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THE WAY MAKERS PROTOTYPE: PRINCIPLES OF DIY DESIGN

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ABSTRACT

Recent research demonstrates the importance of prototyping to support early stage design efforts. There remains a substantial opportunity to provide tools that codify the leap between the logical objectives of the design effort, and an individual's intuitive design and fabrication experience. This study investigates project articles on the open source, Do-It-Yourself (DIY) design repository, Instructables.com. The database contains guides for producing low cost functional prototypes. Many entries in the repository include documentation of the design process along with instructions for fabrication. Through a systematic research methodology, we extract five prototype design and fabrication principles from articles in the database. An online crowdsourced assessment enables inter-rater testing, with multiple parallel raters. This assessment validates presence of the principles in the database. A controlled study was conducted in which one of two groups was exposed to the principles. This study evaluates connectivity, successful adoption of the principles by participants in the experimental group, and resulting design performance effects. Two case studies of prototyping are also provided. Observations indicate that application of the principles positively impacts prototyping outcomes. A potential area for improvement is edge case evaluation, i.e. principles only found in a single extraordinary sample.

INTRODUCTION

Numerous critical insights have been gained from empirical studies of prototyping, including: strategic planning methods [1-7], time dependency factors [8-12], the benefits of parallel and iterative testing [1, 13], and fixation effects [14-16]. A relatively rich opportunity is to explore methods that inform prototype fabrication. This opportunity complements previous work on strategic prototyping [1-7]. Strategy guides high level planning for the number, and fidelity of prototypes to pursue. Applied fabrication principles can reduce effort, and improve build quality.

The value of successful early stage functional prototyping is often seen on incubation platforms such as Kickstarter, where projects without a working prototype seldom succeed. This leads to the question 'What are the techniques for successful prototype fabrication?' Simultaneously, explosive growth of the Do-It-Yourself (DIY) movement has resulted in large repositories of projects which include catalogued procedures of the prototyping process. This work provides results from a systematic review of projects in the open-source database Instructables.com

The DIY Design Movement

What is DIY design? DIY design is typically implemented outside of the framework of professional design, for the purpose of practical gain [17]. It may often be an individual activity; however, sharing communities have recently evolved [18]. Although research suggests that DIY communities are social in origin [19], there are currently numerous platforms with a high technology orientation. Information moves organically in these communities. Experts may seed forums with extensive topic knowledge [20]. This exchange can directly lead to the mutual benefit of participants [21]. In turn, a forum of creativity is emerging where open-sharing is highly valued [22]. The paradigm permits individuals a self-reliance to modify or develop certain technologies [23]. It is possible for individuals without a technical background to fabricate a cellphone, or other complex tools [24]. This movement does not eliminate the need for large-scale manufacture of basic components; however, it does act to democratize technology through information sharing [24]. The DIY development can share benefits of craft such as high quality aesthetic [25].

However, the opportunity is much greater than this alone. Genuine technological advancements are within the scope of non-experts [23].

Figure 1: Example DIY project; an eye tracking system for the mobility impaired that costs two orders of magnitude less than commercial alternatives (The 'Eyewriter' [26]).

What opportunities does the DIY movement present for design research? Often in a traditional design scope, needs assessment is conducted in partial isolation from the user [27]. For DIY projects, the designer is often also the final user. Open sharing permits iterative evolution as each participant advances a design to fit their needs [28]. The development of personal fabrication also provides a novel design arena. Open source part databases (e.g. Thingiverse, Shapeways), in combination with free modeling software [29], and low cost digital manufacture (3D printers or laser cutters), make design and fabrication of geometrically complex parts a desktop activity [29]. Distributed manufacturing networks (e.g. Alibaba) provide means of accessing components and materials in low volume directly from suppliers [30]. Other platforms (e.g. Instructables, Make, Highlowtech, Reprap, Opendesk, DIYlife) provide project guidance [29]. There are companies deploying DIY centered hardware and software (e.g. Arduino, Adafruit). Labs are also experimenting with DIY, enabling hardware development, including paper mechatronic platforms [31], haptic interface designs [32], or modeling toolkits [33]. Open source software enables generative design, to reduce the effort of digital modeling [34]. Hacker-spaces, incubators, and online platforms exhibit creative and inquisitive design. The results of these efforts can be seen as functioning in parallel to industry and research [35]. In this framework, designer, manufacturer, supplier, and consumer act as distributed networks. There is thus an open opportunity to connect directed research with these emergent activities [36].

Design Principles

Heuristics or principles are fundamental to the engineering method [37], and to rationalization in design [38]. They are characterized by a provision of plausible aid or direction in the solution of a problem, they guide, but may not in and of themselves resolve a problem [37]. Categorization and classification are essential to the development of design principles, as categorization facilitates the representation of large amounts of information in a compact form [39]. This work seeks to identify the implicit principles present in the DIY movement for prototype fabrication.

There is a substantial potential for this project, as radical innovation has been cited as both human-centered, and inclusive of novel interpretation of meaning [40].

OVERVIEW AND OBJECTIVES

Research Overview

This paper presents the findings of two years of research into DIY and maker design. The project began with a multi-stage deductive extraction procedure by which principles were identified from the online database, and subsequently tested. The presence of these principles in the database was also tested through a study with multiple parallel online raters. An empirical study was then conducted across two university courses, a control in which a traditional stage gate prototyping methodology was employed, and a second in which a new prototyping method based on DIY principles was provided. A high-level overview of the research methodology is depicted in Figure 2. The goal is to learn if there are principles present in the database, and if these principles can have a positive impact on outcome. The following sections detail the extraction procedure, the online evaluation, and the controlled experiment. A consistent linguistic and logical scheme, as well as multiple verification procedures, are employed. This is to match with guidelines established in foundational classification research [41, 42].

