, and helped them consider aspects of prototyping they had not thought of before. As shown in Table 1, each of these criteria had an average rating of 4.0 or greater. These results validate that the methodology has a positive experiential benefit on the perception of the participant designers across a suite of design problems, team sizes and team relational dynamics. The Likert scale method is a well-established research tool in design science [24]. This section does not address technical or performance effects of the method, as discussed in section 3.2. However, it does demonstrate the integration of the strategy method into long-term multi-system projects that allow evaluation of the method on more complex design problems.

Table 1. CAPSTONE DESIGN CLASS PROTOTYPE STRATEGY DEVELOPMENT GUIDE EVALUATION

The prototype strategy development guide:	Avg	Stdev
...is easy to follow.	4.36	0.81
...is useful in helping my team formulate a prototyping strategy.	4.00	0.85
...helped my team consider aspects of prototyping that would have otherwise been overlooked.	4.00	0.85
...is an efficient tool for formalizing a prototyping strategy.	4.00	0.76
...is an important part of the design process.	4.57	0.62
Likert scale: 1 (completely disagree) - 5 (completely agree), Sample size: N=14		

Along with these positive responses to the method, we also received invaluable feedback to improve the method, including:

- We should clarify whether the strategy must be followed strictly or is re-workable after initial efforts.
- The generalizability of the criteria should be further explored.
- Alternate orders for the strategy should be considered.

4. FUTURE RESEARCH

Results from both the controlled and capstone studies are encouraging. Future research should consider several additions as well as attempts to address the feedback. These may be guided by the following questions:

1. Implementation of a prototyping effort often appears to be a very multi-faceted and dynamic process – meaning that plans change based on new information gained at each stage of the prototyping effort. How can the method be augmented to address time-dependent context variables that influence the preferred strategy?
2. The strategy development tool (Figure 1) has multiple criteria for each of the 'strategy variables'. What alternatives to the Likert scale averaging method may be effective?
3. Is the order of the strategy development correct? That is, can a team decide how many concepts to do in parallel before considering how many iterations may be necessary to carry out each concept?

We also intend to continue to follow the capstone design teams throughout their prototyping processes. We will again follow up with the USAFA design students at the end of the course and evaluate how the method was used and measure its effectiveness.

While the current method is limited in its scope, the initial results are quite exciting and illuminating, and we aim to expand the method to include more prototyping decisions made by design teams, such as material choices (using the same materials in prototypes as planned in production), manufacturing techniques, etc.

5. CONCLUSION

This paper reports on a newly developed heuristics-based tool that guides designers in planning a prototyping strategy based on answers to Likert-scale questions that embody empirically validated heuristics. Results from a controlled study indicate the method did improve students' performance across a number of assessment metrics. We found that teams who use the method tend to iterate earlier and more often than those that did not use the method. Furthermore, those who used the method managed their time better and were able to improve performance at a faster rate. As shown in various other experiments, these variables are directly correlated with higher success. Based upon our results we know the method enhances performance, and these additional metrics show us how.

In conjunction with the controlled study, the method was introduced to a capstone design class at the US Air Force Academy with a diverse range of open-ended sponsored design projects. The students and faculty reacted positively towards the method, indicating that it was easy to follow, useful, efficient, and helped them consider aspects of prototyping they had not thought of before.

6. ACKNOWLEDGMENTS

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