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Virtual versus Physical Prototypes: Development and Testing of a Prototyping Planning Tool

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Virtual versus Physical Prototypes: Development and Testing of a Prototyping Planning Tool

by

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Abstract

Virtual versus Physical Prototypes: Development and Testing of a Prototyping Planning Tool

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This thesis documents the development of a heuristics-based decision-making tool to guide a designer's choice between virtual or physical prototypes, based in part upon published prototyping strategies, as well as the design, implementation, and results of a pilot experimental study used to test this virtual-vs-physical decision-making tool for prototypes. Eighty undergraduate mechanical engineering students volunteered for a pilot experiment to test the decision-making tool. They were given the choice of physically or virtually prototyping a four-bar linkage. Forty participants in this pilot study were instructed to use a Likert-scale instrument to choose their prototyping technique, and an additional 40 participants, who did not use the instrument, served as a control group for evaluating the effectiveness of the instrument. Analysis of participants' performance metrics undeniably shows that virtual prototyping is the optimal technique for this design problem, as virtual prototypers on average across both test groups achieved performance metrics almost five times higher in about half the time compared to physical prototypers. With the aid of a heuristics-based decision-making tool, 10%

more participants in the experimental group picked the best technique versus those who did not use the tool in the control group (32 of 40, and 28 of 40, respectively). The prototyping choices of participants among each test group were analyzed using the comparison of two population proportions, and results from a two-tailed z-test yielded $p = 0.303$, thus the null hypothesis cannot be rejected with statistical significance for the test of two population proportions. Although the difference in choice of the optimal prototyping technique between test groups of this pilot study is not statistically significant, it serves as a preliminary model for a systematic approach that incorporates consideration of type of prototype as a strategic decision. Although the findings of this four-bar linkage study cannot be extrapolated to a generic prototyping process, this work provides a paradigm for thinking critically about virtual vs. physical prototyping decisions using a heuristics-based, structured prototyping strategy. The pilot results provide a template and motivation for conducting a larger scale experiment for generic prototyping applications.

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Chapter 1: Introduction

The word prototype originates from Greek *prōtotupos*, a combination of *prōtos* "first" + *tupos* "impression" (Harper, 2014). Oxford Dictionaries defines *prototype* as "a first, typical or preliminary model of something, especially a machine, from which other forms are developed or copied" (2014). Modeling of product metrics as a means to understand the form, fit, and function of an artifact, as opposed to trial-and-error approaches, distinguishes engineering from other professions. Engineers use models as characterizations, simplifications, or estimations of a final product's realization. In this milieu, a model is an abstraction of a real-world system that approximates complex physical phenomena (Otto & Wood, 2001). Prototypes are models by definition, and these two terms are used synonymously in this thesis. Presently, prototypes play an integral part in the product design process and provide design and management teams with much more than a first impression of a potential final product.

1.1 Engineering Prototypes

In the context of engineering, as used throughout this thesis, a prototype (either physical or virtual) is an initial manifestation of a design concept, either a scaled or full-size model of a structure or piece of equipment, which can be used to evaluate performance, form, and/or fit. *Prototyping* is the process of generating prototypes, and is usually performed between the concept generation and design verification stages of the product design process. Designers have also used prototyping during the concept generation phase in order to expand or contract the set of potential concepts, in certain cases (Christie et al., 2012). Prototypes provide design engineers the opportunity to determine if a concept is technically feasible, optimize performance, understand interfaces between subsystems, and/or identify potential assembly and manufacturing issues. In addition, prototypes serve as an effective method of communicating the functionality and/or progress of a design concept, to both technical and non-technical audiences. For these reasons prototyping is an integral part of the product development process.

1.2 PHYSICAL PROTOTYPES

Prototypes can be classified as either physical or virtual. A *physical prototype* is the preliminary embodiment of a design concept in a tangible model. Physical prototypes may be fully or partially functional, and allow for sensory evaluation of the concept, possibly including aesthetics and ergonomics. Sensory evaluation of a physical prototype can also include taste, as exemplified by an experimental prototype for a coffee brewer (Figure 1). Physical prototypes provide "hands-on," tactile engagement with a design concept, and they may offer palpable understanding of the physical phenomena experienced by a concept during testing.

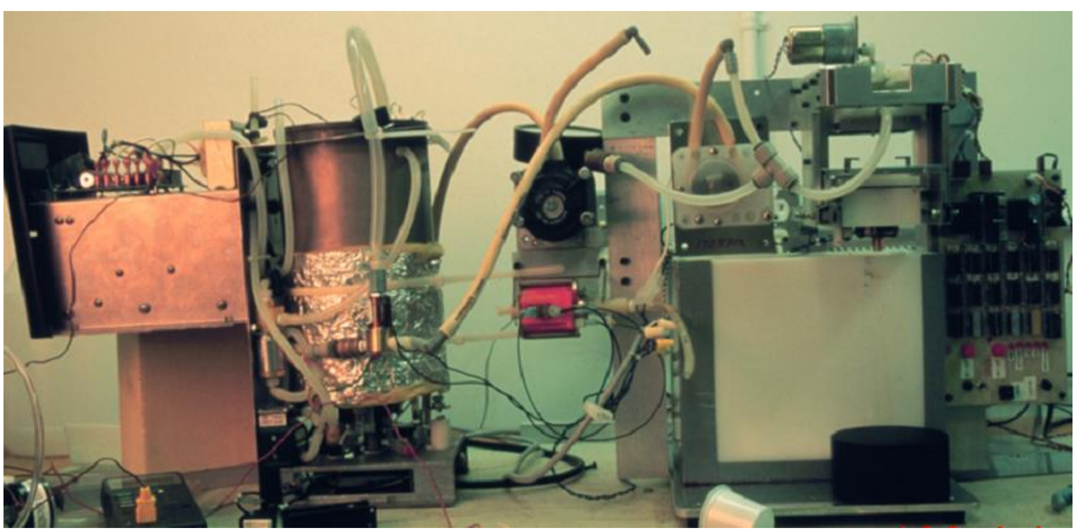

Figure 1: Keurig Coffee Brewer Experimental Prototype (Otto & Wood, 2001)

Perhaps dating back to the invention of the wheel, physical models are the original form embodied by prototypes, ranging in fidelity (detail) from very simple to highly complex. Engineering educators often rely on low-fidelity physical models to teach hands-on design experience in a classroom environment, and frequent use of physical prototypes is widely advocated by industry and government agencies (Kelley & Littman, 2001). The highly respected product design firm, IDEO (Palo Alto, CA), encourages the use of physical models as an aid in design selection and communication between engineers and customers (Kelley, 2001). Contrary research discourages the utilization of certain kinds of physical models. For example, Leonardi (2011) claims that building high-fidelity prototypes early in the product development process can lead to "innovation blindness," where designers concentrate on the initial prototype's detailed form and function while forgetting to consider the intended overarching purpose of the final product or obstacles that stand in the way of its progress. Additionally, some researchers (Christensen & Schunn, 2007; Kiriyama & Yamamoto, 1998) argue that building physical models can actually hinder creativity in idea generation by causing design fixation. When designers fixate on their prior experiences, they reproduce variations of their initial solutions or familiar examples while generating new ideas (Jansson & Smith, 1991). Thus, this design fixation phenomenon results in less novel and more redundant solutions. However, Vishwanathan and Linsey (2011) claim that design fixation associated with physical modeling is due to the *Sunk Cost Effect*, which is the reluctance to choose a different path of action once significant money, time, or effort has been invested in the present course of action. The results of their experiment to test this hypothesis are in agreement and show that design fixation is not inherent in physical modeling, which can in fact supplement designers' mental models and lead them to higher quality ideas. Additional research extols the use of physical models, which enhances communication between design teams (Lidwell et al., 2003; Carlile, 2002; Boujut & Blanco, 2003) and helps designers visualize concepts (Ward et al., 1995) and externalize ideas to identify flaws in their designs (McKim, 1972). Despite these conflicting recommendations, physical modeling, when used appropriately, can be a potentially valuable tool for concept generation and prototyping phases.

Physical prototypes used in industry vary widely in purpose, fidelity, and approximation of final product, i.e., geometry, material composition, and/or fabrication technique. Otto and Wood (2001) differentiate physical prototypes into six general classes based on previous industry trends (Table 1).

Type of Prototype	Purpose	Approximation of Final Product
Proof-of-concept	Prove feasibility of specific function; identify actual/unforeseen physics involved	Typically focus on one subsystem/component
Industrial Design	Demonstrate/communicate look and feel	Similar aesthetics and geometry only
Design of Experiments	Determine performance of subsystem(s) empirically	Similar materials and geometry (perhaps scaled)
Alpha	Evaluate overall layout and integration of subsystems	Actual *predicted* materials, geometry and layout
Beta	Test fully functional model over range of operating conditions	Actual materials, geometry and layout (part fabrication and assembly may vary)
Pre-production	Perform final part production and assembly assessment	Same as Beta, but using actual production tooling

Table 1: Types of Physical Prototypes (Otto & Wood, 2001)

1.3 Virtual Prototypes

In contrast to physical prototypes, *virtual prototypes* are digital mock-ups (computer simulations and/or analytical models) of physical products that can be analyzed, tested, and presented in order to serve the principal purposes of prototyping (outlined above) in the product development process. Some reviews delineate virtual prototypes with two distinct digital components: (1) a product model, containing geometric component models with assembly information, e.g., a 3D solid parametric model; and (2) a process model, which can used to test or simulate a process related to design-for-life-cycle aspects that the product model will undergo, e.g., an assembly or disassembly process for evaluating manufacturability or recyclability of a design concept based on geometric mating and spatial relationships contained in the product model (Gupta et al., 1997; Siddique & Rosen, 1997). Subsequent reviews of virtual prototyping[1] include a third component in addition to the product and process models: a human-product interaction model, which provides sensory evaluation of a product, such as form, feel, or fitness (robustness), with the goal of serving at least the same functions of a physical prototype in the testing of a product's embodiment or performance (Wang, 2002; Deviprasad & Kesavadas, 2003). With at least three interrelated component models that are integrated via a user interface (Figure 2), the most detailed virtual prototypes provide a complex representation of a physical product that is ideally more functionally comprehensive than a physical prototype for a given product. Depending on specific applications, however, a virtual prototype may only incorporate a subset of these component models (Wang, 2002).

[1] Also known as Simulation-Based Design (SBD).

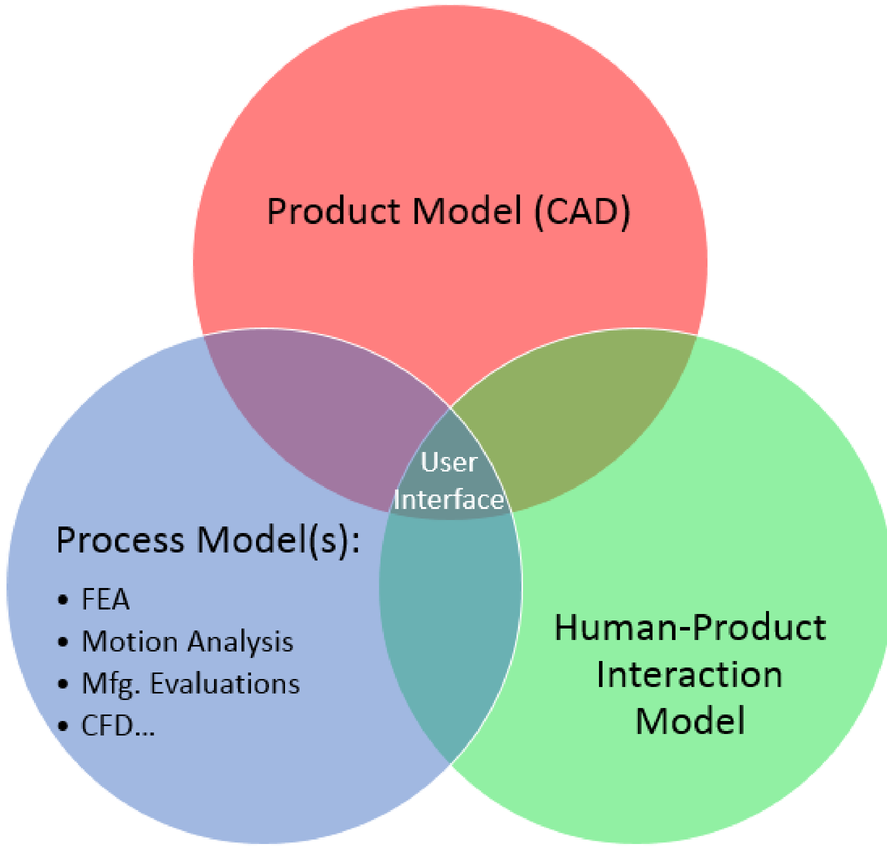

Figure 2: Components of a Virtual Prototype - Adapted (Wang, 2002)

In this thesis, the definition of virtual prototypes is simplified to encompass all software-generated models and numerical analysis methods used in the development of design concepts, i.e., any prototype that is created and/or tested entirely in digital form. Specifically, in Chapter 3, a four-bar linkage that is created using linkage design software that provides kinematic analysis constitutes a virtual prototype.

Computational advances have vastly expanded the possibilities of virtual prototyping in the past few decades. Practical examples of virtual prototyping techniques include 3D CAD models that incorporate motion analysis, finite element analysis (FEA), manufacturability evaluations, and/or computational fluid dynamics (CFD) software package(s). Virtual prototypes may be preferable for instances when physical prototypes are prohibitively expensive. For example, Northrup Grumman has virtually modeled an entire U.S. Navy aircraft carrier with over three million parts (Alpern, 2010). This complex virtual model (Figure 3) allows engineers to foresee potential piping layout issues, predict overall buoyancy/draft height/center of mass, and estimate drag forces without constructing a costly physical model.

Figure 3: Virtual Model of Aircraft Carrier (Alpern, 2010)

In practical applications, a lack of tangible immersion and evaluation distinguishes virtual prototypes (which typically may not include a human-product interaction component) from physical prototypes. However, decades of research in the development of Virtual Environments, also known as Virtual Reality[2], may offer

[2] The phrase Virtual Reality is either an oxymoron or pleonasm (Negroponte, 1993). Virtual Reality has been the most commonly used phrase to describe a Virtual Environment, but Augmented Reality is gaining popularity as its replacement (McGrath, 2014).

additional opportunities for incorporating a *digital*, human-product interaction component in virtual modeling (Dai & Göbel, 1994). Virtual Environments provide platforms for integrating multiple component models in virtual prototyping in the form of immersive and interactive digital representations of sensory information that simulates physical environments in real time for users, who typically must wear or inhabit an appropriate apparatus (Ellis, 1995). For example, in a Virtual Environment an architect may "walk" through a proposed building design and have the ability to visualize interior layout and aesthetics (Wang, 2002). Moreover, important facets of the design for the entire life-cycle of products, from conceptual design through disassembly/disposal, can be simulated in Virtual Environments (Siddique & Rosen, 1997), where a designer can address potential manufacturability, serviceability, and sustainability issues without the need for physical prototypes (Bauer et al., 1998).

CAVE, a recursive acronym for Cave Automatic Virtual Environment, was first unveiled over two decades ago (Cruz-Neira et al., 1992), and it has been the most widely installed immersive visualization system in the world (Alhadeff, 2007), with clients including NASA (Adams, 2007), Mercedes-Benz and Renault (McGrath, 2014), John Deere (Cissé & Wyrick, 2010), as well as the U.S. Air Force and Army (Thilmany, 2000). In a CAVE a user is surrounded in a cavern of projection screens on at least three, and up to six, sides, bringing the science-fictional *Star Trek*™ "Holodeck" one step closer to reality (Peckham, 2013). Specialized glasses allow the user to see projected images in 3D. A tracking option can monitor the position and orientation of the user's head, which allows the images to be projected based on the user's point-of-view and remain stationary as the user moves (Grimes, 2013). An upgraded version, CAVE2, features a hand-held interactive controller and continuous curved screen (Figure 4) allowing maximum peripheral vision for an immersive experience in real-time perspective (Nesbitt, 2013). In Germany, Ford Motor Company has been using CAVE to simulate interior layout and aesthetics, design controls and switches, and virtually test drive its cars (Nan et al., 2013). Additionally, by integrating 3D printing technology with CAVE, Ford can produce complex prototyping components up to 700 mm (27 ½") long composed of three different types of resins, when physical models are needed for design verification (Bell, 2013). Ford claims that CAVE has fundamentally changed its design process as physical prototypes that once took years to complete can now be ready to test virtually in a matter of weeks (Grimes, 2013).