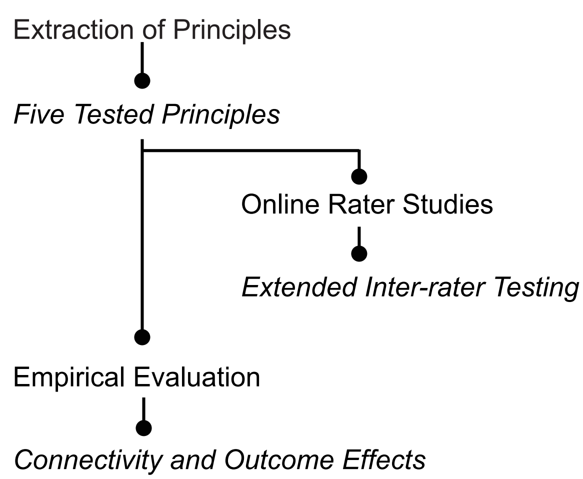

Figure 2: Overview of research methodology.

Research Objectives
This section details the experimental objectives of the work, and research method employed (Figure 2). The literature provides a strong foundation that a new design paradigm is emerging. With the development of open-source prototyping technologies, individuals typically considered the end user are now capable of design and fabrication of complex devices (e.g. DIY cell phones). The emerging paradigm goes beyond the concept of massively customized design, to a context in which designer, manufacturer, supplier, and consumer are not distinctly clear individuals or single entities, but distributed networks. There is an opportunity to quantify the approach to prototype design taken on emerging databases or repositories such as Instructables, where many DIY projects are recorded.

The objectives of this research, are to quantify core practices used in DIY design and furthermore to evaluate whether these can have a positive impact on prototyping when provided as a methodology in a traditional design experiment. The utility of incorporating crowd-sourced analysis into the design research process is also explored. The specific research questions are:

1. Are there common identifiable practices embedded in repositories such as Instructables' entries?
2. Are the identified practices repeatable?
3. If formulated as principles:
   3.1. Is there a successful rate of connectivity (transmission) when presented to designers?
   3.2. What are the measurable effects on prototyping outcome?

The scope of this project is limited to analysis of Instructables as these projects closely map to the development of electro-mechanical prototypes. Furthermore the scale of the projects evaluated is typically on the order of hand-held devices, but ranges up to devices with equivalent complexity to transport vehicles. Finally, the objective of this project is limited to principles that are related to prototyping. There may be principles of social organization, or information sharing that are essential to the success of DIY projects. These are beyond the scope of this work.

EXTRACTION OF PRINCIPLES
Instructables Repository Overview
Instructables is an open-source database developed at MIT's media lab and currently hosted by Autodesk. It is relatively novel among DIY repositories in that entries include documentation of early failures, and reasoning processes. On January 9th, 2015 a total of 152,729 unique entries were counted on Instructables.com; 37,370 were counted on the Technology category. Figure 3 depicts the repository structure. The Technology category was considered the most relevant to our research in development of electro-mechanical products, as the analogy is direct. Other categories include Food or Outside projects. The Technology category is further subdivided into 38 unique channels such as Arduino or Gadgets. To extract principles from this database, a multi-stage procedure was taken. In general the extraction process begins holistically and progresses towards quantification.

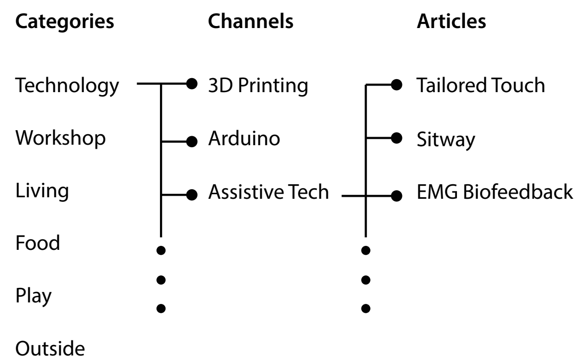

Figure 3: Wireframe structure of the Instructables repository.

Identification of Potential Principles
A preliminary set of entries was reviewed for potential repeatable principles. A set of 70 articles was selected. The two most viewed entries from each channel were taken. These articles were selected as some of the less viewed entries are incomplete. The researchers read this initial set closely and recorded specific practices. The practices should either save resources or improve performance. Four criteria were used for identifying potential practices, which were based on design principles theory. These criteria are as follows:

I. Design oriented - the principle relates to an aspect of fabrication or design.
II. Actionable - the principle describes a series of steps or actions.
III. Objective paired - a specific benefit or objective is expected as a result of implementing the principle.
IV. Recurrent - the principle occurs in multiple articles.

The first criterion is specific to the scope of this study, wherein only principles that relate to prototype design and fabrication are explored. Criteria two, three, and four are given requirements from design principles theory. A principle should be actionable and lead to a specific goal. The fourth criterion satisfies the requirement that a principle is not a specific solution, but a general guide that aids in developing a solution across varied contexts.

Data Saturation Test
Data saturation testing was employed to determine whether the initial sample set was large enough. Data saturation is used to determine if most of the unique potential principles have been found. Essentially, the number of unique principles found (in total) is plotted against the total number of articles examined. As each new article is added, the number of unique principles found in that article (and no previously examined article) starts

to decrease. This plot (Figure 4) nearly reaches asymptotic convergence at about forty articles, and appears fully converged at seventy articles. Examining more than seventy articles is not very likely to result in identification of a new principle.

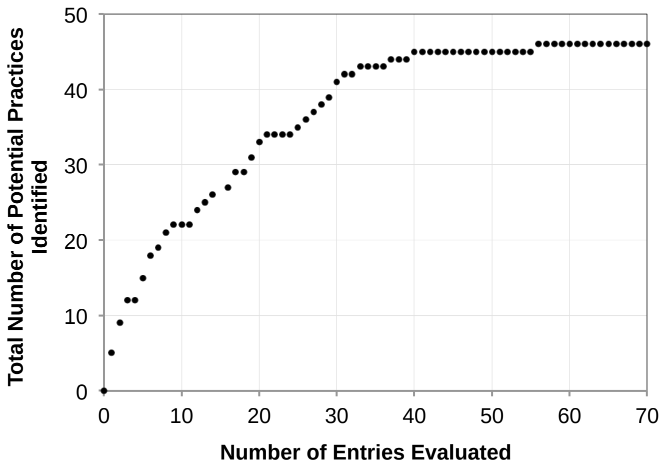

Figure 4: Data saturation for extraction of specific practices.

Quantification of Principles

After the initial identification, the next step was to quantify the principles. This step was achieved by listing metrics for each principle. For example, if an identified principle is ‘Hacking’, components that were hacked and their function were listed for each entry. This approach helped to more precisely define the principles and to eliminate potentially vague or untestable descriptions. The information that was extracted from the initial set of Instructables is listed in Table 1:

Table 1: List of data collected in the quantification study.

Feature	Data recorded
All components	Source, cost, and function
Planning	Representation tools used
Custom components	Fabrication, and sequence
Structural features	Reinforcement techniques

Synthesis of Core Principles

Results of the quantified tests were used to guide a synthesis, or 'binning', process. Logistically, this process was achieved by listing each potential principle, alongside key features which quantify the principle. Potential principles which overlap were listed under a common core principle. Figure 5 represents a sample of three potential principles which were grouped. This process resulted in a set of five core principles.

Independent raters were supplied with the criteria, and a sample set of articles. These independent raters found each of the five principles. Although the additional raters used slightly different wording, agreement was reached that the core concept was the same.

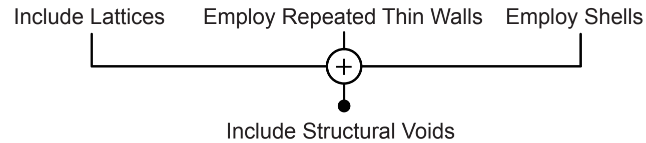

Figure 5: Sample of the synthesis process.

Expanded Database Testing

An additional set of articles was examined to determine if the principles occur outside of the initial sample set, and to add statistical significance to the testing. Sample size calculation is employed to define the minimum sample size required to be confident that the sample is representative of the population. The goal was to achieve the 99% confidence level with a margin of error, or precision, of 0.05. For this calculation, Equation 1 was employed [43]:

$$n \geq \left(\frac{Z^2 P(1-P)}{d^2}\right); \quad (1)$$

where n is the minimum sample size, Z^2 is the statistic for a level of confidence (for 95% confidence, Z = 1.96; for 99% confidence Z = 2.58), P is the expected prevalence or proportion (which ranges from 0 to 1; for example if the prevalence is 20%, P = 0.2), d is the precision.

This equation requires an initial estimate of the prevalence of each principle in the repository. Prevalence is the percentage of cases in which each principle is present. The prevalence of each principle in the sample set was calculated from the initial sample of 70. Equation 1 was then used to determine a minimum sample size that would be required to achieve the target confidence levels. Since the prevalence varies by principle, so does the required sample size. The largest minimum sample size was 653 articles. To achieve a substantial safety factor, 1000 articles were reviewed. The first 30 articles, (those with the most views and bookmarks) were taken from each Technology channel, using the same selection criteria as for the initial sample set.

A reviewer closely examined each article in this expanded sample set to determine whether each principle was employed or not. A table of principle usage across the entire sample was constructed (Table 2). The data was validated with inter-rater agreement. Pearson’s correlation was r = 0.68 between raters for a sample set of 30 articles. This can be considered substantial agreement. The raters achieved full agreement after discussion.

Most articles employed several principles. The average was 3.84 principles per article (with n = 1,000), and the standard deviation is 1.2. These principles are introduced and defined in the following subsection.

Table 2: Principle prevalence from extended sample study.

Principle	Articles with given principle
Employ basic crafting	947
Hack commercial products	895
Prepare fabrication blueprints	734
Repeat fabrication processes	695
Include structural voids	105

Definition of Principles

The five principles are constructed to meet the four criteria listed in the introduction. They are design oriented, actionable principles that may aid a designer in the achievement of a given objective. A consistent semantic scheme is employed.

Hack commercial products to reduce the effort and cost required to achieve functionality (Figure 6). An existing product (or product subsystem) is repurposed, modified, and re-deployed as a subsystem in the prototype.

Hacking is a means to reduce effort and cost required to achieve subsystem functionality. Hacking does not imply illegal modification of systems. Using commercial parts, as intended for a subsystem, does not constitute hacking.

Figure 6: (from left to right) Inductive charge flashlight in candy bottle; atomic force microscope using DVD read head for probe control; a third hand tool from tripod.

Employ basic crafting to reduce cost and effort required to acquire materials (Figure 7). Readily available materials are used to achieve complex function with reduced cost.

Basic crafting implies use of tools and components that are readily available, easy to use and require little overhead maintenance or special training to operate; for the objective of reducing cost and effort. It is critical to have a deep understanding of relevant physical phenomena to avoid failure modes. Use of machinery, e.g. CNC milling, would typically not be considered basic crafting.

Figure 7: (from left to right) A projection system using cardboard, LEDs and a small LCD; a 3D magnetic field mapping tool using acrylic sheet, permanent magnets, and a handheld laser pointer; a 3D motion capture interface using an Arduino and three aluminum foil sheets.

Prepare fabrication blueprints to manage complexity and increase accuracy of fabrication (Figure 8). Sketches (sometimes even made onto components), stencils, CAD models, and schematics are used to directly aid in fabrication.