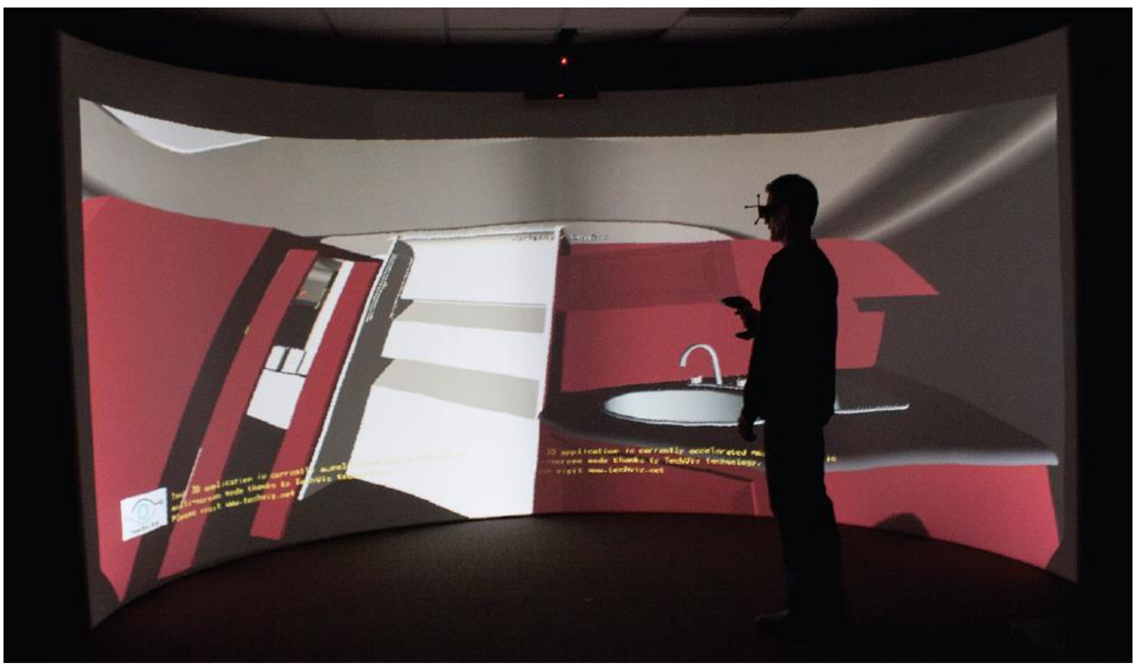

Figure 4: CAVE with Curved Screen Used to Simulate a Ship Cabin (Nesbitt, 2013)

Wang (2002) states that the goal of virtual prototypes is to replace physical prototypes, and the marketers of virtual prototyping software packages, such as Autodesk (Autodesk, Inc., San Rafael, CA), Maple (Maplesoft, Waterloo, ON, Canada), and ESI

(Paris, France), claim to have achieved this goal on their websites[3]. Nevertheless, for certain products, physical prototypes may never be completely replaced digitally. Thomke (2003) provides an example of how automobile crash simulation software can completely replace physical prototype testing. However, automotive manufacturers will likely continue performing crash tests using real vehicles to understand and evaluate real-life physics involved in collisions, regardless of software capabilities or government safety regulations requiring destruction of physical models. For example, Lexus has recently released an improved crash test dummy that is capable of obtaining almost 17,000 times more data than a traditional crash test dummy, and the assumption can be made that the development of this physical model with enhanced sensitivity is more cost-effective and informative, compared to adding millions of data points to a virtual FEA model, in the analysis of collisions (Christie et al., 2012). Furthermore, makers of coffee and tea brewers will almost certainly continue to rely on *physical* prototypes to test the taste of drinks produced by their final products for the foreseeable future, as will makers of automatic air freshener dispensers to test the smell and speaker manufacturers to test the sound produced by their respective final products, to list a few.

Both virtual and physical prototypes may be developed for an entire system or a specific subsystem in order to serve the primary purposes of prototyping, and both may originate with a 3D CAD model. Elements of physical and virtual models may even be combined to form *hybrid* or *mixed* prototypes, e.g., a physical model with embedded sensors that provide real-time feedback to enhance accuracy of virtual simulations (Otto & Wood, 2001). However, for the purpose of distinguishing between types of prototypes

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[3] http://usa.autodesk.com/digital-prototyping/; http://www.maplesoft.com/solutions/engineering/AppAreas/virtualpro.aspx; http://www.esi-group.com/company/about

and consideration of the relevant choices involved in making this distinction, the scope of this thesis does not include hybrid prototypes.

1.4 Problem Statement

Choosing between a virtual or physical prototype is a critical decision faced by interdisciplinary design teams. Advances in parallel processing coupled with cheaper and more widely available software (particularly CAD) have made virtual prototyping increasingly more pervasive in the product design process of the 21st century. Virtual prototyping can potentially decrease costs and increase efficiency in bringing new products to market by providing faster concept iterations and testing earlier in product development cycles (Fixson & Marion, 2012). However, the building, iterating, and testing of virtual models can account for up to 75% of total product development cost (Marion & Simpson, 2009). Conversely, constructing physical prototypes can offer sensory evaluation and/or tactile engagement with design concepts that cannot be realistically simulated. Thus, it is imperative for designers to consider the practical capabilities and limitations of both physical and virtual prototypes in the context of their specific design scenarios. A primary goal of the research presented in this thesis is to provide a paradigm for thinking critically about physical vs. virtual prototyping decisions by means of a novel, strategic aid for decision making.

Traditionally, selection of the type of prototype(s) was likely ad hoc, determined based on budget and time constraints as well as the experience of a design team. However, these three factors might not be sufficient in informing the optimal choice between the types of prototypes for every individual final product. Reliance on historical precedent ("that's the way we've always done it") can limit options for prototyping techniques and may not contribute to improving overall project success rates (Camburn et al., 2013). In a particular product design scenario, using a strategic methodology that provides consideration of the relative accuracy and effort of virtual models with respect to physical models will provide more guidance in the selection of the most appropriate prototyping technique, compared to ad hoc efforts. As described in Chapter 2, there have been relatively few methodologies published over the last few decades that focus on organized development of prototypes compared to other aspects of the product design process, such as concept generation, design selection, and product architecture (Christie et al., 2012). However, a structured approach can potentially benefit engineers' choices involving the type, fidelity, and/or number of prototypes needed to produce a successful final product. Therefore, a new structured prototyping strategy formation method addressing the choice of virtual or physical prototypes is needed.

> *This thesis documents the development of a heuristics-based decision-making tool to guide a designer's choice between virtual or physical prototypes.*

The research is based in part upon published prototyping strategies. The virtual-vs-physical decision-making tool for prototypes is evaluated through the design, implementation, and results of a pilot experimental.

1.5 Thesis Organization

The next chapter details prototyping strategy and presents a literature review of extant engineering approaches to prototyping strategy. Chapter 3 documents the development of a heuristics-based approach to guide prototyping decisions as well as the design of a pilot experimental study to test this approach for the choice between virtual and physical prototypes. Next, Chapter 4 describes the procedural steps in running this pilot experimental study in detail. The analytical results of this virtual-vs-physical prototyping experiment follow in Chapter 5, and the validity and implications of these experimental results are explored in Chapter 6. Finally, this thesis concludes with a critical evaluation of the research and recommendations for future work.

Chapter 2: Background

Prototyping is not a "cottage industry." For example, Proto Labs®, a company based in Maple Plain, MN, that fabricates custom prototypes and low-volume parts globally, commissioned an independent market assessment, which estimates that the size of its specific market (prototyping and low-volume manufacturing using injection molding and CNC machining) is $14.7 billion in the U.S. alone (Hepp, 2013). On the virtual side of the spectrum, ANSYS, Inc. (Canonsburg, PA), which provides FEA, CFD, and other simulation software to 96 of the Forbes 500 companies, estimates that the virtual prototyping global market will grow to $20 billion in the next five years (Palaniswamy, 2014).

It is estimated that in the development of new products, 40-46% of resources are invested in products that ultimately are cancelled or unprofitable (Cooper, 1993). A continuing Product Development and Management Association (PDMA) study, which supports this data, found that industry-wide product success rates consistently remain below 60% (Barczak et al., 2009). Prototyping is a vital phase in the development of new products, and it has been shown that the greatest portion of sunk costs in the product design process typically occurs during the prototyping phase (Cooper, 1993). Consequently, a systematic tool to assist design teams' prototyping efforts could be beneficial in mitigating improper use of time, money, and other resources.

Compared with concept generation, product architecture, design selection, and manufacturing, for which numerous methodologies have been developed and experimentally evaluated in efforts to augment the design process (Dodgson, 2005; Krishnan & Ulrich, 2001; Kelley, 2001; Schrage, 2000; Ruffo et al., 2007), there is a relative dearth of literature on approaches for strategically planning prototyping activities

(Camburn et al., 2013). Product development and prototyping in particular are highly *project-specific*, in that the unique circumstances of each design scenario and design team likely dictate how/when/why decisions are made. The diverse nature of real-world product development efforts offers a plausible explanation for the lack of documentation for universal prototyping methodologies. Most recently published attempts to organize prototyping activities focus on management logistics aspects such as lead times, budgets, and project efficiency, rather than the actual processes involved in transforming a concept into a final product (Christie et al., 2012); however, there are several relevant engineering methodologies that concentrate on a tactical approach for prototyping.

A *prototyping strategy* refers here to *the set of choices that dictate the actions that will be taken to accomplish the development of prototype(s)* (Moe et al., 2004). A general prototyping strategy (such as "one should prototype multiple concepts early") leads to a *project-specific* prototyping strategy (such as "prototype concepts A, D, and E by week #3"). The next section presents the foundations and current state-of-the-art that provide the basis for creating an engineering approach to prototyping strategy development.

2.1 Engineering Approach

Otto and Wood (2001) provide a foundation for an engineering approach to prototyping strategy in the form of a basic method for designing physical prototypes, including a case study that implements this method, and an eight-step design procedure to be used as a "skeleton checklist" for systematic *physical* prototype creation. In summary, the procedure asks designers to consider the following:

- the purpose(s) and functionality of the prototype in the context of customer needs;

- the physical principles that need to be understood (and how they will be measured) in the testing of a potential physical model;
- if the prototype will be completely or partially functional, as well as full-size or scaled;
- if the prototype will be produced using actual materials and fabrication methods of the final product, or what other options are available (including rapid prototyping).

Otto and Wood also give guidelines for prototype development to be used in conjunction with this prototype design procedure, with the goal of saving time and preventing wasted resources, as well as a sample template for recording prototype-planning decisions (2001). Additionally, they cover analytical (virtual) and physical prototyping techniques and appropriate testing procedures to ensure that physical models satisfy design requirements. The authors acknowledge that virtual modeling is important in the prototyping process, but they recommend that designers must ultimately develop and test *physical* prototypes for the successful instantiation of design concepts, which requires obtaining customer feedback and demonstrating design requirements in addition to determining feasibility, scheduling, and interfacing between subsystems. Although prototyping strategy is not the main focus of Otto and Wood's textbook, they establish the initial framework for subsequent prototyping strategy methods (Moe et al., 2004; Christie et al., 2012), which are detailed in the next two sections.

2.1.1 Quantitative Prototyping Strategy Method

Recently a team of researchers from The University of Texas at Austin, Singapore University of Technology and Design, Georgia Institute of Technology, and U.S. Air Force Academy presented generalized methodologies for developing *project-specific* *prototyping strategies* (Camburn et al., 2013). This methodology simply translates the context of a specific design problem into prototyping decisions, yielding a project-specific prototyping strategy. In other words, the prototyping strategy formation methodology uses the independent variables of a design problem (e.g. available budget/time, difficulty in meeting design requirements, and designer's experience) in order to determine dependent prototyping strategy variables (e.g., number of prototypes to build, prototype scaling, and subsystem isolation). These dependent strategy variables, representing many critical prototyping decisions, were amalgamated from heuristics for prototyping best practices outlined by Moe (2004), Christie (2012), and Viswanathan (2012). This prototyping strategy formation method, illustrated in Figure 5, provides a systematic framework to translate independent context variables into dependent prototyping strategy variables in the following four steps:

1. Predict how many iterations each concept requires to satisfy design requirements by calculating Uncertainty, U, with the equation:

   $$U = \frac{\left(\frac{R_{eq}+D}{2}\right)}{E_x} \quad (1)$$

   (where E_x = designer's experience, D = design requirement difficulty, and R_{eq} = design requirement rigidity). Uncertainty is intended to be roughly proportional to the number of iterations required to meet design requirements.

2. Determine appropriate prototype scaling, subsystem isolation, and functional relaxation for each iteration of each concept using diagrammatic flowcharts.

3. Quantitatively determine which concepts to prototype in parallel, based on equations for available budget and time.

4. Document the resulting prototyping strategy.

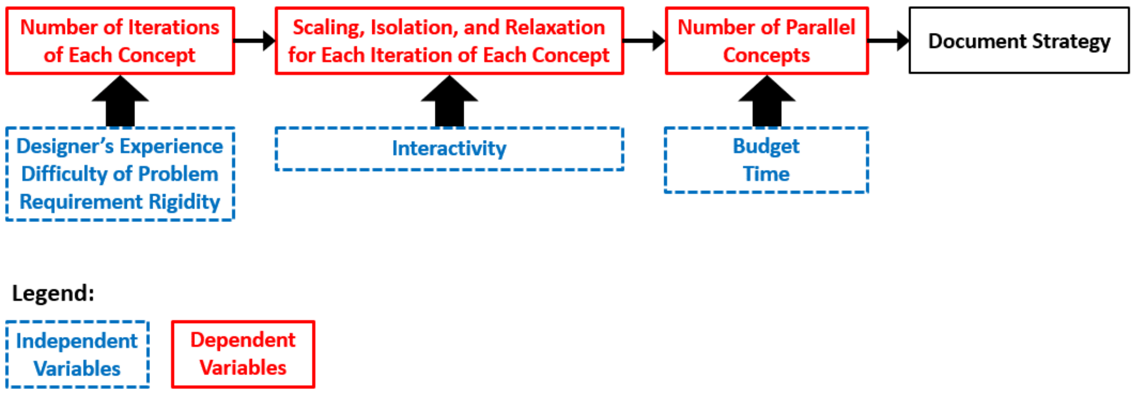

Figure 5: Flowchart of Prototyping Strategy Method (Camburn et al., 2013)

Using this quantitative methodology results in a practical prototyping strategy (example pictured in Figure 6), in which for every iteration of every parallel design concept, a designer must decide whether:

- Subsystem(s) will be isolated or integrated,
- Prototype will be full-size or scaled,
- Design requirements will be relaxed or rigidly enforced.

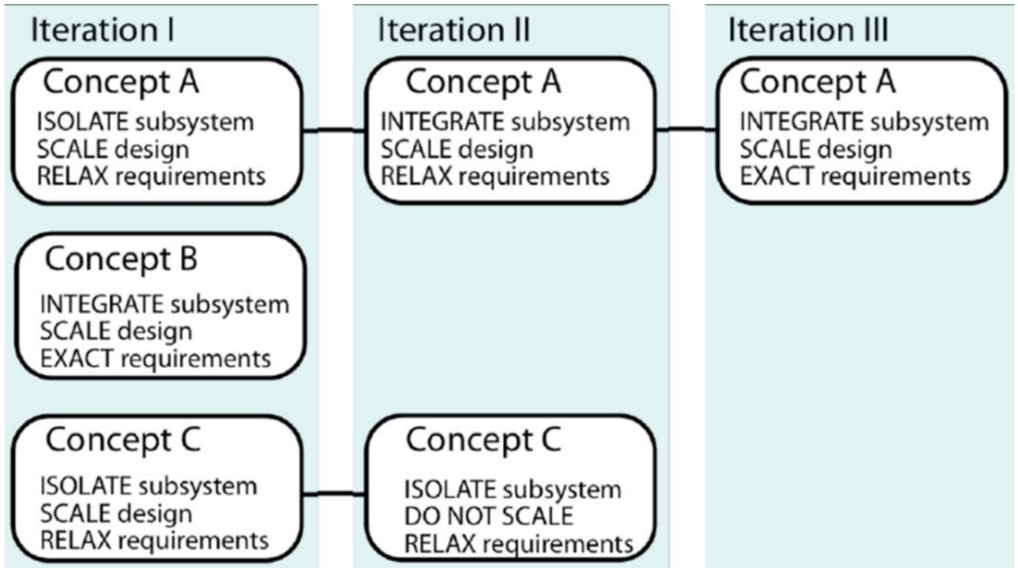

Figure 6: Example Project-Specific Prototyping Strategy (Camburn et al., 2013)

The above methodology was previously experimentally evaluated in a controlled design environment using primarily mechanical engineering students (Camburn et al., 2013). The published experimental results indicate using the prototyping strategy formation method above is positively correlated with early-stage design success. Thus, implementing this method can potentially improve design performance while increasing the likelihood of staying within budget and time constraints. The need for more comprehensive prototyping planning and this ground-breaking research on an engineering approach to prototyping strategy formation both motivate and shape the new work presented in this thesis.

2.1.2 Heuristics-based, Qualitative Prototyping Strategy Method

The latest version of the prototyping strategy method described above was designed by the same multi-institutional team, but was led by Dunlap and assisted by the author of this thesis. An experimental study showed the previous method was not as clear-cut, time-efficient, and intuitive as originally envisioned (Dunlap et al., 2014).

Addressing the quantitative nature of the previous method provided a principle avenue for its improvement. For example, the novel approach of calculating uncertainty (the inverse of certainty) using Equation (1) above in order to determine the number of iterations of a single concept versus the number of parallel concepts proved to be somewhat unintuitive or arbitrary. The logic behind this reasoning was that high uncertainty in meeting design requirements necessitates more iterations for a single concept; whereas, when uncertainty is low, a team is freer to explore the design space and more inclined to pursue multiple concepts simultaneously (Camburn et al., 2013). The design team for this new prototyping strategy method decided that replacing the half-dozen equations of the previous method with a *heuristics-based approach* would significantly simplify and streamline the instrument for guiding prototyping decisions (Dunlap et al., 2014). This shift from a quantitative method towards a more qualitative method enables a more flexible approach to developing a strategy on behalf of the designer and takes considerably less time to implement than the previous method.

In practice, a methodology for prototyping strategy should be generally applicable, since every design problem (and design team) is unique. With this in mind, the new method is designed to allow consideration of the designer's experience with strategic research-based heuristics. The tool guides a strategy that covers a broad range of concerns a designer may have when prototyping. Experimental assessment (described below) shows that the new method increases efficiency and effectiveness in the prototyping process; therefore, it is applicable to a broader range of design problems than the previous method (Dunlap et al., 2014). Specifically, this tool contributes a Likert-scale assessment of context to guide designers in translating context variables into prototyping strategy variables (decisions). The heuristics for each strategy variable in this methodology are based on synthesis of the empirical and theoretical research findings, which are discussed in detail in Chapter 3. The six strategy variables for prototyping (Dunlap et al., 2014) are summarized as follows:

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. Parallel concepts permit more rapid breadth-first exploration of the design space and may be explored when cost permits.