This principle implies the use of any representation of the design for the purpose of managing fabrication complexity. An abstract design concept sketch would not be an example of this principle.

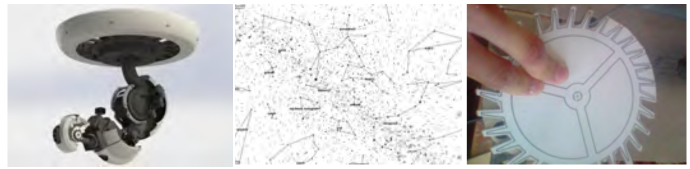

Figure 8: (from left to right) CAD model of a robotic lamp; star map used as placement guide to make a realistic light up star map; gear fabrication using a paper stencil as cutting guide.

Repeat fabrication processes to increase the efficiency of fabrication (Figure 9). Repetition is a means to reduce overall costs from fabrication. Multiple, functionally distinct components are made with a single fabrication process.

The objective of this approach is to reduce startup costs. Preparing any machine or toolset for use has a certain associated cost. This principle strictly applies to custom component fabrication (not the purchase of COTS).

Figure 9: (from left to right) Clamp system for a modular MAV design where all custom parts are 3D printed; a light up clock, both the circuit and light stencil have been fabricated with the inkjet print and transfer PCB method; structural components for a CNC mill, all formed on laser cutter.

Include structural voids to increase strength-to-weight ratio of the prototype (Figure 10). Elements such as lattices, hollow shells, or repeated thin walls are examples of structural voids.

Aligning supports in a lattice can increase the strength-to-weight ratio of a prototype. Steel suspension bridges demonstrate structural voids, while traditional stone or concrete bridges typically do not.

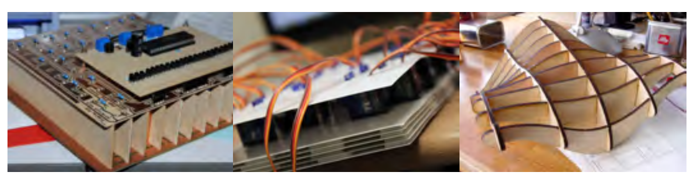

Figure 10: (from left to right) Light up display with polystyrene thin walls; servo actuated with paper case; laptop stand with bilaterally segmented laser-cut sheet assembly.

ONLINE RATER STUDIES

Introduction to Crowdsourcing

Crowdsourcing has emerged as a powerful tool that combines the benefits of parallelization with applied human reasoning. One example is the project 'Foldit', in which crowd analysis resolved a long-standing protein folding problem. Results from the Foldit project have laid the first step for fuel-producing enzymes [44]. Crowdsourced classification has been demonstrated in a wide range of problems, from ecological monitoring [45], to modeling experimental particles physics

[46]. This work employed crowdsourced analysis to provide extended inter-rater testing for presence of the principles in the Instructables database.

Pilot Studies

A series of pilot studies were conducted to inform design of the surveys. A key observation is that concrete tasks (e.g. describe a feature) leads to a higher percentage of usable replies than conceptual tasks (e.g. rate quality) [47, 48]. With several iterations, a survey design was achieved for which 91% of responses were relevant. A relevant response is both not blank, and directly addresses the topic of the question.

Data saturation testing was employed to determine how many parallel raters should answer each survey. A sample set of surveys was posted to the online tool. The number of unique replies per rater was also listed, as in a data saturation test. When a logarithmic curve was fit to the data (r^2 = 0.99), the expected marginal gain of unique replies per new rater (after 25 raters) is less than 1% of the total number of unique solutions found by the first 25 raters. Therefore, for the full study, 25 parallel raters were employed for each survey.

Full Study and Results

A study was conducted to determine if independent raters would identify the principles in provided examples from the Instructables database. Parallel rater sampling provides an expansion beyond traditional inter-rater testing. Amazon's tool, Mechanical Turk, was employed.

Instructables from the sample set were coded into surveys. The surveys included images from the Instructable, the text-based instructions from each entry, and a short series of questions at the end. Online raters were asked to describe something done in the example which could be re-applied to another design, and to provide a binary yes/no response if a given principle was present. Respondents were given the opportunity to reply that they did not understand the question. For each of the five principles, 30 samples were posted in which the researcher had identified the given principle. A control set was posted alongside these where the researcher had not found each given principle. From the prevalence calculations, this sample size passes the 95% ± 0.10 expected confidence level. Each survey was then evaluated by 25 raters, which resulted in a total of 4,200 individual surveys.

A novel approach is taken to evaluate the online rater responses. It is an adaptation of the technique introduced by Green for synthesizing multiple raters in design assessment [49]. For each sample, if the Fleiss' Kappa of online raters is higher than k = 0.8 between raters that the principle is present, then the response is taken as positive, i.e. the principle was found. This approach essentially forms a 'Synthesized Rater', or a calculated rating that represents the subset of observations provided with substantial agreement among the online raters. In the online rating system employed, each of the raters do not necessarily complete more than one entry, therefore n = 1 and the form for Fleiss' Kappa is simplified as in Equation 2 [50]:

$$P_i = \frac{1}{n(n-1)}\left[\left(\sum_{j=1}^{k} n_{ij}^2\right) - (n)\right] = \kappa \; ; \qquad (2)$$

where P_i is the agreement for raters on a given topic (principle), N is the number of subjects (entries), the categories are indexed by j from 1,..,k; and n_{ij} represents the number of raters who assigned the i^{th} subject to the j^{th} category; $P_i = \kappa$ only in this special case where n = 1.

The results of this comparison are shown in Table 3. In Table 3, cases where the researcher did (or did not) find the given principle are compared to whether the Synthesized Rater found the given principle in that case. The overall Pearson's correlation between the Synthesized Rater and the researcher is r = 0.85. This provides a validation that outside raters identify the principles in the provided examples. This study validates that an independent group of raters identify the same principles as the researcher in the sample set (as substantiated by the high Pearson's correlation); however, this study does not address whether the principles are useful as a design tool. An empirical evaluation was employed to address this limitation.

Table 3: Principle identification in samples by researcher and Synthesized Turk. Cases of agreement highlighted in bold.

Researcher	**Synthesized Rater**		**Pearson's**
Hack commercial products	Present	Not present	r = 0.852
Present	**29**	1	
Not present	**0**	**3**	
Employ basic crafting	Present	Not present	r = 0.803
Present	**29**	1	
Not present	**0**	**2**	
Prepare fabrication blueprints	Present	Not present	r = 0.819
Present	**28**	2	
Not present	**0**	**5**	
Repeat fabrication processes	Present	Not present	r = 0.920
Present	**29**	1	
Not present	**0**	**7**	
Include structural voids	Present	Not present	r = 0.696
Present	**29**	1	
Not present	1	**1**	

EMPIRICAL EVALUATION

A controlled experiment was employed to empirically evaluate prototyping outcome differences between a group of design teams that were exposed to the principles and a control group that was not. This controlled experiment took place over two semesters of design course projects. Participants completed a design task in teams of five individuals as a dedicated activity during one week. In one course, the principles were introduced via a brief presentation and handout. In the other course, a typical stage gate requirements process [51] was the only prototyping method introduced. Participants in the experimental course were also provided a survey to self-evaluate their prototypes. The participants of the study consisted of university students majoring in engineering product development. There were 61 teams in the control group, and 49 teams in the experimental group. This difference is due to class sizes and the voluntary nature of participation. There were a total of 550 individual participants in the study. There were no repeat participants between the two courses, and the control course occurred first (to eliminate potential for crosstalk). In the control course, teams were designing a cooling system for milk delivery; in the experimental course teams were designing a device that demonstrates one of the physical concepts in Newtonian physics. Although these two projects were somewhat different, the scope, expectations, and variety among solutions are equivalent. The budget, time allocation, and prototyping requirements of the two courses were the same. Participants were given equal opportunities for prototyping.

Applied case studies are reported at the end of this section. The researchers executed the principles during these case studies. This provides a holistic assessment of the principles.

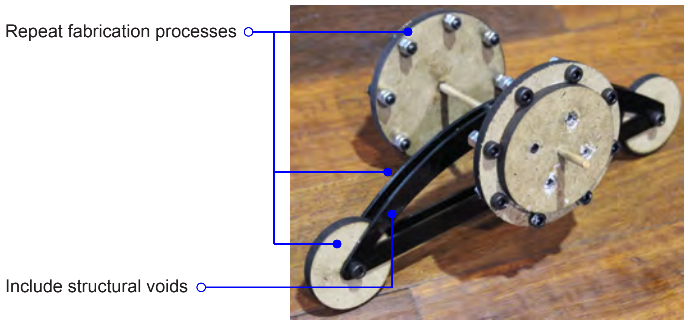

Figure 11: Sample prototype from experimental group; note the use of structural voids (hollow frame) and repeated manufacture (all custom parts were laser cut).

RESULTS AND CONCLUSIONS

Evaluation of Prototypes:

The final prototypes of participating teams were evaluated. First, detailed photographs, and project reports, were collected for the final prototypes. A researcher evaluated whether each prototype employed principles or not using the same testing approach as in the extended database testing. A second rater evaluated a sample of 30 solutions (Pearson's $r = 0.85$). This is a metric for connectivity of the principles, i.e. whether participants employed them or not.

These results can be seen in Table 4, which shows the average total number of principles per prototype from each group. The average number of principles identified in the Instructables study ($N = 1000$) is included as a baseline. It was observed that teams in the experimental group employed the principles more often on average. This difference is significant with Students *t*-test at $p < 0.01$.

Table 4: Connectivity of principles, average number of principles used per prototype in each group.

Group	Number of principles	Standard Error
Experimental group	4.0	0.13
Control group	2.9	0.14
Instructables articles	3.9	0.04

Teams in the experimental group were also rated by an independent set of judges (course instructors). A set of 11 teams were selected to participant in a final judging competition. This decision was based on design quality and execution of their prototype. The average number of principles, per prototype, for teams that entered the final competition is compared to the average for other teams (Table 5). This provides an external quantification of prototype quality. It was observed that the teams in the final competition employed the principles more, on average, than other teams. This difference is significant with Student's *t*-test at $p = 0.05$.

Table 5: Average number of principles per prototype between teams in the final competition and other teams. This data is from the experimental group.

Competition level	Number of principles	Standard error
Teams in final round	4.4	0.14
Other teams	3.9	0.16

Another comparison was made, between groups, of the percentage of teams that were able to provide a physical prototype at the end of the project. Some teams were unable to complete a prototype. The ratio of teams with a prototype to the total number of teams is a measure of overall process quality in each group. More teams in the experimental group produced a prototype (Table 6). This difference in proportions is significant with a transformed *z*-test of the difference of two defective proportions at $p < 0.001$.

Table 6: Total percentage of teams which constructed a prototype between groups.

Group	Fabricated a prototype
Experimental group	91%
Control group	51%

Evaluation of Surveys

In addition to the quantified testing, participants in the experimental groups were also provided a survey for self-assessment of prototype performance. Table 7 reports average results for several questions to help participants reflect on the prototyping process. Responses are separated based on binary self-reported execution of the principles. There are two possible conditions for each principle, use of the principle or use of another approach. Other responses are on a five point Likert scale from [-2] strong disagreement, to [2] strong agreement.

Table 7: Experimental team's survey results, with *t*-test values.