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." The strategy encourages the design team to explore multiple iterations when feasible.

3. **Scaled or full system** – 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. A scaled model may be much lower in cost and allows rapid iterations.

4. **Subsystem isolation or integration** – Often a subsystem of a design concept can be prototyped and evaluated in isolation. When it is relatively difficult to construct the full system, or when the team perceives the need to understand a critical subsystem fully, and the team is confident that sufficient information is obtainable from building and testing an isolated subsystem, a subsystem prototype can be used.

5. **Relaxation of design requirements** – Prototypes may be built with "relaxed" design requirements to simplify the process. By carefully constructing a test that may not meet full system requirements, but does in fact capture some critical aspects of system function, the design team can determine potential

benefits or drawbacks of a design without investing an unnecessary amount of effort or resources to the build.

6. **Physical vs. virtual models** – Chapter 1 of this thesis examines the differences between types of models. One improvement over the previous method is the inclusion of this strategy variable.

As an improved alternative to the quantitative approach of the previous method, Figure 7 (below) shows the new method that uses Likert-scale answers to questions that embody empirically validated heuristics in the six multi-point prompts of the strategy tool. Each strategy variable is determined by averaging the Likert response to the multi-point prompts. With the understanding that material and time allotments are not always explicit or pre-determined, this heuristics-based approach accounts for the designer's experience and allows human discretion in these choices, while at the same time providing a guide based on known best practices.

	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.**	**Do 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.					

Figure 7: Likert-Scale Matrices for Determining the Six Prototyping Strategy Variables (Dunlap et al., 2014)

The new tool was experimentally assessed in two environments: (1) a controlled experiment in which volunteers completed a given prototyping design challenge, and (2) an open-ended capstone design class with a variety of sponsored design projects. In the controlled experiment, entitled "Going the Distance," 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. The design problem prompted teams to build a freestanding triggered device to propel an 8.5x11 inch sheet of paper the farthest distance with maximum repeatability. Results from the controlled study indicate the method did improve students' performance across a number of assessment metrics. It was 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.

In conjunction with the controlled study, the method was introduced to a capstone design class at the U.S. 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. Details of this method and the experimental results are available in (Dunlap, 2014).

2.2 Virtual versus Physical Prototyping Strategy

The research reported in this thesis supplements the existing prototyping strategy formation method outlined above by adding a new prototyping decision – whether a prototype will be virtual or physical. The goal of this work is development and evaluation of a systematic decision tool that guides the choice between physical or virtual (hardware vs. software) prototyping for engineering design problems.

Excluding the heuristics-based prototyping strategy method (described above) that was developed concurrently and in collaboration with the work presented in this thesis, no pertinent research was located addressing a structured method aiding engineering designers in deciding between virtual and physical prototyping. However, Ulrich and

Eppinger (2000) detail the practicality of considering virtual versus physical prototyping in a generalized description of the prototyping process. By charting prototyping decisions in two dimensional space (Figure 8), they provide a graphical decision making tool based on the relative accuracy and expense of virtual versus physical prototypes. Ulrich and Eppinger stipulate that comprehensive virtual prototypes are generally not feasible, and that the most cost effective model should ultimately be pursued (2000). While this work offers an interesting approach for comparing prototyping options and guidance for choosing the most appropriate option in obvious situations (e.g., a virtual prototype will provide significantly higher accuracy while requiring much less effort compared to a physical prototype, and vice versa), for many, if not most, design scenarios, more information is needed to make a definitive choice between prototyping options.

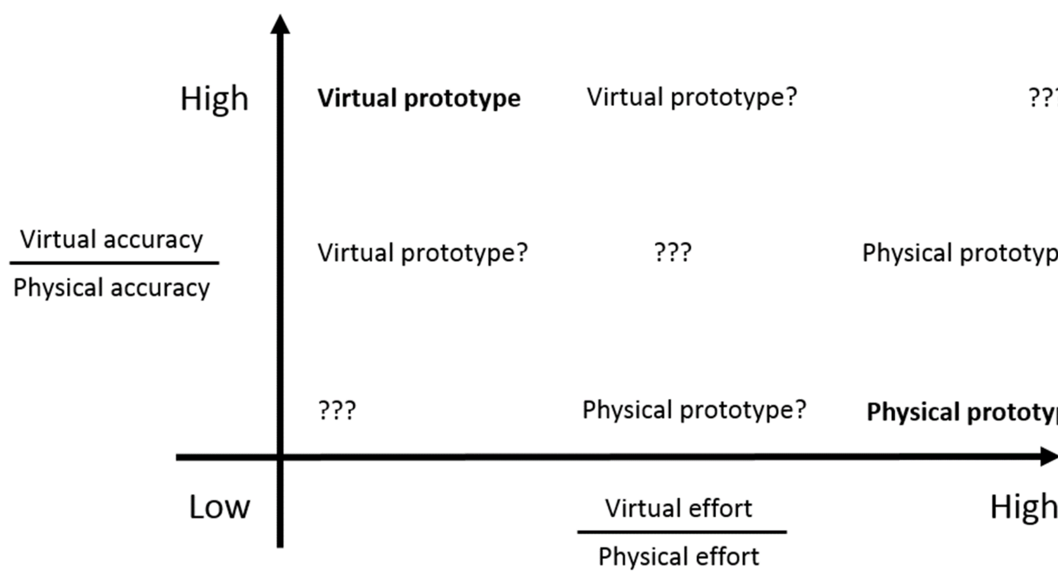

Figure 8: Decision Trade-off between Virtual and Physical Models (adapted from Ulrich and Eppinger, 2000)

The benefits attributed to virtual prototyping have been examined. For example, Clin et al. demonstrate the adaptability and uniqueness of virtual modeling in the design of intricate, one-of-a-kind prototypes for braces used to treat spinal abnormalities due to scoliosis (2007). Goldstein et al. also describe how physical models of complex 3D objects that normally take weeks to embody can be virtually modeled in a matter of hours in an example clothing design scenario (2009). Additionally, Wen details how virtual FEA models can be correlated with real-world field test data to produce an expanded validation model, which can potentially aid in the identification of faulty structural members prior to failure in service (2008).

In an experimental study to assess the quality of final designs for a computer mouse, Wojtczuk compared CAD models created by one group of students using Rhinoceros® with physical models created by a second group of students that used polystyrene blocks and an assortment of shaping tools, including hot-wire cutters. A panel of 20 judges, including five professional designers, ranked the CAD models higher in terms of aesthetics, originality, and marketing; however, no difference was observed among the two groups for the criterion of functionality (2010). Another design study (Bonnardel & Zenasni, 2010) sought to compare the quality of models for a computer mouse, but with three experimental conditions: (1) physical modeling, (2) CAD modeling, and (3) modeling using a digital design tool incorporating multimodal haptic interfaces called *Touch and Design* (T'nD). T'nD allows users to create preliminary digital forms with CAD software and make modifications using two separate haptic interfaces, a 6-DOF scraping tool similar to a rake used for clay modeling and a sanding tool that conforms to the curvature of the virtual surface for finishing operations, both of which simulate real-world subtractive manufacturing techniques (Cugini & Bordegoni, 2007). Analysis of the computer mouse models produced by 30 masters students for the three experimental conditions in the design study proved inconclusive, and the researchers posit that the prior training in using T'nD provided to the third group did not sufficiently familiarize them with this new modeling technique; consequently, participants focused more on using the novel T'nD system in practice than they did on creatively addressing the design problem (Bonnardel & Zenasni, 2010). Furthermore, Sefelin evaluated the use of low-fidelity physical (paper-based) and virtual prototypes in a controlled experiment in which participants designed both a touch screen ticket machine and an original calendar system. The results indicate that performance was about 15% higher for the virtual prototyping condition, but the results were not statistically significant (2003).

Obtaining meaningful experimental results comparing virtual and physical prototypes presents a unique yet difficult challenge. Assessing a prototype's quality can be highly subjective, especially for attributes that are not easily quantified, such as aesthetics, ergonomics, and usability. The inherent difficulty in evaluating the performance of a prototype composed of 0's and 1's relative to a real prototype may provide further explanation for the lack of definitive experimental results and structured methods for steering the choice of type of prototype.

2.3 SUMMARY

"Prototyping may be simultaneously one of the most important and least formally explored areas of design," (Camburn et al., 2013). Although prototyping is an integral phase in the development of new products, relatively few methodologies have been published on structuring prototyping activities compared to other aspects of the product design process. Additionally, most recently published attempts to organize prototyping activities focus on management logistics aspects, such as lead times and budgets (Christie et al., 2012). However, a novel, heuristics-based approach for formulating prototyping strategies (Dunlap et al., 2014) provides the foundation and direction for the continuing evolution of an engineering framework for prototyping. The next chapter presents the development of a heuristics-based methodology for guiding the choice between virtual and physical prototypes, which is intended to supplement and build upon the work of Dunlap et al. (2014). In addition, the design of the pilot experimental study used to test this heuristics-based approach are detailed in the next chapter.

Chapter 3: Research Methodology

Choosing between a virtual or physical prototype is a critical decision in the product design process. Selection of the type of prototype(s) will most likely be determined based on budget and time constraints as well as the experience of a design team. A structured prototyping strategy formation method addressing the choice of virtual or physical prototypes can be a useful addition to the prototyping strategy formation tool developed by Camburn et al. (2013) described in the previous chapter. A major contribution of this work is the use of a heuristics-based approach, rather than the strictly quantitative approach of prior work. The new virtual-vs-physical module of the prototyping strategy formation method includes a newly developed tool employing Likert-scale questions.

3.1 Heuristics-based Approach

The modern scientific term *heuristic* was coined by seventeenth-century French philosopher Rene Descartes, and roughly translates to "discovery aid" (Yilmaz, 2010). In engineering, a heuristic is an experience-based method that can be an aid in solving design problems or making decisions, in general (Altshuller, 1984). Heuristic methods are particularly used to quickly arrive at a solution that is reasonably close to the optimal solution; thus, a heuristic is considered to be a mental shortcut, "rule-of-thumb," educated guess, or intuitive judgment (Nisbett et al., 1983). The use of heuristics as cognitive strategies does not guarantee successful solutions, but they derive their validity from the usefulness of their results (Cox, 1987). Technical problems can be solved by utilizing principles previously used to solve similar problems in other inventive situations (Altshuller, 1984), and these principles can be generalized into best practices. Heuristics can provide an effective starting point for generating conceivable solutions in a design space, which consists of all possible designs (Newell & Simon, 1982). By using specific, design context heuristics, designers can more effectively explore a particular design space by viewing it from a different perspective. In the application of a heuristic method, a designer can actively and dynamically construct new solutions, rather than replicating previous solutions for similar problems (Yilmaz, 2010).

A number of projects have explored heuristic observations of potential best practices in prototyping. Viswanathan et al. (2012) conducted an in-depth tracking study of graduate design students to determine beneficial practices of prototyping. 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 (Drezner, 2009):

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. Thomke and Bell (2001) find that significant savings can be achieved through multiple low fidelity prototypes. Dahan and Mendelson (1998) add that parallel designs succeed in time-constrained environments while sequential designs succeed in cost-constrained environments. They provide equations that leverage basic assumptions about 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. Yang (2005) shows that time spent testing is positively correlated with outcome and conversely, time spent fabricating is negatively correlated with outcome. Kershaw, et al. (2011) found that teams that 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. Jang (2012) confirms in another, independent empirical study that more successful teams prototype earlier and more often throughout the entire process. Furthermore, Haggman, et al. (2013) 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. Additionally, Dow and Klemmer (2011) 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.

In Chapter 2, the prototyping strategy methodology pioneered by Dunlap et al. (2014) derived heuristics for each strategy variable based on synthesis of the empirical and theoretical research findings described above in conjunction with the heuristics for prototyping best practices outlined by Moe (2004), Christie (2012), and Viswanathan (2012), which 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.

No heuristics for best practices for *virtual-vs-physical* prototyping were found. Most recent product design literature makes the distinction between types of prototypes and recommends that designers should consider using virtual models in the prototyping process (Schrage, 2000; Otto & Wood, 2001; Thomke, 2003; Drezner, 2009), but offers only minimal guidance in the decision making process of selecting one type of prototype over the other.

In addition to heuristics, no structured methodologies pertaining to choosing physical or virtual prototypes were uncovered; however, Ulrich and Eppinger's two-axis graphical decision-making tool (Figure 8), which plots suggested choices based on the *accuracy* of virtual models relative to physical models versus the *effort* of virtual models relative to physical models, provided the starting point for developing a heuristics-based instrument. Following the logic of the methodology for project-specific prototyping strategies presented by Camburn et al. (2013), the context of a unique design problem can be translated into prototyping decisions. For a particular design problem, prototype *accuracy* and prototyping *effort* are independent design context variables that can be used to derive dependent prototyping strategy variables (i.e., decisions), such as whether prototype(s) will be virtual or physical. For simplicity, prototyping *effort* can be characterized as the overall *time* needed to create and test a prototype. A heuristics-based approach can provide an intuitive, experience-based method for qualitative comparison of the relative *accuracy* and *time* required for physical modeling with respect to virtual modeling, as opposed to a quantitative approach, which may be unintuitive or arbitrary if assumptions/equations for calculating accuracy and time are not well defined or available. Dunlap et al. (2014) report that their qualitative prototyping strategy method offers designers a simpler and more flexible approach to developing a strategy and takes considerably less time to implement than the previous quantitative method proposed by Camburn et al. (2013), on which it is based.

3.2 Design of Heuristics-based Instrument

While the proliferation of virtual prototyping in recent decades can be attributed to its potential to reduce product development project *cost*, by allowing iterating and testing to be performed faster and earlier in the design process when compared to physical prototyping (Barbieri et al., 2013), recent research suggests that typical virtual prototyping activities can be costly in practice (Fixson & Marion, 2012) and account for up to 75% of total project development cost (Marion & Simpson, 2009). Because the cost of producing prototype(s) can be difficult to accurately estimate and may not always be clear-cut, cost was not chosen as an independent design context variable for this virtual-vs-physical decision making tool. Nevertheless, cost is driven, in part, by the *number of iterations* of a final prototype. A primary advantage of virtual modeling is the ability to rapidly iterate designs, and the anticipated *number of iterations* (a dependent prototyping strategy variable) should be considered when choosing type of prototype for this reason. Although *number of iterations* and *virtual-vs-physical* prototyping are strategic decisions, these two dependent variables are inherently coupled, as the choice of type of prototype will likely be influenced by how many iterations are needed to satisfy design requirements in practice. In anticipation of future work on their prototyping strategy methodology, Dunlap et al. (2014) ask the question: "Is the order of the strategy development correct?" More specifically, should a design team decide if a prototype will be virtual or physical after considering how many iterations are needed and/or how many parallel concepts will be pursued? Chapter 7 addresses this question as well as the need for human-product interaction heuristics. A primary advantage of physical prototyping is hands-on, tactile engagement with design concepts, and incorporating the importance of human-prototype interaction as a heuristic in decision making could be the next step in the evolution of a virtual-vs-physical prototyping strategy tool.

Ultimately, *accuracy*, *time*, and *number of iterations* were selected as prototyping strategy variables that would guide choice in the decision-making instrument presented in this thesis. In order to employ a heuristics-based approach, a survey format developed by Rensis Likert (1932) was chosen for this instrument. A Likert-scale is a psychometric survey that uses a fixed-choice response format for the purpose of measuring attitudes or opinions (Bowling, 1997; Burns & Grove, 1997). By recording an individual's responses to multiple statements on an ordinal scale, typically from "Strongly Disagree" to "Strongly Agree," a Likert-scale measures degrees of opinion, including no opinion (e.g., "Neutral"), rather than binary yes/no responses, thereby providing data that is more amenable to statistical analysis (McLeod, 2008).

Assigning numerical weighting for Likert-scale responses (e.g., -2 = "Strongly Disagree", 0 = "Neutral", +2 = "Strongly Agree") allows quantitative evaluation of respondents' opinions for qualitative statements. Additionally, the sum or average of all responses, if positive or negative[4], can be used to guide choice between two options, such as virtual or physical prototyping. For example, the Likert-scale developed by Dunlap et al. (2014) is designed to allow consideration of a designer's experiential knowledge with strategic research-based heuristics in order to determine strategy decisions based on the average of Likert responses to a multi-point prompt (Table 2).

Fixed-Choice Ordinal Scale →

Numerical Weighting →

		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
		-2	-1	0	+1	+2
a)	Virtual prototype(s) will require less time than building physical prototype(s).					X
b)	Virtual prototyping will be sufficiently accurate to model critical physics, or interfaces and/or help evaluate critical design requirements.		X			
c)	A CAD model is needed for advanced engineering analysis (FEA, CFD, etc.) or for manufacturing purposes.				X	
d)	There is sufficient time & budget to construct both virtual & physical prototypes.			X		
	Use the average of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive average would suggest pursuing virtual prototyping).	← Physical				Virtual →

Average = +0.5

Table 2: Example Application of Virtual vs. Physical Prototyping Likert-scale Decision Making Tool (Dunlap et al., 2014)

Table 2 above represents one step of the six-step overarching prototyping strategy guide (PSG) pioneered by Dunlap et al. (2014) that is detailed previously in Section 2.1.2. The PSG was developed concurrently and in collaboration with the work presented in this thesis; however, this work focusses primarily on the development of an instrument

[4] Section 5.5 discusses the scenario when the sum/average of Likert-scale responses equals zero.

for steering the choice between physical or virtual prototypes. In consideration of evaluating its efficacy in a pilot experimental study, the Likert-scale created specifically for this instrument (pictured in Table 5 in Chapter 4.4 below) addresses designers' perceptions of the following:

- ratio of *accuracy* between virtual and physical models,
- ratio of *time* between virtual and physical models, and
- *number of iterations* to address the relative ratio effort/time of virtual compared to physical models.