Hack commercial products	With	Without	*p* value
Components were easy to find	0.1	0.1	0.482
Component quality was high	0.6	0.4	0.313
Employ basic crafting	With	Without	*p* value
Fabrication required minimal effort	0.8	0.6	0.356
Fabrication quality was high	0.5	0.7	0.304
Prepare fabrication blueprints	With	Without	*p* value
Schematics were accurate	1.2	0.7	0.01
Schematics were helpful	1.4	0.7	0.003
Repeat fabrication processes	With	Without	*p* value
Fabrication required minimal effort	0.5	0.2	0.239
Fabrication quality was high	0.7	0.4	0.126
Include structural voids	With	Without	*p* value
The prototype was durable	0.9	0.3	0.013
The prototype was light	0.6	0.3	0.186

The survey results indicate general concordance with the objectives of the principles defined in Section 3; some new insights were also observed. For example, basic crafting appears to have reduced effort required to find components but may have also reduced quality. Several of the results are statistically significant using the Student's *t*-test, however, repeated tests may be required to obtain significant results in all comparisons.

Evaluation of Case Studies

Several case studies were employed by the researchers to holistically evaluate use of the DIY principles as a design tool. In the development of a fluid mechanics course, one of the researchers produced a flow chamber that simulates lid driven cavity circulation. The prototype served as an example that was used by students in a fluids course to understand how to develop cavity flow before prototyping.

In this sample prototype, two of the principles were used (Figure 12). An existing fish tank was hacked to contain the fluid. This re-purposing resulted in a substantially higher quality of sealing. Batches of custom components were produced using repeated fabrication. The drive shaft, gears, passive rollers, and structural support separator were 3D printed. The drive belt, and inner casing were all laser cut. This was novel in that it removed the need to purchase a timing belt.

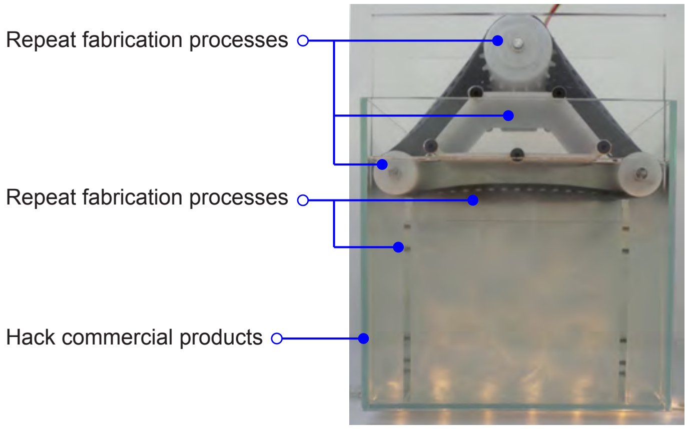

Figure 12: Development of a lid driven cavity flow chamber.

Another case trial was fabrication of a handheld wireless trackball mouse (Figure 13) that does not require a desk surface to use. In this design, a wireless mouse was hacked to achieve the core functionality of a mouse. This was possible, because sensor casing design is the only difference between a standard mouse, and a trackball mouse. The roller ball was also repurposed from a commercial personal care product. Basic crafting was used to connect these two components. One observation of employing hacking in this case is that while the design demonstrated full functionality, the casing was not very ergonomic. This could be improved with a second iteration where the casing was remade (perhaps with additive manufacture), and only the circuit was reused from the mouse.

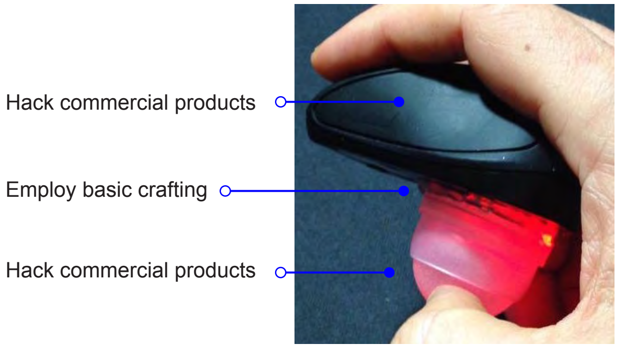

Figure 13: Development of a handheld optical trackball mouse.

The principles provided insight into unique possibilities for prototype design and fabrication in the case trials. These prototypes were produced for relatively low cost, and in a shorter time period than would be expected for their given function. One observation from these case studies is that implementation of a prototyping strategy, analogous to previous work [1], may help to guide decision making regarding the objective of various prototypes. Overall, the design and fabrication principles provide an avenue for inspiration and problem solving.

DISCUSSION

The traditional engineering design approach strongly emphasizes the importance of testing. However, there are not currently any widely accepted methods to inform the development (embodiment) of prototypes. In challenging design contexts, the development of a prototype may seem logistically infeasible. The prototype design and fabrication principles provide avenues for increasing the efficiency of a prototyping effort. These principles provide a codified tool to leap from an individual's intuitive design and fabrication experience, to the logical objectives of the design effort. This codification also addresses the critical need of enabling prototyping in cases where a project has apparently high risk or uncertainty and the design team may be averse to early testing. Low risk prototyping is ultimately an enabler of innovation.

As a result of this study, five unique principles have been extracted from the DIY repository, Instructables. These five principles consist of generic actionable guidelines for achieving efficiency of process or enhanced prototyping outcome. Multiple parallel online raters provide substantial agreement that the indicators are present in the sample set. The impact of these principles in a design context was also evaluated through a controlled design study. A high adoption rate, connectivity of the principles to participants, was observed. Furthermore, presentation of the principles to design teams appears have a positive impact on prototyping outcome. In particular, a significantly higher percentage of experimental teams produced a prototype at the end of their project.

Each of the principles have varied objectives and potential limitations. Hacking of commercial products can result in reduced effort or improved function. It may not be obvious, however, what kind of product can be modified appropriately.