Instead of asking designers to calculate *accuracy*, *tim*e, and *number of iterations* for both virtual and physical prototypes, this heuristics-based approach directs designers to qualitatively compare virtual-vs-physical models for each of these strategy variables based on their experience. A Likert-scale survey provides an intuitive and convenient format for recording respondents' subjective opinions for statements based on objective heuristics, thus ascribing quantitative values to qualitative perceptions. By easily calculating a single numerical value for the sum or average of Likert responses, engineers will likely feel more confident in making a decision on whether their prototypes will be physical or virtual, compared to ad hoc efforts. The remainder of this chapter details the design of a pilot experimental study to evaluate this heuristics-based instrument.

3.3 Design of Pilot Experimental Study

The pilot experimental study reported in this chapter tests a heuristics-based, Likert-scale tool for choosing between virtual or physical prototypes. A classical four-bar linkage design problem was chosen for a controlled experiment based on practical considerations. The feasibility of prototyping four-bar linkages both physically and virtually, with basic materials and easy-to-use software, enables testing of the new virtual-vs-physical module of the prototyping strategy formation method.

3.3.1 Pilot Experiment Design Problem

The most difficult aspect of designing an experimental study to test a virtual-vs-physical prototype decision making tool was selection of a practical design problem. In order to properly evaluate a decision making tool, the optimal choice between multiple options must not be obvious. Consideration of this requirement along with the feasibility of potential prototyping techniques available, both virtual and physical, resulted in a wide variety of preliminary design problems, including the following:

- an apparatus to drop an egg without breaking from a predetermined height;
- a catapult (or other launching mechanism) to repeatably hit a target with a projectile;
- a basic structure to span a certain distance or support a specific load.

Design problems particularly applicable for virtual modeling techniques were also explored in the creation of a suitable experiment. For example, minimizing the time required for an object of varying cross-sectional profile to drop through a column of liquid can be modeled virtually using CFD as well as physically with basic materials, and the optimal solution is not initially apparent to an undergraduate engineering student. However, virtual prototyping software, such as CFD and FEA, can have prohibitively high licensing fees and learning curves needed for basic proficiency. For this experiment, four-bar linkages were deemed the most logical choice, in terms of prototyping techniques available and logistical concerns. A four-bar linkage has basic two-dimensional geometry for each individual link, and coupled with four revolute joints that connect pairs of links, the result is a highly interactive yet relatively simple 1 DOF system. Upper division mechanical engineering undergraduate students have basic familiarity with linkage design; thus, they are likely not intimidated by prototyping a four-bar linkage, even with no prior prototyping experience. The simplicity of components and the interconnected nature of four-bar linkages offers viable options for physical prototyping using basic materials and for virtual prototyping using easy-to-use software in a reasonable amount of time. These options are described in detail below.

3.3.2 Pilot Experiment Performance Metric

After selection of four-bar linkages, which are classically used in mechanical engineering, for the test design problem, a performance metric was derived to provide an objective for the design problem. In terms of a performance metric, a line's "straightness" can be quantified as the ratio of deviation in one dimension relative to the deviation in an orthogonal dimension, e.g., $\Delta x/\Delta y$ (Figure 9). In other words, maximizing a line's trajectory in the $\boldsymbol{x}$ direction, while minimizing its trajectory in the $\boldsymbol{y}$ direction ultimately results in a straight line once deviation in the $\boldsymbol{y}$ direction reaches zero ($\Delta x/\Delta y \rightarrow \infty$), or if travel in the $\boldsymbol{x}$ direction is significantly greater than that in the $\boldsymbol{y}$ direction (i.e. a line segment with virtually no slope).

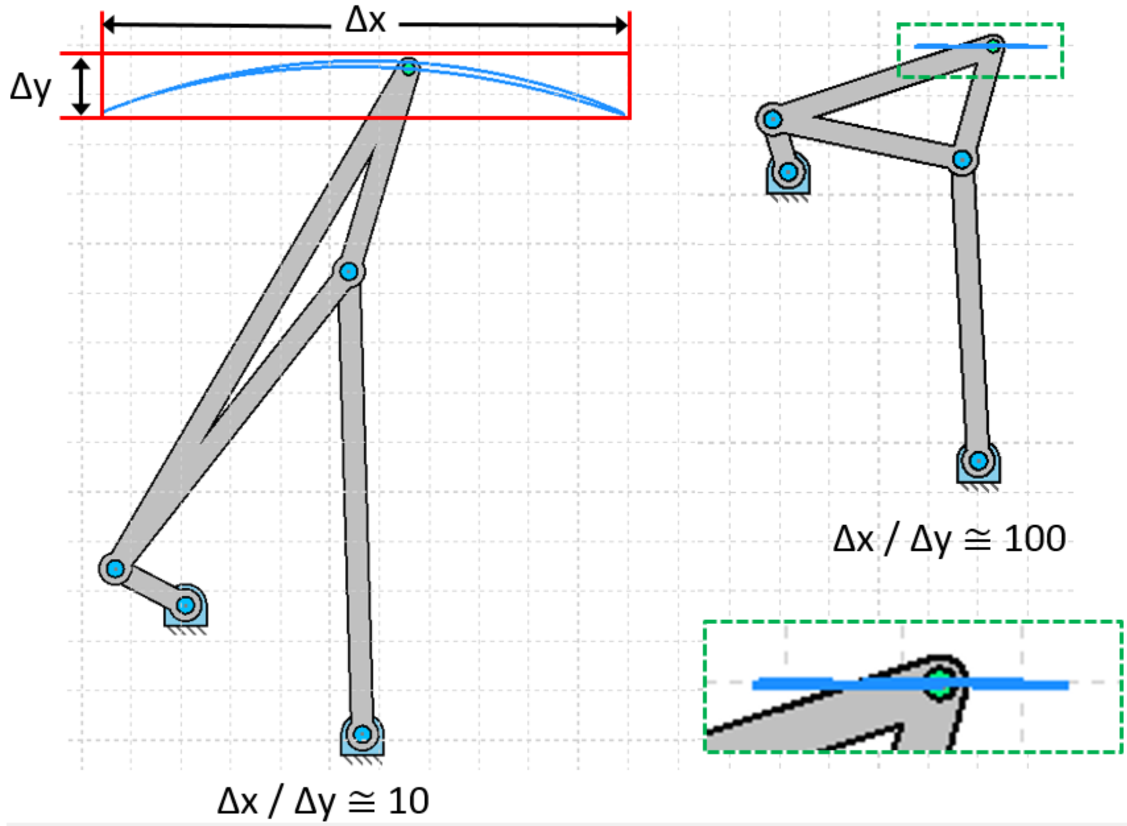

Figure 9: Depiction of Performance Metric - Maximize $\Delta x/\Delta y$ for Line Drawn (in Blue)

Maximizing $\Delta x/\Delta y$ as a performance metric proved to be more straightforward in presentation of the design problem and easier to measure than the other considered performance metrics for this design problem, such as deviation of four-bar linkage trajectory from a predefined, arbitrary arc or curve. In practice, the path of a line drawn by a four-bar linkage with a *triangular*, rigid coupler link, as opposed to a *linear* coupler link, can be significantly straighter. Figure 10 illustrates how a triangular coupler link versus a linear coupler link can produce a relatively straighter line in two otherwise identical four-bar linkages, in terms of link lengths. All participants in the pilot study (detailed below in this chapter) were informed that a triangular[5] coupler link is advantageous in maximizing the performance metric ratio for this design problem, and all provided examples and demonstrations of virtual and physical four-bar linkages included triangular coupler links.

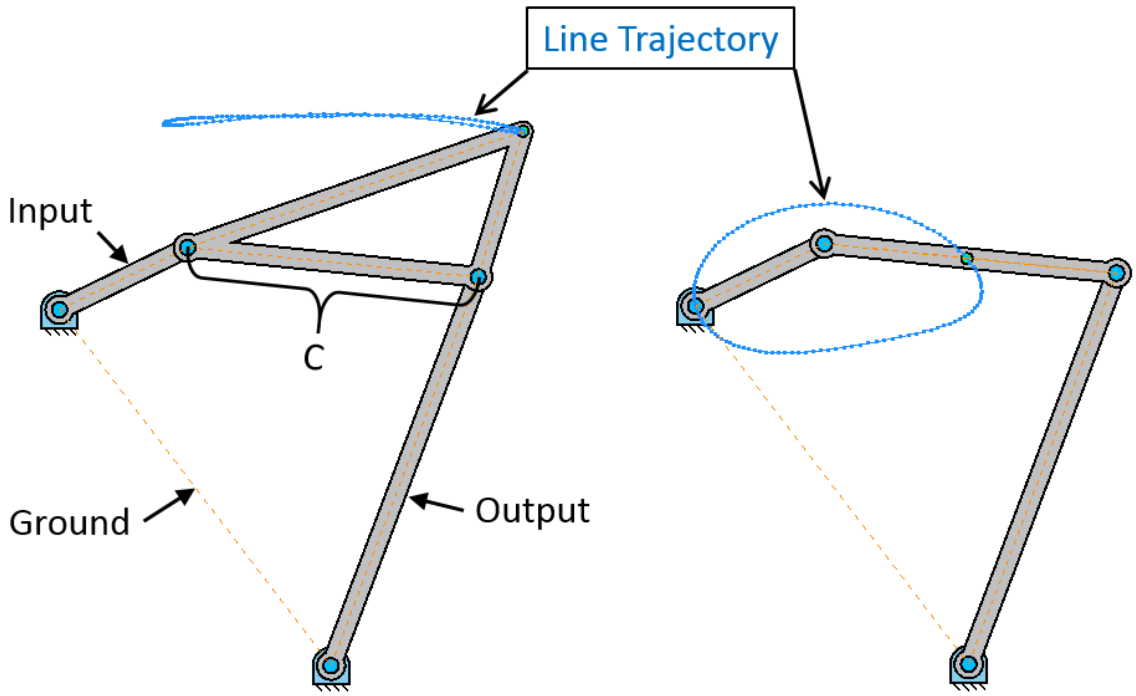

Figure 10: Lines Trajectories for Triangular (Left) vs. Linear (Right) Coupler Links with Identical Input, Output, Ground Link Lengths and Coupler Length C

3.3.3 Pilot Experiment Virtual Prototyping Software

A critical aspect of this or any virtual-vs-physical prototyping experiment is the choice of software for virtual modeling. For this four-bar linkage pilot study design problem, virtual prototyping software must be comparable to physical prototyping techniques (covered below) in terms of:

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[5] The term triangular is used in this thesis for convenience, but was not used in the pilot study (detailed below) to prevent bias in creation of coupler link geometry for prototypes.

(1) prior experience needed – none;

(2) time to complete prototyping – less than 1 hour; and

(3) visualization and measurement of the performance metric – $\Delta x/\Delta y$.

After a careful search of available freeware, the best option to satisfy these three criteria was determined to be GIM®, a kinematic analysis program for planar mechanisms created by a research group at the University of the Basque Country in Spain (Petuya et al., 2011). The free (with registration[6]) GIM® software provides an interactive and relatively intuitive environment for the design and simulation of simple linkages. GIM® allows users to quickly create and modify links and joints, and display the resulting trajectory of a point (on the coupler link) on a four-bar linkage in order to visualize the performance metric ratio for this design problem. The simple, icon-based user interface (Figure 11) allows users with no prior experience to begin using GIM® and learn about its features on-the-fly. However, participants in this experimental study were given a brief (< 5 minute) GIM® tutorial to ensure that they had the ability to maximize the performance metric ratio by following the correct sequence of operations (the tutorial is detailed in Section 4.3 below).

[6] GIM® software, CompMech, Alfonso Hernández, Department of Mechanical Engineering, UPVEHU, www.ehu.es/compmech, Accessed September 20, 2013.

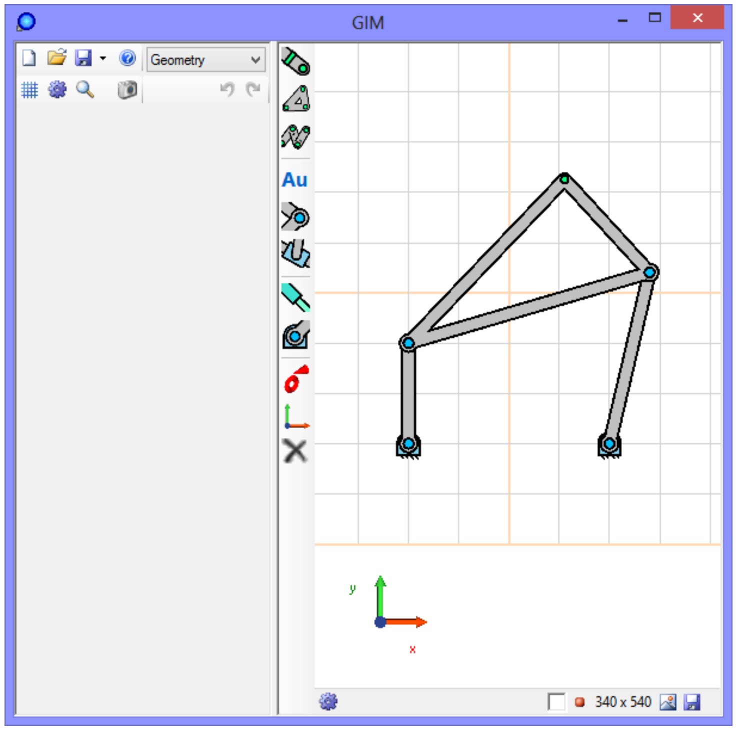

Figure 11: GIM® Software User Interface

3.3.4 Pilot Experiment Physical Prototyping Materials

The next step in the design of the experiment was determination of materials and tools to be used in physically prototyping a four-bar linkage. LEGO® construction blocks (The LEGO Group, Billund, Denmark), which are ubiquitous in undergraduate engineering education, were considered first. After preliminary experimentation, it was discovered that the fixed geometry of LEGO® blocks provides a finite amount of possible link lengths and joint positions, which severely limits the number of continuously rotating four-bar linkages that can be built from a reasonably sized LEGO® kit. In addition, ensuring that individual links could rotate freely with respect to one another proved to be overly complicated for the intent of the pilot study. Building a three-dimensional LEGO® structure (Figure 12), which is required to permit continuous rotation of a planar (two-dimensional) four-bar linkage, potentially distracts participants from the goal of maximizing the performance metric associated with line straightness. The additional time and effort involved in assembling a 3D LEGO® linkage (with a limited number of possible configurations) would provide an inherent advantage for GIM®-created virtual linkages that only require 2D geometric manipulation; thus, LEGOs® were eliminated from consideration.

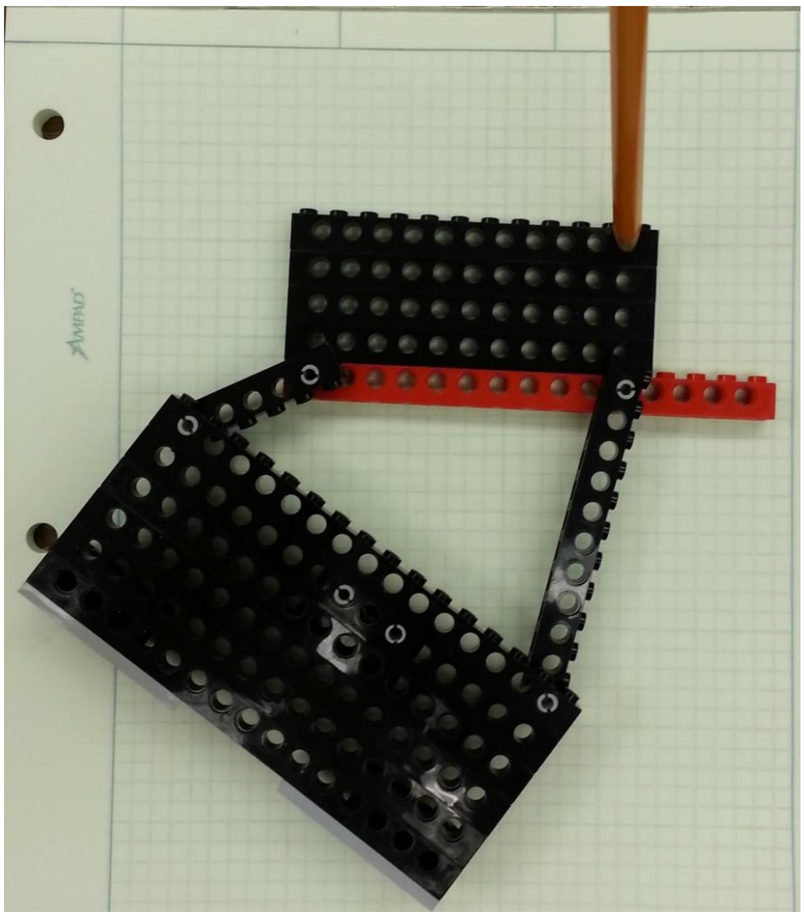

Figure 12: Four-bar Linkage Built with LEGOs®

Cardboard links and plastic joints were considered next as potential physical prototyping materials. A sample four-bar linkage was built with cardboard links connected via screw-inserts[7] for examination (Figure 13). The distance between the shoulder of the screw and the shoulder of the threaded insert was greater than the thickness of two cardboard links, which required the use of spacers in each joint. Without spacers, two links are free to move in the gap between the constraints of the screw and insert shoulders, resulting in an ineffective joint. The joining of links proved to be overly cumbersome as threading the screw into the insert, while simultaneously maintaining alignment of two links and four spacers sandwiched in between, required considerable dexterity and patience for the installation of each joint. In addition, cardboard lacked the rigidity needed for robust testing – deformation (bending and crumpling) readily occurred in links while attempting to rotate the assembled four-bar linkage.

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[7] Also known as "insert nuts." Examples available at http://www.mcmaster.com/#standard-threaded-inserts/.

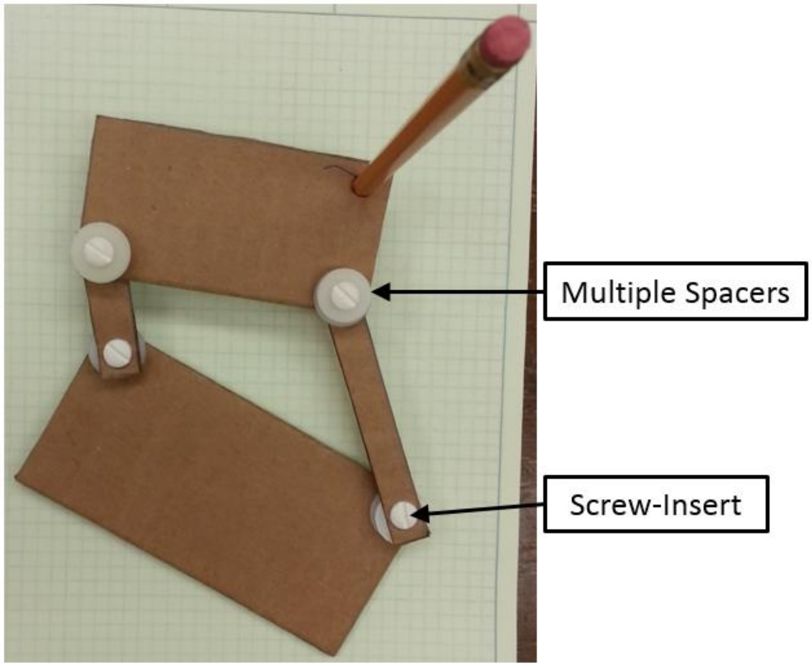


Figure 13: Cardboard Four-bar Linkage with Screw-Inserts and Spacers

The unsuccessful attempts at selecting suitable physical prototyping materials by building preliminary-model linkages, using LEGOs® and cardboard, highlight the importance of prototyping in the design process as a method to eliminate unviable options from further consideration. Ultimately, following a guideline for building physical models proposed by Viswanathan (2012) to "… *use commonly available parts (available in the immediate environment)*" led to the selection of physical prototyping materials. Leftover foam-board from the "Going the Distance" experiment, described previously in Section 2.1.2, was determined to be sufficiently rigid and workable for use as link material. Additionally, the 5 mm nominal thickness of the foam-board allowed the use of the previously mentioned screw-inserts (also found in the immediate environment) as joints. When fully tightened, the distance between the shoulders of screw and insert (Figure 14) is approximately 10 mm, thereby producing a "snug" joint between two foam-board links while permitting unimpeded rotation. Quite fortuitously, the roughly 7 mm diameter hole produced by a hand-held hole-punch provides just the right amount of clearance in which the screw-insert, with a ¼" (6.35 mm) nominal outside diameter, can rotate freely without any noticeable concentric deviation.

Figure 14: Screw-insert (Detachable Pin), Foam-board, Hole-punch for Four-bar Linkage Physical Prototyping

Next, in order to facilitate physical prototyping by reducing the amount of effort/tools needed, the threads of all inserts were drilled out with a ⅛" bit on a stationary drill press using freehand[8] technique. Removal of the threads (Figure 15) eliminated the need for screwdrivers to attach and detach the separate screw and insert parts in making joints, while still providing enough friction between internal mating surfaces of the two parts to keep the joint intact during light-to-moderate testing. Finally, every screw-insert (which will be called a *detachable pin* from here on) was manually checked to verify that

[8] Not recommended. Do not attempt.

it could easily be attached and detached by hand, before inclusion in a physical prototyping kit provided to participants in this pilot experimental study.

Figure 15: Close-up of Detachable Pins; Inserts with Threads Drilled Out (Bottom), Screws (Top)

3.4 SUMMARY

An engineering heuristic is an experience-based, rather than strictly quantitative, method that can be an aid in solving design problems or making decisions. We developed a heuristics-based tool that guides designers in choosing physical or virtual prototypes based on answers to Likert-scale questions in conjunction with the prototyping strategy methodology pioneered by Dunlap et al. (2014). Using this heuristics-based approach, designers take into consideration the relative accuracy and effort of virtual models with respect to physical models to provide guidance in the selection of the most appropriate prototyping technique. In order to test this Likert-scale decision-making instrument, we designed a pilot experiment in which participants were given the choice of either virtually or physically prototyping a four-bar linkage. This pilot experiment features a design problem with the objective of prototyping a four-bar linkage that maximizes the length of a line drawn in one dimension, while minimizing deviation in the orthogonal dimension. A requirement of the design problem was that the optimal choice between types of prototype should not be obvious. Thus, we chose GIM® software for four-bar linkage virtual prototyping along with foam-board and detachable pins for physical prototyping in this experiment. Chapter 4 details the step-by-step procedure presented to participants in this pilot experiment.

Chapter 4: Pilot Study Experimental Procedure

All 80 participants in this pilot experiment were junior or senior mechanical engineering students at The University of Texas at Austin, with at least basic familiarity with four-bar linkage design. All participants were recruited from an undergraduate design methodology course that has a prerequisite machine elements course in which linkage design is taught. Prior to starting the pilot experiment, each participant voluntarily signed an informed consent form as per Institutional Review Board (IRB) protocol[9] for human subject testing. Each participant was required to work individually for the entirety of the approximately 45 minute-long pilot experimental study, which is described in the next five sections, beginning with an introduction to the experiment.

4.1 Pilot Experiment Introduction

As shown in the experiment worksheet in Appendix A, the experiment began with a five minute introduction. During this time the difference between virtual and physical prototypes was defined. In addition, participants were shown both a graphical depiction and physical example of a four-bar linkage with a *triangular coupler link* (previously detailed). Next, Grashof's Law (Hartenberg & Denavit, 1964) was presented in order to inform participants of the condition necessary to achieve continuous rotation of the shortest link in a four-bar linkage, which is based on link lengths using the following equation:

$$(shortest\ link + longest\ link) < (sum\ of\ other\ two\ links) \tag{2}$$

This equation and examples were provided to participants to demonstrate link rotation relative to other links in a continuously rotating four-bar linkage, but participants were informed that they would not be required to perform any calculations pertaining to

[9] IRB Exempt status, study number 2012-09-0053

Grashof's Law. In retrospect, inclusion of Grashof's Law mainly serves a pedagogical purpose and should be optional in any future trials of a similar experimental study.

4.2 Participant Background Survey

Participants were then instructed to complete an initial Likert-scale survey (Table 3), and record their familiarity with four-bar linkages, experience using computer simulation software, experience building physical models, and preference of using software versus building physical models.

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly agree.
		-2	-1	0	+1	+2
a)	I have an understanding of four-bar linkages.					
b)	I have experience using computer simulation software (e.g., CAD, FEA, etc.).					
c)	I prefer to design using software, rather than building physical models.					
d)	I have experience building physical models.					

Table 3: Pilot Study Initial Survey

4.3 Demonstration of GIM® Software and Building Materials

Next, the participants were instructed in the steps for creating a virtual four-bar linkage using GIM® software (Petuya et al., 2011) software. Participants were provided a step-by-step demonstration of the sequence of six GIM® operations needed to create and modify a four-bar linkage, which are summarized as follows:

- In **Geometry** mode (default on start-up) – Figure 16:
    1. Select *Points* icon. Place 5 points in desired locations by single-clicking (5^{th} point is needed for 'triangular' Coupler link).

2. Select *Elements* icon. Create Input, Coupler, and Output links by single-clicking starting point and double-clicking end point.
3. Select *Revolute joint* icon. Create 4 joints by single-clicking 2 nodes (shared points) between links and 2 free-standing points, which automatically become fixed joints (Ground link is the invisible line segment between fixed joints).

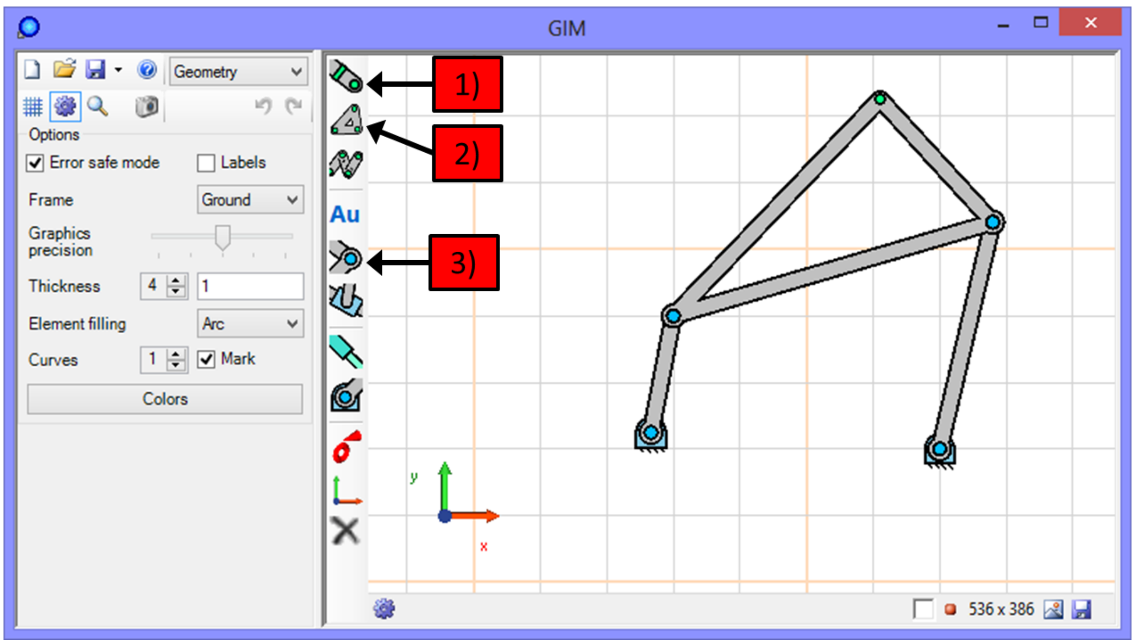


Figure 16: GIM® **Geometry** Mode for Creating 1) Points, 2) Links, and 3) Joints

- Choose **Motion** mode from drop-down box – Figure 17:
    4. Select *Absolute rotation actuator* icon. Single-click the Input link (shortest link which can freely rotate).

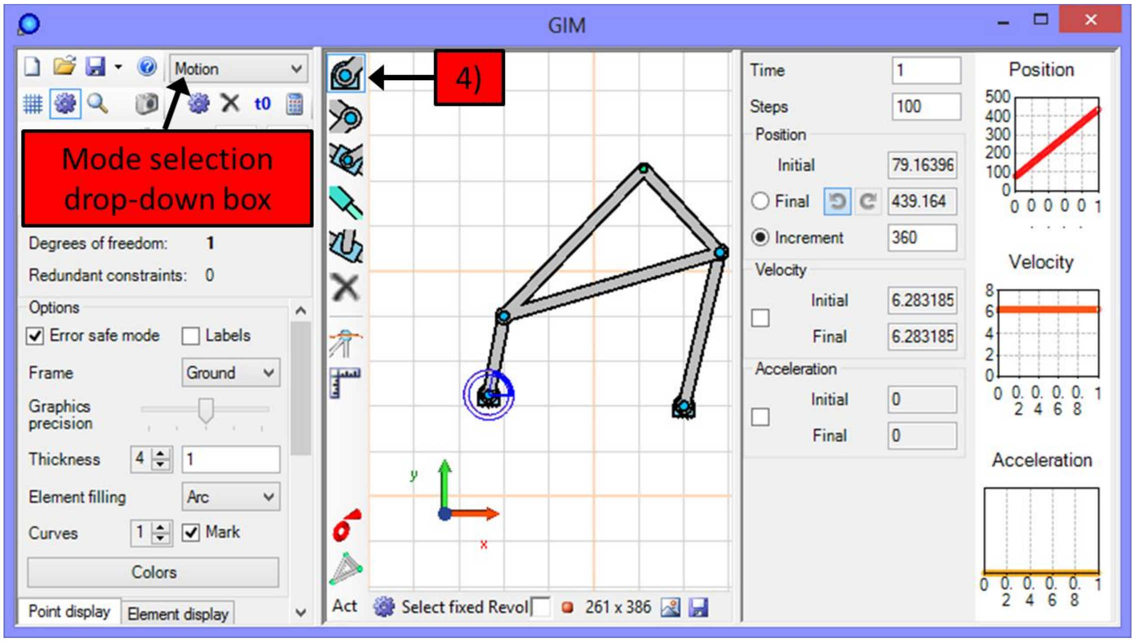


Figure 17: GIM® **Motion** Mode for Creating 4) Fixed Point of Rotation

- Choose **Synthesis** mode from drop-down box – Figure 18:
  5. Select *Modify data* icon. Single-click any point – drag-and-drop the point to desired location to modify link geometry, and trajectory automatically updates.
  6. By manually changing the numeric value in the φ text-box, the entire linkage can be rotated (in polar coordinates) to align the trajectory displayed with the horizontal/vertical gridlines in order to provide visual approximation of the performance metric ratio ($\Delta x/\Delta y$) for the design problem.

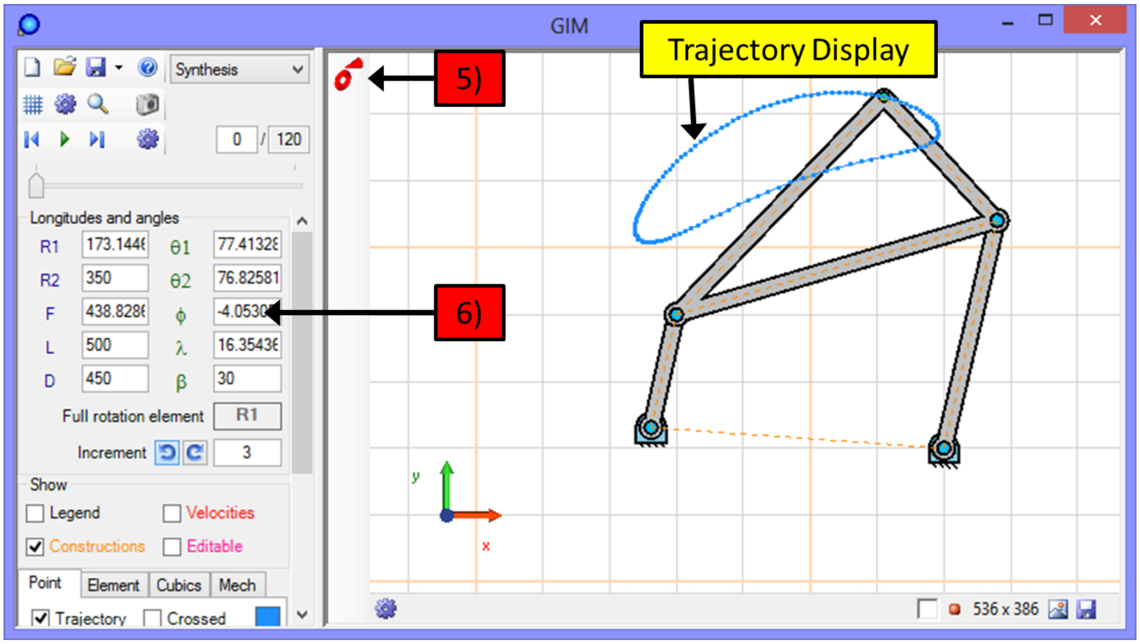


Figure 18: GIM® **Synthesis** Mode for 5) Modifying Link Geometry and 6) Aligning Trajectory Display with Gridlines

After a brief demonstration of the GIM® software, participants were presented with the materials and tools, pictured in Figure 19 and listed individually in Table 4 below, to potentially construct a physical four-bar linkage.

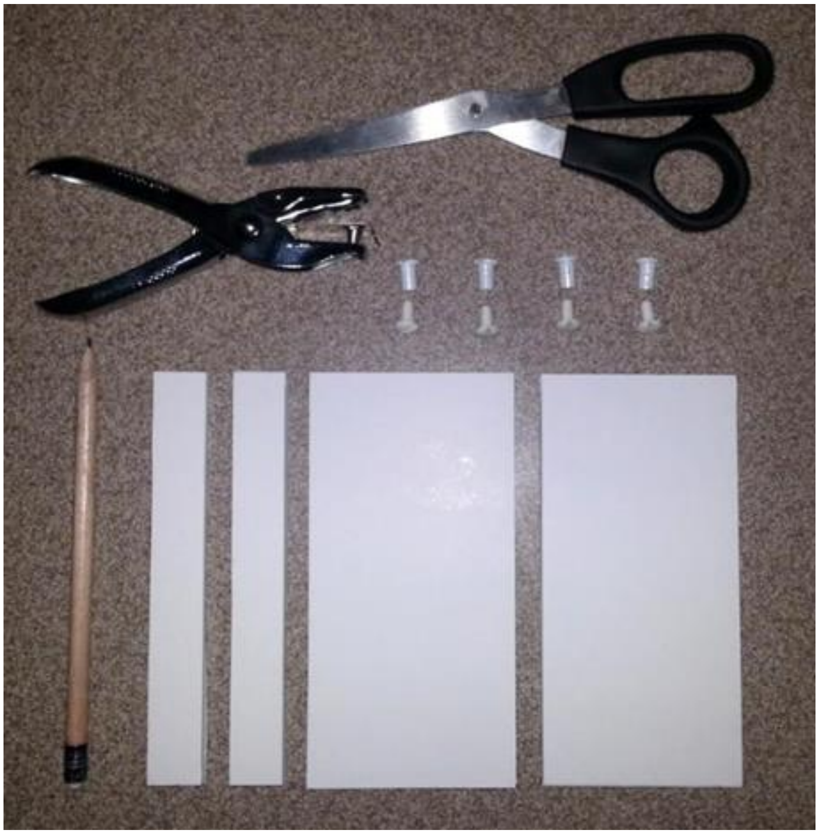


Figure 19: Materials and Tools for Four-bar Linkage Physical Modeling, Excluding Paper

Materials:		Qty	Purpose
	Precut foam board link (6" x 3")	2	Creating ground (frame) link. Creating coupler link (used to position pencil for marking trajectory).
	Precut foam board link (6" x 0.75")	2	Creating input (rocker) link. Creating output (follower) link.
	Detachable pins	4	Connecting individual links in revolute joint.
	Blank letter-size sheet of paper	6	Recording trajectory of four-bar linkage.
Tools:			
	Hole-punch	1	Installing detachable pins in desired locations.
	Pencil	1	Marking trajectory of four-bar linkage.
	Scissors	1	Cutting foam board link to desired length, if needed to eliminate interference between link rotation relative to one another.