Basic crafting may reduce the cost and effort of fabrication. However, it may also require more skill to produce a robust design. Fabrication blueprints may provide the possibility of fabricating complex geometry without an automated tool. The approach may be limited by materials (e.g. difficult to cut metal accurately). Repeated use of a core fabrication process across multiple custom components can reduce the startup costs of the overall process. This may also result in compromise or design changes so that all parts can be made with a selected process. Including structural voids may enhance the strength to weight ratio of a low cost prototype. However, designing and adding structural voids may increase complexity of planning and fabrication.

Discussion of general limitations to the scope of this project, as well as new avenues for future research, follow in the next subsection.

Limitations and Future Work

The principles provided in this paper are intended to reduce cost, or improve outcome of a concept development prototyping effort. It is critical, however, that these efforts are integrated with a larger design method. This would include methods for other aspects of design (e.g. customer needs analysis, robust design), as well as other aspects of prototyping (e.g. strategic resource allocation and planning).

This study did not consider certain aspects of the DIY community (e.g. designing social impact) that may also lead to key research insights. The scope was limited to DIY prototyping activities.

In terms of experimental design, the control group and experimental group had a slightly varied design problem. This could have resulted in different implementations of the principles via an untested characteristic of the design problems. The similarities in duration, participant experience, available materials, final project requirements, and skill level of participants, as well as the large sample size helps to mitigate this limitation.

The criteria for design principles reduce potential false positives. The approach may be subject to false negatives (missed principles) in cases where documentation was incomplete, or a single, exceptional, design embodied a principle that others did not. The Instructables database was chosen over other DIY project databases in that entry authors provide substantial discussion of early failures, and design reasoning in the documentation.

Future work can include identifying the marginal effects of each principle in terms of cost savings or performance increase. Another important future contribution would be to compare design outcome between several means of deploying the principles to design teams.

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REFERENCES

[1] B. Camburn, B. Dunlap, T. Gurjar, C. Hamon, M. Green, D. Jensen*, et al.*, "A Systematic Method for Design Prototyping," *Journal of Mechanical Design,* 2015.

[2] B. A. Camburn, B. U. Dunlap, R. Kuhr, V. K. Viswanathan, J. S. Linsey, D. D. Jensen*, et al.*, "Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment," in *ASME 2013 IDETC*, Portland, 2013.

[3] B. A. Camburn, B. U. Dunlap, V. K. Viswanathan, J. S. Linsey, D. D. Jensen, R. H. Crawford*, et al.*, "Connecting Design Problem Characteristics to Prototyping Choices to Form a Prototyping Strategy," presented at the ASEE Annual Conference and Expoisition, Atlanta, GA, 2013.

[4] B. U. Dunlap, C. L. Hammon, B. A. Camburn, R. Crawford, D. Jensen, M. G. Green*, et al.*, "Heuristics-based prototyping strategy formation: development and testing of a new prototyping planning tool," presented at the ASME IMECE, Montreal, Canada, 2014.

[5] C. L. Hammon, M. G. Green, B. U. Dunlap, B. A. Camburn, R. Crawford, and D. Jensen, "Virtual or Physical Prototypes? Development and Testing of a Prototyping Planning Tool," presented at the ASEE Annual Conference and Exposition, Indianapolis, IL, 2014.

[6] R. Moe, D. D. Jensen, and K. L. Wood, "Prototype partitioning based on requirement flexibility," in *ASME-IDETC*, 2004, pp. 65-77.

[7] E. J. Christie, D. D. Jensen, R. T. Buckley, K. K. Ziegler, and R. H. Crawford, "Prototyping strategies: literature review and identification of critical variables," presented at the ASEE Annual Conference and Exposition, San Antonio, TX, 2012.

[8] C. Elsen, A. Häggman, T. Honda, and M. C. Yang, "Representation in early stage design: an analysis of the influence of sketching and prototyping in design projects," in *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Chicago, IL, 2012, pp. 737-747.

[9] D. Faas, Q. Bao, and M. C. Yang, "Preliminary sketching and prototyping: comparisons in exploratory design-and-build activities," presented at the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Buffalo, NY, 2014.

[10] A. Häggman, T. Honda, and M. C. Yang, "The Influence of Timing in Exploratory Prototyping and Other Activities in Design Projects," in *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2013, pp. V005T06A023-V005T06A023.

[11] W. L. Neeley Jr, K. Lim, A. Zhu, and M. C. Yang, "Building fast to think faster: exploiting rapid prototyping to accelerate ideation during early stage design," in *ASME-IDETC*, Portland, OR, 2013, pp. V005T06A022-V005T06A022.

[12] M. C. Yang, "A study of prototypes, design activity, and design outcome," *Design Studies,* vol. 26, pp. 649-669, 2005.

[13] S. P. Dow, A. Glassco, J. Kass, M. Schwarz, D. L. Schwartz, and S. R. Klemmer, "Parallel prototyping leads to better design results, more divergence, and increased self-efficacy," *ACM Transactions on Computer-Human Interaction (TOCHI),* vol. 17, p. 18, 2010.

[14] V. Viswanathan and J. Linsey, "Design fixation in physical modeling: an investigation on the role of sunk cost," in *ASME-IDETC*, Washington, DC, 2011, pp. 119-130.

[15] V. K. Viswanathan and J. S. Linsey, "Physical models in idea generation: Hindrance or help?," in *ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Montreal, Canada, 2010, pp. 329-339.

[16] R. J. Youmans, "The effects of physical prototyping and group work on the reduction of design fixation," *Design Studies,* vol. 32, pp. 115-138, 2011.

[17] C. Edwards, "'Home is Where the Art is': Women, Handicrafts and Home Improvements 1750–1900," *Journal of design history,* vol. 19, pp. 11-21, 2006.

[18] D. Rosner and J. Bean, "Learning from IKEA hacking: i'm not one to decoupage a tabletop and call it a day," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2009, pp. 419-422.

[19] T. Triggs, "Scissors and glue: Punk fanzines and the creation of a DIY aesthetic," *Journal of Design History,* vol. 19, pp. 69-83, 2006.

[20] C. Torrey, E. F. Churchill, and D. W. McDonald, "Learning how: the search for craft knowledge on the internet," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2009, pp. 1371-1380.

[21] W. Salmond, "A Matter of Give and Take: Peasant Crafts and Their Revival in Late Imperial Russia," *Design Issues,* pp. 5-14, 1997.

[22] S. Kuznetsov and E. Paulos, "Rise of the expert amateur: DIY projects, communities, and cultures," in *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries*, 2010, pp. 295-304.

[23] P. Atkinson, "Do it yourself: Democracy and design," *Journal of Design History,* vol. 19, pp. 1-10, 2006.

[24] D. A. Mellis and L. Buechley, "Do-it-yourself cellphones: an investigation into the possibilities and limits of high-tech diy," in *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*, 2014, pp. 1723-1732.

[25] R. Arnheim, "The way of the crafts," *Design Issues,* pp. 29-35, 1994.

[26] (2015). *http://www.instructables.com/id/The-EyeWriter/?ALLSTEPS*.

[27] Y. Reich, S. L. Konda, I. A. Monarch, S. N. Levy, and E. Subrahmanian, "Varieties and issues of participation and design," *Design Studies,* vol. 17, pp. 165-180, 1996.

[28] D. Saakes, "Big lampan lamps: designing for DIY," in *Proceedings of the seventh ACM conference on Creativity and cognition*, 2009, pp. 403-404.

[29] C. Mota, "The rise of personal fabrication," in *Proceedings of the 8th ACM conference on Creativity and cognition*, 2011, pp. 279-288.

[30] C. Anderson, *Makers: the new industrial revolution*: Random House, 2012.

[31] G. Saul, C. Xu, and M. D. Gross, "Interactive paper devices: end-user design & fabrication," in *Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*, 2010, pp. 205-212.

[32] C. Moussette and R. Banks, "Designing Through Making: Exploring the Simple Haptic Design Space," presented at the Fifth international conference on tangible, embedded, and embodied interaction, 2011.

[33] K.-J. Wu and M. D. Gross, "TOPAOKO: interactive construction kit," in *CHI'10 Extended Abstracts on Human Factors in Computing Systems*, 2010, pp. 3619-3624.

[34] L. Devendorf and K. Ryokai, "Being the machine: exploring new modes of making," in *Proceedings of the 2014 companion publication on Designing interactive systems*, 2014, pp. 33-36.

[35] S. Lindtner, G. D. Hertz, and P. Dourish, "Emerging sites of HCI innovation: hackerspaces, hardware startups & incubators," in *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*, 2014, pp. 439-448.

[36] E. Paulos, "The rise of the expert amateur: DIY culture and the evolution of computer science," in *ACM SIGARCH Computer Architecture News*, 2013, pp. 153-154.

[37] B. V. Koen, "Toward a definition of the engineering method," *European Journal of Engineering Education,* vol. 13, pp. 307-315, 1988.

[38] C. Alexander, S. Ishikawa, and M. Silverstein, "Pattern languages," *Center for Environmental Structure,* vol. 2, 1977.

[39] K. L. Wood and J. S. Linsey, "Understanding the Art of Design: Tools for the Next Edisonian Innovators," 2007.

[40] D. A. Norman and R. Verganti, "Incremental and Radical Innovation: Design Research vs. Technology and Meaning Change," *Design Issues,* vol. 30, pp. 78-96, 2014.

[41] R. B. Stone and K. L. Wood, "Development of a functional basis for design," *Journal of Mechanical Design,* vol. 122, pp. 359-370, 2000.

[42] V. Singh, S. M. Skiles, J. E. Krager, K. L. Wood, D. Jensen, and R. Sierakowski, "Innovations in design through transformation: A fundamental study of transformation principles," *Journal of Mechanical Design,* vol. 131, p. 081010, 2009.

[43] L. Naing, T. Winn, and B. Rusli, "Practical issues in calculating the sample size for prevalence studies," *Archives of Orofacial Sciences,* vol. 1, pp. 9-14, 2006.

[44] C. B. Eiben, J. B. Siegel, J. B. Bale, S. Cooper, F. Khatib, B. W. Shen*, et al.*, "Increased Diels-Alderase activity through backbone remodeling guided by Foldit players," *Nature biotechnology,* vol. 30, pp. 190-192, 2012.

[45] C. B. Cooper, J. Dickinson, T. Phillips, and R. Bonney, "Citizen science as a tool for conservation in residential ecosystems," *Ecology and Society,* vol. 12, p. 11, 2007.

[46] F. Grey, "Citizen cyberscience: the new age of the amateur," *CERN Courier,* 2011.

[47] A. Burnap, Y. Ren, P. Y. Papalambros, R. Gonzalez, and R. Gerth, "A Simulation Based Estimation of Crowd Ability and its Influence on Crowdsourced Evaluation of Design Concepts," in *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2013, pp. V03BT03A004-V03BT03A004.

[48] G. J. Hardie, "Community participation based on three-dimensional simulation models," *Design studies,* vol. 9, pp. 56-61, 1988.

[49] M. Green, C. C. Seepersad, and K. Hölttä-Otto, "Crowd-Sourcing the Evaluation of Creativity in Conceptual Design: A Pilot Study," in *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2014, pp. V007T07A016-V007T07A016.

[50] J. L. Fleiss, "Measuring nominal scale agreement among many raters," *Psychological bulletin,* vol. 76, p. 378, 1971.

[51] K. Otto and K. Wood, "Product design: techniques in reverse engineering and new product design," ed: Prentice-Hall, 2001.