Table 4: Detailed List of Materials and Tools for Four-bar Linkage Physical Modeling

4.4 Design Problem

a) Overview

Participants were then presented with the problem of designing a continuously rotating four-bar linkage to be used to draw the straightest possible trajectory (the closest approximation of a straight line). The design objective is to maximize $\Delta x/\Delta y$ (Figure 20) over the entire range of motion of a four-bar linkage. As previously described in Section 3.3.2, the goal of the design problem is to prototype a four-bar linkage that maximizes the length of the line drawn in one dimension, while minimizing deviation in the orthogonal dimension. The term *triangular* was not used in this experimental study in reference to coupler link geometry in order to prevent any bias among participants in this respect. However, participants were informed that it is advantageous in maximizing the performance metric ratio to draw a line from a point that is "offset" from the axis between the joints connecting the input and output links to the coupler link. Participants were permitted an unlimited number of modifications within a recommended 30 minute time limit, with 48 minutes being the longest time taken.

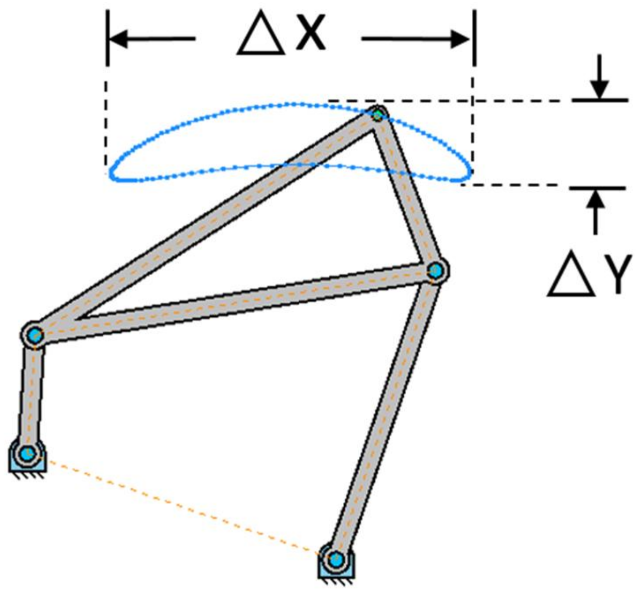


Figure 20: Depiction of Performance Metric: Maximize $\Delta x/\Delta y$

b) Likert-scale Decision Making Tool

After participants had an understanding of the design problem and the process for creating both virtual and physical four-bar linkage prototypes, they were instructed to complete a second Likert-scale survey (Table 5). Based on the sum of their survey responses (bottom of Table 5), participants then chose to either virtually or physically prototype a four-bar linkage in order to achieve the design objective of drawing the closest approximation of a straight line by maximizing $\Delta x/\Delta y$.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	+1	+2
a)	Virtual prototyping will require less time than building physical prototype(s).					
b)	Virtual prototyping will be sufficiently accurate to model critical physics or dynamic motions.					
c)	Prototyping a four-bar linkage will require many iterations.					
	Use the sum of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive sum would suggest pursuing virtual prototyping).	← Physical				Virtual →

Table 5: Likert-scale Survey for Guiding Choice between Virtual and Physical Prototyping

The Likert-scale in Table 5 expands upon Ulrich and Eppinger's two-axis graph of suggested choices based on the *relative accuracy* of virtual with respect to physical models versus the *relative effort* of virtual with respect to physical models (Figure 8). Statement (a) addresses participants' perceptions of the ratio of accuracy between virtual and physical models, and statement (b) addresses the ratio of effort between virtual and physical models. Statement (c) has the designer consider the number of design iterations to address the relative ratio of both effort and time of virtual compared to physical models. Participants use the sum of their responses to choose which type of prototype to create.

Participants who chose virtual prototyping received a short (<5 min.) GIM® software tutorial, while those choosing physical prototyping received a brief (<5 min.) demonstration of physical construction with the provided materials. Each participant recorded the time when he/she began and completed building a four-bar linkage, and prototyping time was tracked as a performance metric in this pilot study. However, participants were not explicitly instructed to minimize the time spent prototyping. A recommended (but not strictly enforced) thirty minute time limit was provided to encourage all participants to draw the closest approximation of a straight line, using as many iterations as they deemed necessary to achieve this design objective.

Maximizing the ratio $\Delta x/\Delta y$ was the primary objective of this design problem, but during construction of their four-bar linkages, participants were not permitted to physically measure or calculate the performance metric ratio of their prototypes. Both virtual and physical prototyping groups were instructed to visually approximate the performance metric ratio they achieved in order to provide consistent experimental conditions among all participants.

4.5 Exit Survey

After completion of either a virtual or physical prototype, all participants completed the exit survey depicted in Table 6. For this design problem, the exit survey recorded participants' opinions of the following:

(a) the best technique for designing a four-bar linkage;

(c) the efficacy of the Likert-scale as a decision making tool; and

(e) their choice of prototyping technique.

Statement (b) was included to document the usefulness of GIM® software in designing four-bar linkages as perceived by all participants, including physical prototypers who only received a brief demonstration of GIM® software, for consideration of using alternative linkage software in future trials of this experimental study. Statement (d) was intended as a means to identify any bias among physical prototypers against using virtual prototyping in future designs, as well as to provide insight concerning the decision making process of virtual prototypers who did not agree that they chose the best prototyping technique. In addition to the exit survey, all participants were asked to respond in their own words to the short-answer question "why did you choose virtual or physical prototyping?"

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly agree.
		-2	-1	0	+1	+2
a)	Virtual prototyping (vs. physical prototyping) is the best technique for designing four-bar linkages.					
b)	GIM software is a useful tool for virtually prototyping four-bar linkages.					
c)	The Likert Scale above was useful in choosing between virtual and physical.					
d)	I will consider using virtual prototyping in future designs.					
e)	I chose the best technique for my prototype.					

Table 6: Pilot Study Exit Survey

The Likert-scale format was used in all three surveys for this experimental study to familiarize participants with this type of survey in order to minimize the learning curve. In addition, using a consistent scale of responses among all surveys (e.g., -2 = "Strongly Disagree", 0 = "Neutral", +2 = "Strongly Agree") facilitates side-by-side quantitative comparison of virtual and physical prototypers' opinions for each survey when displaying results in tabular form (as shown in the next chapter).

4.6 SUMMARY

The 80 undergraduate mechanical engineering students that volunteered for this pilot experiment were given the choice of physically or virtually prototyping a four-bar linkage. The experimental procedure consisted of the following five sections:

1. An introduction to define types of prototypes and explain the condition necessary for continuous rotation of a four-bar linkage;
2. An initial background survey to record participants' prototyping experience and preference for modeling technique;
3. A demonstration of creating a virtual four-bar linkage using GIM® software and a presentation of the materials and tools for potentially building a physical four-bar linkage;
4. An explanation of the design problem of prototyping a continuously rotating four-bar linkage to be used to draw the closest approximation of a straight line (i.e., maximize $\Delta x/\Delta y$) - **a Likert-scale instrument to guide the choice of physical or virtual prototyping**; and
5. An exit survey to document participants' opinions regarding the best technique for prototyping four-bar linkages and whether they chose the best technique for their prototype.

Exactly half of the 80 total participants in this pilot study were instructed to use the Likert-scale instrument (Table 5) to choose their prototyping technique, and the other half, who did not use the instrument, served as a control group for evaluating the effectiveness of the instrument. Chapter 5 details the experimental trials in addition to analysis and results of the experimental data obtained.

Chapter 5: Pilot Study Results

This chapter describes the preliminary testing used in the design of this pilot study and the results obtained from two experimental trials, which established an experimental and control group to test the effectiveness of using a heuristics-based Likert-scale to aid participants in choosing between virtual or physical prototyping a four-bar linkage. Next, the acquisition of experimental data for both physical and virtual prototypes is explained, and the analysis of prototype performance metrics and participant survey responses are detailed.

Twenty out of the 80 total participants in this pilot experimental study chose to create a physical prototype of their four-bar linkage, and Figure 21 pictures an example being used to draw a pencil line on paper and the resulting line.

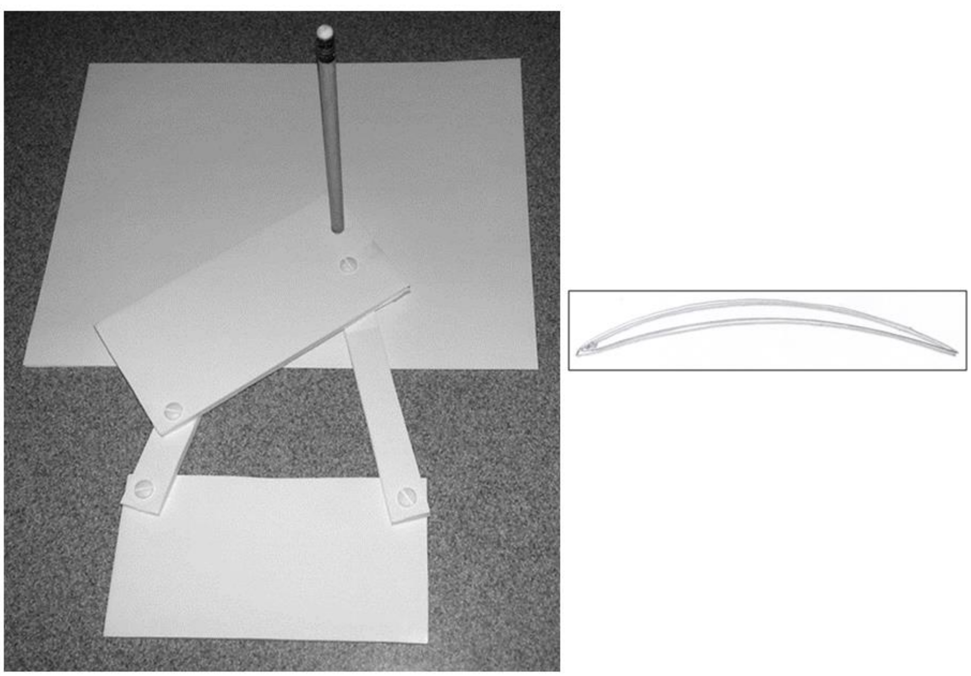


Figure 21: Example of Four-bar Linkage Physical Prototype, with Pencil to Draw a Line on Paper; Inset: Example Line Drawn

5.1 Preliminary Testing

Prior to running actual experimental trials, two graduate students worked through an initial version of the experimental procedure described last chapter. Both chose to build a virtual four-bar linkage prototype using GIM®, and in approximately ten minutes each achieved respective $\Delta x/\Delta y$ performance metrics of 9.4 and 8.8. These performance ratios were comparable to those produced by the test four-bar linkages, each built in less than an hour, for the selection of physical prototyping materials: (a) foam-board and detachable pins, $\Delta x/\Delta y$ = 9.7; (b) cardboard, $\Delta x/\Delta y$ = 8.2; and (c) LEGOs®, $\Delta x/\Delta y$ = 7.1. In addition, these two participants found GIM® easy to learn with minimal training (~5 minute tutorial), and they gained sufficient familiarity with the software in this time to avoid the difficulty encountered in the *Touch and Design* study (Section 2.2), in which participants focused more on using a new design tool than on creatively solving a design problem (Bonnardel & Zenasni, 2010). Thus, the choice of GIM® linkage software and the tutorial on its usage were validated for the purpose of the virtual-vs-physical design study, prior to experimental trials.

Originally, the experimental trials of the virtual-vs-physical design study were planned to take place immediately following the "Going the Distance" experiment (Section 2.1.2) using the same participants, primarily for logistical convenience. While these students were paid $20/hour to participate, after building and testing physical prototypes for nearly three hours during the first experiment, their performance in the subsequent virtual-vs-physical experiment clearly appeared to be adversely affected by mental fatigue (Figure 22). For example, multiple participants produced four-bar linkages that did not rotate continuously, which is a requirement for the design problem, and a majority of those who met the requirement attained $\Delta x/\Delta y$ performance metrics that were significantly (as much as an order of magnitude) lower than the metrics measured for every linkage prototype, both virtual and physical, built for preliminary testing.

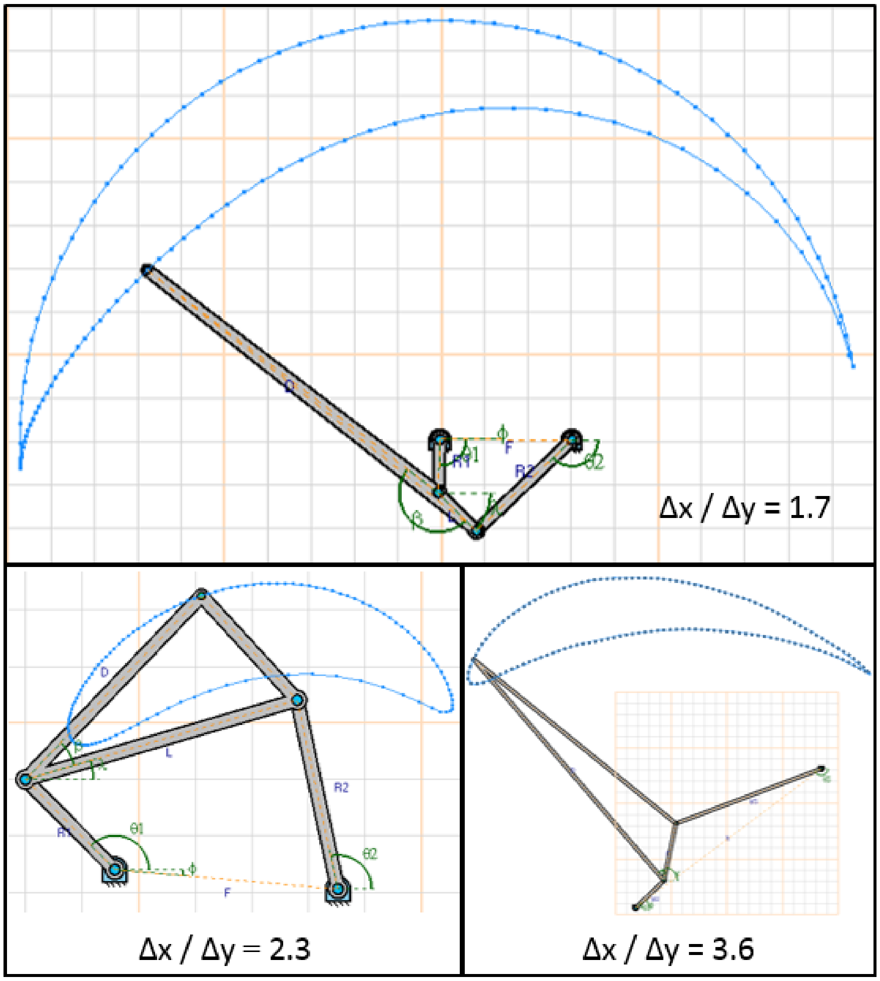


Figure 22: Examples of Poor Performance Metrics Measured in Unsuccessful Experimental Trial, Likely Attributable to Mental Fatigue

Ultimately, this unsuccessful experimental trial served as a proto-prototype (i.e., design iteration number zero) for future trials. From a cognitive point-of-view, Franck and Rosen showed that a principal benefit of prototyping is that "failure is reframed as an opportunity for learning" (2000). In this sense, the key experiential knowledge gained during the failed experimental trial was that GIM® linkage software is not compatible with Apple® operating systems, and Windows® versions 7 and 8 must have the corresponding *.NET Framework*[10] installed in order to run GIM®. In addition to software requirements, the first-hand knowledge gained from proctoring and addressing logistical concerns during preliminary testing was incorporated into the actual experimental trials, which are described next.

5.2 Experimental Trials

The first experimental trial was originally intended to be a pilot study, a prototype for future experiments in of itself, to provide insight into the development of a tool aiding designer choice between virtual and physical prototypes. The first trial, which represents the experimental group, was administered in two separate parts. First, eight students in the "Going the Distance" study, who did not participate in the unsuccessful trial described above, were recruited for the virtual-vs-physical prototyping experiment, which was rescheduled to take place several weeks after "Going the Distance" had concluded. These eight students were each paid $15 for their participation during the first week of December 2013. For the second part of the first experimental trial, 32 students were compensated with five bonus points on an assignment for the design methodology course from which they were recruited. These 32 participants completed the virtual-vs-physical experiment during the spring of 2014 (late-February to early-March). In the first experimental trial, all 40 total participants worked the five-part experimental procedure detailed last chapter, including the Likert-scale instrument for choosing type of prototype, thereby serving as a test group.

A second experimental trial was subsequently added to provide a controlled environment for evaluating the effectiveness of the Likert-scale instrument in steering

[10] Not tested on earlier versions of Windows®. For more information on the *.NET Framework* see http://www.microsoft.com/net.

decisions for prototype type, with the intention of providing statistically significant results. For the control group, 40 students were recruited from the same design methodology course the following semester (Fall 2014). These participants were compensated with five bonus points on an exam for this course, and they completed the virtual-vs-physical experiment during the penultimate week in November. All 40 participants in the control group used the experiment worksheet shown in Appendix B. The control group worksheet is identical to the worksheet used by the experimental group, except for the following omissions:

- Step 4. Prototype Four-bar Linkage ➞ Section (a) Design Problem ➞ 3rd bullet-point: *Complete Likert-scale below and choose to virtually* ***or*** *physically prototype a four-bar linkage*.
- Step 4. ➞ Section (b): *Likert-scale multi-prompt survey.*
- Step 5. Exit Survey ➞ Statement (c): *The Likert-scale above was useful in choosing between virtual and physical.*

The experimental and control groups both were presented with the same introduction to prototyping, background survey, and design problem. However, the control group was instructed to choose to physically or virtually prototype a four-bar linkage without the aid of the Likert-scale decision instrument. The participants in both groups were all undergraduate mechanical engineering students enrolled in the same semester-long design methodology course that was taught in consecutive semesters.

For both experimental trials, a maximum of four participants completed the virtual-vs-physical experiment individually during each 45-minute-long session offered for sign-up; however, participants who wished to continue prototyping were permitted to work for up to an hour, and 48 minutes was the most time spent prototyping. Sessions for the first experimental trial were held in a private laboratory and sessions for the second trial were held in a small conference room. The locations for both trials had four separate workstations, each of which included the following:

- a Dell Latitude™ E6530 laptop computer, running Windows® 7 with GIM® pre-loaded, a mouse, and power cord;
- four foam-board links and detachable pins, a hole-punch, scissors, pencil and paper (Table 4).

5.3 Data Acquisition

Due to the inherent difference in physical and virtual prototypes, the performance metric ratios, $\Delta x/\Delta y$, for this design problem were measured using different methods for the two groups of prototypers, with the goal of achieving the closest possible "apples-to-apples" comparison between virtual and physical four-bar linkage prototypes.

5.3.1 Physical Prototypes

Physical prototypers were not given any constraints on the orientation of the lines they drew; thus coordinate axes for measuring $\Delta x/\Delta y$ must be determined manually. Manual measurement of the length in one dimension relative to length in the orthogonal dimension of a shape drawn by a physical four-bar linkage can be accomplished by overlaying two perpendicular sets of parallel lines (i.e., a rectangle) on the original shape. First, a straight line is drawn to orient one axis (which will be defined as the $\boldsymbol{x}$-axis) along the major dimension of the shape slightly below the lowest extrema on the concave outer side of the shape (Figure 23). Note: for ovular shapes having only a convex outer surface, the choice of side to orient the first axis is arbitrary – only three out of the 20 shapes drawn by physical prototypers were ovular, and these shapes produced the three lowest $\Delta x/\Delta y$ measured. After establishing an $\boldsymbol{x}$-axis, a parallel line is drawn just above the extrema on the opposing side of the shape. Next, using a drafting square, two lines perpendicular to the ***x***-axis are drawn slightly outside both sides of the shape, enclosing the entire shape in a rectangle (Figure 24). All lines are drawn as close as possible to the outside of the shape without touching it, and Δx and Δy are measured using the respective inside dimensions of the rectangle. To verify that opposite sides of the bounding rectangle are parallel, distances ***A*** and ***B*** must be equal and distances ***C*** and ***D*** must be equal (Figure 25). Additionally, axes are orthogonal if diagonal distances ***E*** and ***F*** are equal.

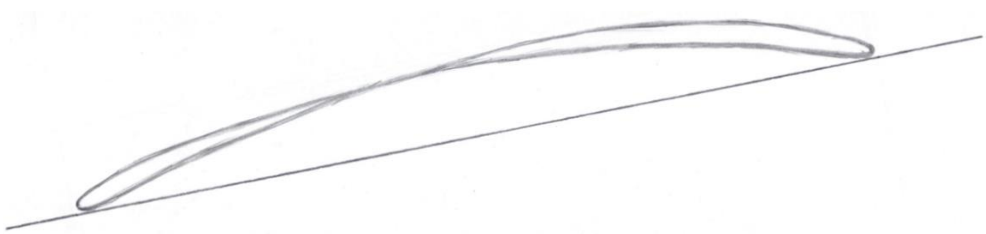


Figure 23: First Line Drawn to Define X-axis along Major Dimension of Shape

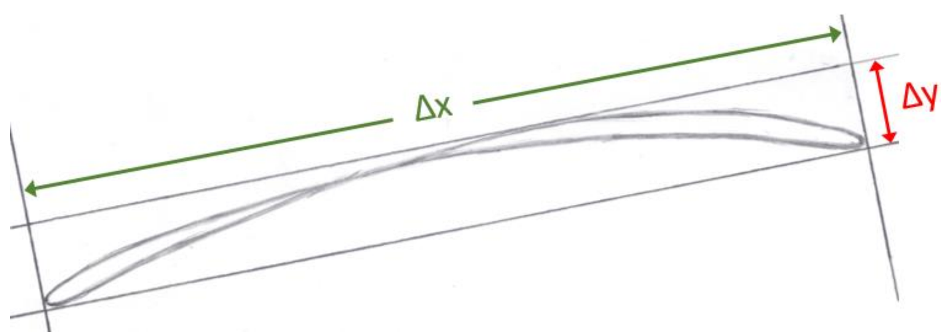


Figure 24: Bounding Rectangle used to Measure $\Delta x/\Delta y$

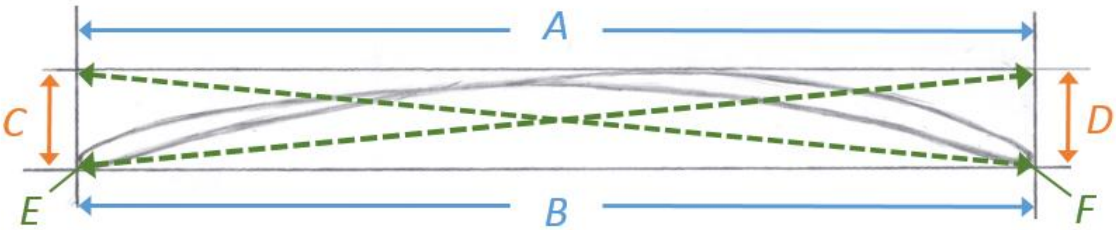


Figure 25: Distance A=B for Parallel Vertical Boundaries; C=D for Parallel Horizontal Boundaries; Diagonals E=F for Orthogonal Axes

All 20 shapes drawn by physical prototypers were measured in one sitting by the author. A standard metric ruler was used to measure Δx and Δy in millimeters for each shape, and the highest performance metric ratio achieved among all physical prototypers was 12.8.

5.3.2 Virtual Prototypes

GIM® does not automatically display Δx or Δy values, which was beneficial for experimentation as physical prototypers were not provided tools to measure their performance metric ratios. Consequently, extracting four-bar linkage trajectory data from GIM® is a multistep process that must be performed with a particular order of operations. After opening a four-bar linkage file in GIM® and selecting **Motion** mode (from drop-down box in upper-left corner of window), the steps for extracting performance metric data are summarized as follows:

1. (a) Select *Absolute rotation actuator* icon (Figure 26). (b) Single-click the Input link (shortest link which can freely rotate 360°).
2. (a) Select *Query* icon. (b) Single-click the point on Coupler link from which line trajectory will be measured.
3. (a) In the *Query* panel, select 'X' from the drop-down box for *Module* (Figure 27). Note: the default choices for the other drop-down boxes were

used (e.g., *Point*, *Position*, and *Time*). (b) Single-click the *Values* button in upper-right corner to display trajectory points in tabular form. Select all 121 values displayed in the second column titled ‘Y’, and Copy/Paste values into a spreadsheet. Note: the first column titled ‘X’ contains values for incremental time steps (displayed graphically as the ***x***-axis) for one complete revolution of Input link, and these values were not extracted.

4. Select ‘Y’ from the *Module* drop-down box, and Copy/Paste all 121 values from ‘Y’ column into spreadsheet.

5. All GIM® data was extracted into Excel®, and the following equation was used to calculate each participant’s performance metric ratio:

$$\frac{\Delta x}{\Delta y} = \frac{MAX(X\text{−}values\ data\ range) - MIN(X\text{−}values\ data\ range)}{MAX(Y\text{−}values\ data\ range) - MIN(Y\text{−}values\ data\ range)} \quad (3)$$

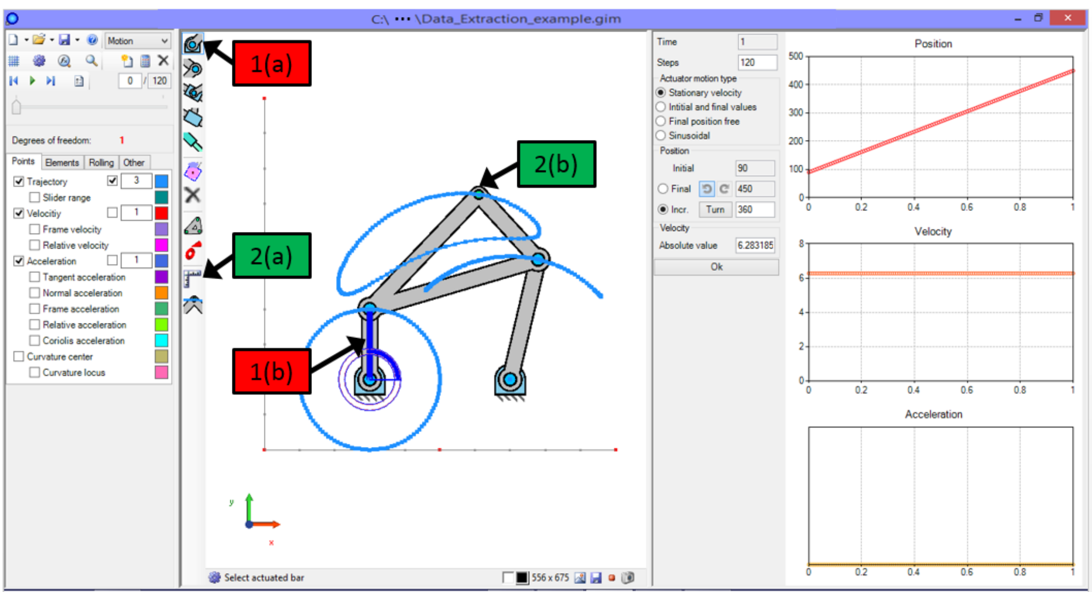


Figure 26: GIM® Steps for 1) Actuating Input Link and 2) Selecting Trajectory for Analysis

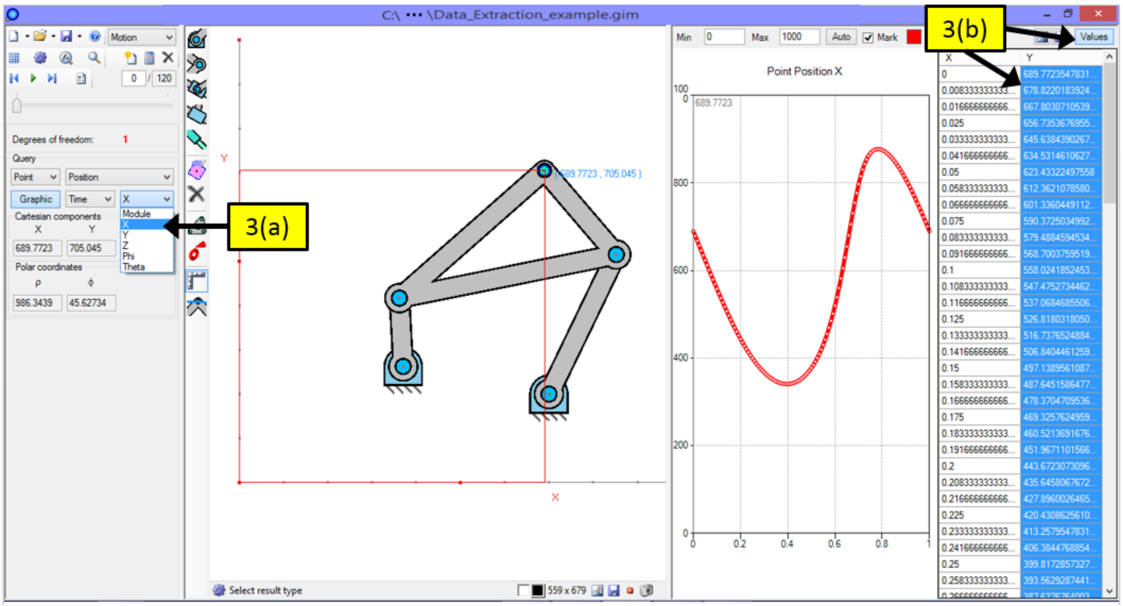


Figure 27: GIM® Steps for Displaying Horizontal Trajectory and Extracting Position Values

Cartesian coordinate axes cannot be rotated in GIM®; however, participants were informed that they could rotate their four-bar linkages (in polar coordinates) to align the trajectory with the horizontal or vertical axis displayed on screen in order to maximize $\Delta x/\Delta y$ (described in Step 6 in Section 4.3). The default axes range in GIM® is 1000 units, which is independent of screen resolution, and was used by all virtual prototypers in the experimental and control groups. The highest $\Delta x/\Delta y$ ratio achieved among all virtual prototypers was 112.4, and analysis of the performance metrics follows.

5.4 Performance Metrics

Among the 40 participants in the experimental group, who used the Likert-scale instrument to choose a prototyping technique, 8 built physical prototypes (20%) and 32 chose virtual prototyping (80%). Table 7 summarizes the results for the experimental group in this pilot study, including the $\Delta x/\Delta y$ performance ratio metrics and time to complete prototyping. Appendix C presents more detailed data for the experimental group.

Experimental Group	Virtual Prototypers	Physical Prototypers	
Sample size:	32	8	
Average Performance Metrics:			Delta (V-P)
Time to Complete (minutes)	17.8	32.0	-14.2
Performance Ratio (ΔX / ΔY)	23.4	6.0	17.4

Table 7: Summary of Performance Metrics for Experimental Group

In the experimental group, participants choosing virtual prototyping achieved $\Delta x/\Delta y$ ratios averaging almost four times higher than the physical prototypers. During preliminary testing (Section 5.1), one additional participant not included in these experimental results was assigned (rather than given a choice) to physically prototype, and outperformed the physical prototypers in the experimental group by 61% (achieving a $\Delta x/\Delta y$ = 9.7, although still significantly less than the 23.4 average of the thirty-two virtual prototypes). The group choosing virtual prototyping also drew straighter lines in roughly half the time of the group choosing physical prototyping, in the experimental group.

Final analysis of the data for the experimental group clearly shows that virtual prototyping is the optimal solution to this specific design problem for the objectives of maximizing the $\Delta x/\Delta y$ ratio in the minimal amount of time. Subsequently, a control group was tasked with the same design problem, but participants chose their prototyping technique *ad hoc*, without using the Likert-scale instrument. Among the 40 participants in the control group, 12 built physical prototypes (30%) while 28 built virtual prototypes

(70%) for their four-bar linkages. Virtual prototypers outperformed their physical counterparts in the control group by over 610% for $\Delta x/\Delta y$ ratios in 23% less time, which provides further proof that virtual prototyping is the best technique for this particular design problem. Table 8 compares performance metrics for the experimental and control groups.

	Experimental Group		Control Group		Group Deltas (Experimental - Control)	
	Virtual Prototypers	Physical Prototypers	Virtual Prototypers	Physical Prototypers		
Total Participants:	32	8	28	12		
Average Performance Metrics:					Virtual Groups	Physical Groups
ΔX / ΔY	23.4	6.0	34.8	5.7	-11.4	0.3
Time to Complete (minutes)	17.8	32.0	22.4	29.1	-4.5	2.9
(ΔX / ΔY) / Time	1.3	0.2	1.6	0.2	-0.2	0.0

Table 8: Average Performance Metrics for Experimental and Control Groups

On average, virtual prototypers in the control group achieved 49% higher $\Delta x/\Delta y$ ratios while spending 26% more time compared to virtual prototypers in the experimental group. Normalizing performance metric ratios with respect to time using Equation (4) below shows that virtual prototypers in the control group outperformed those in the experimental group by over 18% (1.555 versus 1.312 – Note: one decimal point shown in Table 8).

$$\frac{(\Delta x/\Delta y)}{Completion\ Time} \tag{4}$$

Conversely, physical prototypers among both groups performed similarly, with the experimental group attaining slightly higher $\Delta x/\Delta y$ ratios in about three more minutes, on average. Upon comparison of average performance ratios per *completion time*, physical prototypers in the control group measured just 3.79% higher than those in the experimental group. Graphical depictions of performance metric results for both groups are shown in Figures 28 and 29 below.

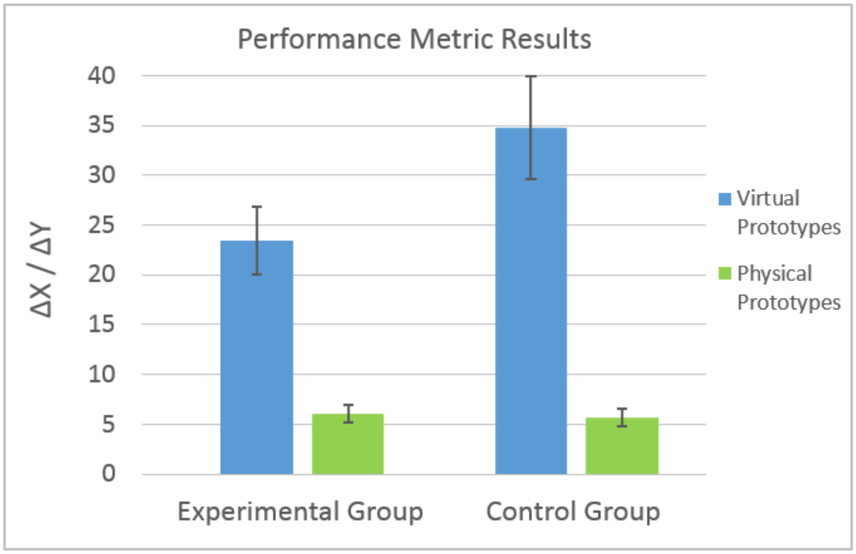


Figure 28: Average Performance Ratio Results for Experimental and Control Group; ±1 Standard Error Shown

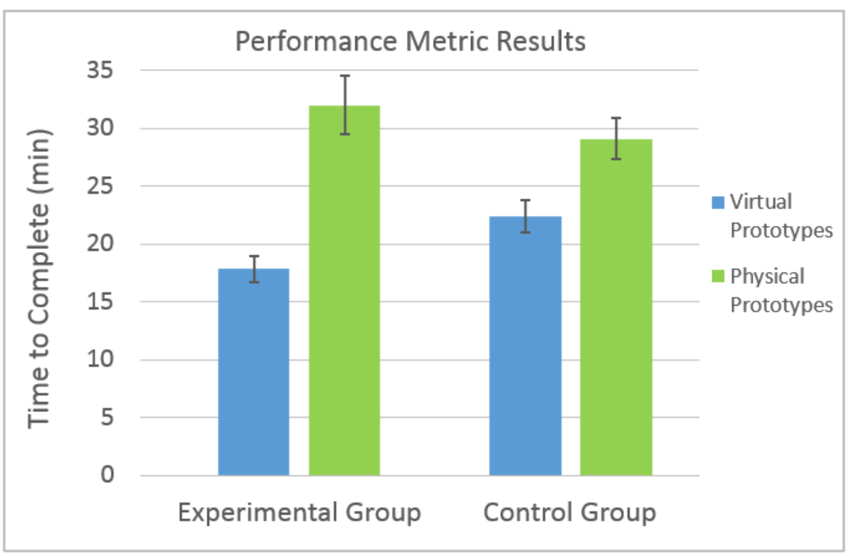


Figure 29: Average Time Spent Prototyping by Experimental and Control Group; ±1 Standard Error Shown

Viewed as a whole, the control group performed better than the experimental group. All the prototypers, both virtual and physical, in the control group surpassed their counterparts in the experimental group by almost 11% in terms of average performance ratio per *completion time* (1.07 versus 0.96). Interestingly, four more participants in the control group built physical prototypes (12 versus 8 out of 40 total for each group), yet the control group as a whole attained higher $\Delta x/\Delta y$ ratios (Table 9). Possible explanations for variance in performance between the control and experimental groups as well as statistical analysis will be discussed in Chapter 6.

				Virtual & Physical Prototypers		
	Total Participants	Chose Virtual Prototypes	Chose Physical Prototypes	Average ΔX / ΔY	Average Completion Time	Average Ratio/Time
Experimental Group	40	80%	20%	19.9	20.7	0.96
Control Group	40	70%	30%	26.1	24.4	1.07

Table 9: Comparison of all Prototypers for Each Group

Although the original intent in the design of this experimental study was that the optimal choice of prototyping technique would not be obvious, virtual four-bar linkages produced significantly higher $\Delta x/\Delta y$ ratios while requiring less build time than physical prototypes, in general. Table 10 compares virtual versus physical prototypers' performance among both groups. Virtual prototypers achieved $\Delta x/\Delta y$ ratios almost five times higher in about ⅓ less time than physical prototypers, resulting in average performance ratio per *completion time* that was nearly 7.5 times greater.

	Total Participants	Average ΔX / ΔY	Average Completion Time	Average Ratio/Time
Virtual Prototypers	60	28.7	20.0	1.44
Physical Prototypers	20	5.8	30.3	0.19

Table 10: Virtual vs. Physical Prototypers' Performance for Both Groups

Thus, the key erudition gleaned from examination of performance metrics in this pilot study is:

10% more participants chose the optimal prototyping option (virtual) using a heuristics-based approach that employs a Likert-scale decision-making tool, compared to ad hoc efforts, amongst the experimental and control group, respectively.

Although the difference in percentage of participants who chose virtual prototyping between the two groups is not statistically significant (Section 6.1), the significance of this work is the introduction of an archetype for experiential determination of prototyping strategy variables, specifically type of prototype. In addition, the fact that 80% of the participants in the experimental group chose the best technique and these virtual prototypers "agree" (+0.9 on a Likert-scale from -2 to +2) that the instrument "… was useful in choosing between virtual and physical prototyping" suggests the efficacy of the heuristics-based, Likert-scale tool presented here. The next section discusses analysis of the pilot study survey responses and insights gained.

5.5 Survey Responses

As detailed in Chapter 4, Likert-scale responses for all surveys in this pilot experiment range from -2 ["strongly disagree"] to +2 ["strongly agree"]. Using numerical weighting in conjunction with Likert's ordinal-scale survey allows quantitative analysis of participants' degree of opinions in the form of responses to qualitative statements, which is the foundation for the methodology used in the design of the heuristics-based tool of this work (Section 3.2).

In general, among both the experimental and control groups, responses to the "initial survey" indicate those who chose physical prototyping had more experience building physical models and less experience using software for design (compared to virtual prototypers), and most physical prototypers expressed a preference for a "hands-on" approach to design. Responses to the "exit survey" indicate a consensus among all participants in both groups that virtual prototyping is the best technique for this four-bar linkage design problem. In addition, virtual prototypers as a whole reported that they believe they chose the best prototyping technique, whereas their physical counterparts disagreed that they had made the best choice, and these opinions are validated by the performance metrics measured in this experimental study.

Table 11 depicts the average differences in opinions between virtual and physical prototypers compiled from the "initial" and "exit" survey responses for both the experimental and control group[11]. The relative degree of agreement with each survey statement for virtual versus physical prototypers can be compared using the average difference in response based on chosen prototyping option. For example, if a *positive* difference results from subtracting the average response of physical prototypers from that of virtual prototypers in the same test group for a given statement, then virtual prototypers more strongly agreed with that statement. Comparison of participants in the experimental group shows that virtual prototypers agreed more strongly to every survey

[11] Participants in the control group did not use a Likert-scale to select a prototyping option and the "exit survey" they completed did not include the statement about the usefulness of the Likert-scale in making their decision. Table 11 includes only the survey statements presented to both experimental and control groups.

statement except "I have experience building physical models" (difference = -0.3). Ultimately, physical prototypers' relatively higher opinion of their hands-on experience likely influenced their choice of prototyping technique to some degree in the experimental group as well as in the control group (difference = -0.2).

		Experimental Group			Control Group		
	Sample size:	**32**	**8**		**28**	**12**	
	Strongly Disagree (-2) → Strongly Agree (+2)	**Virtual**	**Physical**	**Delta (V-P)**	**Virtual**	**Physical**	**Delta (V-P)**
Initial Survey	I have an understanding of four-bar linkages	0.9	0.8	**0.1**	0.6	0.7	**-0.1**
	I have experience using computer simulation software	1.1	0.8	**0.3**	1.1	0.7	**0.4**
	I prefer to design using software vs. building models	0.2	-0.6	**0.8**	0.0	-0.5	**0.5**
	I have experience building physical models	0.9	1.1	**-0.3**	0.7	0.8	**-0.2**
Exit Survey	VP is the best technique for designing four-bars	1.5	0.6	**0.9**	1.6	0.9	**0.7**
	GIM is a useful tool for VP four-bars	1.6	0.3	**1.4**	1.7	0.2	**1.5**
	I will consider using VP in future designs	1.7	1.5	**0.2**	1.6	1.3	**0.4**
	I chose the best technique for my prototype	1.4	-0.9	**2.3**	1.7	-0.5	**2.2**
Metrics	Time to Complete (minutes)	17.8	32.0	-14.2	22.4	29.1	-6.7
	Performance Ratio (ΔX / ΔY)	23.4	6.0	17.4	34.8	5.7	29.1

Table 11: Differences in Average Survey Responses for Virtual vs. Physical Prototypers in both Test Groups

Differences in survey responses of participants in the control group corresponded very similarly to those of the experimental group, with the only exception being that physical prototypers reported a slightly higher agreement that they "have an understanding of four-bar linkages" (average delta: +0.1 vs. -0.1). For every other survey statement, the sign (+/-) of the difference in average response for virtual versus physical prototypers was the same for both test groups, which is analogous to the performance metric deltas (Table 11). The greatest single difference of opinion among participants in both test groups was in their choice of prototyping technique, with 60 virtual prototypers expressing fairly strong agreement on average (+1.6) that they picked the optimal technique, while 20 physical prototypers disagreed moderately on average (-0.7) with this statement. Interestingly, one physical prototyper in the experimental group agreed with the statement "I chose the best technique for my prototype" (+1) as did two in the control group (+1 and +2). Thus, as a result of the variance in responses for relatively small sample sizes, statistical significance cannot be proven in comparing survey responses for each type of prototyper across test groups using the Student's *t*-test (Section 6.2 below); however, the trend in differing opinions between participants in both groups is a generally higher degree of agreement among all virtual prototypers in responses to statements in the "initial" and "exit" surveys.

Focusing exclusively on the experimental group, participants' responses to the Likert-scale decision-making instrument used to select a prototyping option can be visualized in a diverging stacked bar chart (Evergreen, 2014) as shown in Figure 30 below. Although none of the 40 participants "Strongly Disagree[d]" with any of the three survey statements, the eight physical prototypers reported a noticeably higher percentage of *disagreement* - versus agreement - that virtual prototyping would require less time (statement A) and that many iterations would be needed to prototype a four-bar linkage (statement C). Conversely, 25% more physical prototypers *agreed* rather than disagreed that virtual prototyping would provide sufficient accuracy, while half of their responses were neutral for statement B. Thus, accuracy was likely the least important decision factor for participants who chose to build a physical prototype. Percentages of survey responses provided by 32 virtual prototypers were very similar for each statement, with an average agreement of 87.5% (57.3% "Agree" and 30.2% "Strongly Agree") for each statement.

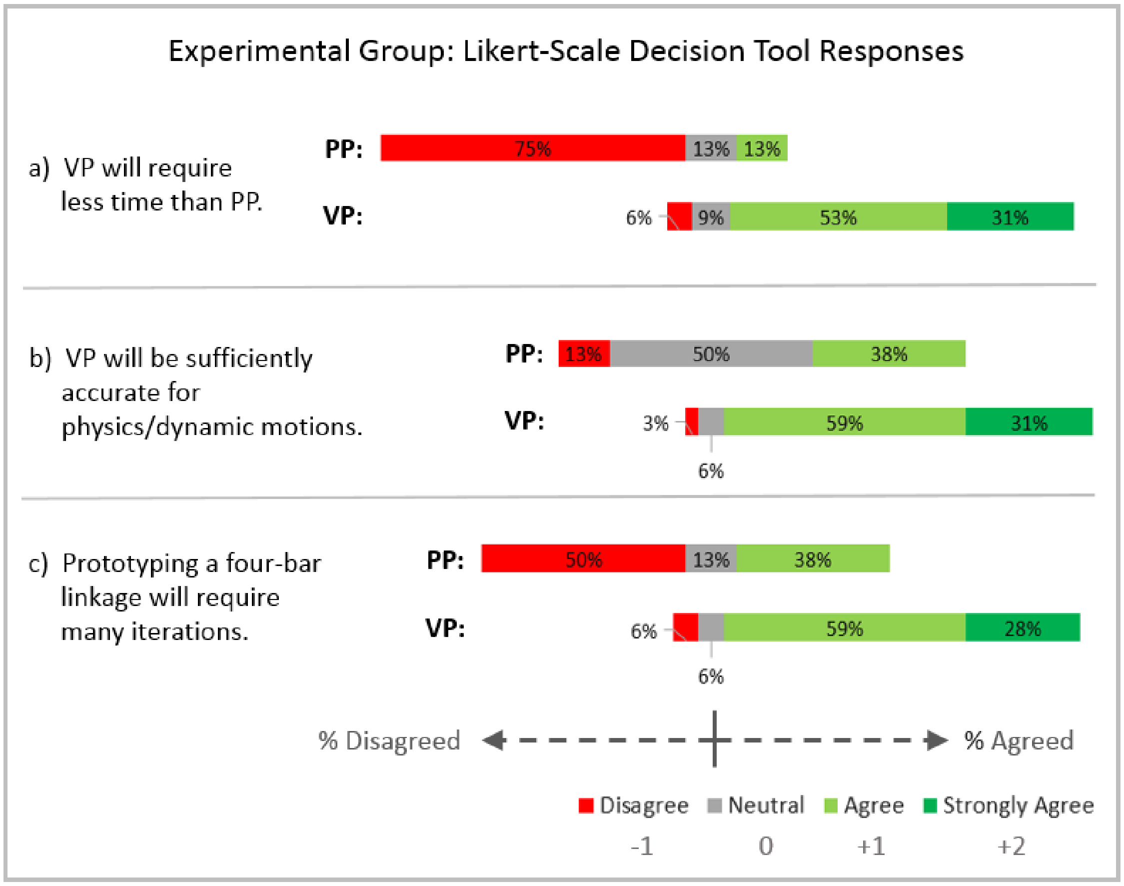


Figure 30: Percentages of Responses for Participants that Chose PP (Physical Prototypes) and VP (Virtual Prototypes) in Experimental Group; Note: Zero "Strongly Disagree" Responses Reported

Participants in the experimental group were instructed to use the *sum* of their responses to the three statements of the Likert-scale decision tool to choose a prototyping technique, where a positive sum would suggest pursuing virtual prototyping (negative sum ➞ physical prototyping). The average sum of responses for virtual prototypers was +3.4 and for physical prototypers it was -0.5; however, a resultant sum = 0 was obtained by four participants, three of whom chose physical prototyping and expressed a preference for "hands-on" modeling. The only participant who questioned how to respond to a zero sum[12] was advised to use his experiential knowledge to make a prototyping choice. Inexplicably, the participant who virtually prototyped a four-bar linkage after calculating a Likert-scale zero sum achieved the highest $\Delta x/\Delta y$ (112.4) measured across both test groups. Ten percent of the 40 participants in the experimental group computed a resultant sum of zero, and three of those four selected the less effective prototyping option for this design study. In addition, the summation of responses for one physical prototyper was +1, which should have advocated virtual prototyping.

Consequently, there is clearly room for improvement in the Likert-scale instrument. Future iterations of a similar heuristics-based decision-making tool may include explicit guidance for the situation when a choice between two options is not definitive or modified numerical weighting for survey statements (exponential vs. linear) that could reduce the likelihood of obtaining a zero sum. Increasing the number of Likert survey statements as well as the range of possible responses (e.g., from "Very Strongly Disagree: -5" to "Very Strongly Agree: +5") may also increase the chance for more perspicuous results to be used in decision making for a similar design problem. Finally, the prototyping strategy guide pioneered by Dunlap et al. (2014) that is detailed previously in Section 3.2 employs Likert-scales for which the *averages* of responses are used in determining prototyping decisions. Examination of the average of responses for each participant in the experimental group in this study, in retrospect, shows no benefit in using the average instead of sum of responses for decision making. On the contrary, the four participants with zero sums would also have averages = 0, while the average of responses for each remaining participant would have the same sign (+/-) but noticeably smaller magnitude when compared to the sum of responses (e.g., +1 sum ➞ +0.333

[12] No explicit guidance was provided in the experimental worksheet/presentation for the situation when the sum of Likert-scale responses were neither positive nor negative.

average). Higher magnitudes obtained by quantifying Likert responses would likely inspire more confidence/decisiveness in choosing between two options.

5.6 SUMMARY

After preliminary testing and a failed initial experimental trial, the experimental procedure and its implementation were modified and fine-tuned for this pilot study. Forty participants were recruited as part of an experimental group, and they used a heuristics-based Likert-scale to choose to prototype a four-bar linkage, either virtually or physically. Subsequently, a control group with forty participants was tasked to select a prototyping technique ad hoc for the same design problem. Performance metric ratios, $\Delta x/\Delta y$, were measured manually for physical prototypes and extracted from GIM® software models for virtual prototypes. Analysis of performance metrics undeniably shows that virtual prototyping is the optimal technique for this design problem, as virtual prototypers achieved $\Delta x/\Delta y$ ratios almost five times higher in about one-third less time than physical prototypers on average across both test groups. With the aid of a heuristics-based decision making tool, 10% more participants in the experimental group picked the best technique versus those who did not use the tool in the control group. Survey responses indicate a consensus among all participants that virtual prototyping is the ideal choice in this instance, and those who used the Likert-scale in making their choice generally agreed that it was useful. Although the difference in choice of the optimal prototyping technique between test groups of this pilot study is not statistically significant, it serves as a preliminary model for a systematic approach that incorporates consideration of type of prototype as a strategic decision.

Chapter 6: Discussion

This pilot study, itself a prototype for future experiments, provides insight into development of a tool aiding designer choice between virtual and physical prototypes. The crux of this thesis is the introduction of a heuristics-based Likert-scale guide for choosing virtual versus physical prototyping, which has been a useful addition to the larger prototyping strategy formulation method proposed by Dunlap et al. (2014). The effectiveness of the Likert-scale decision tool was evaluated in a controlled design problem study. Although exposure to the Likert tool resulted in a 10% increase in choice of the optimal prototyping technique among participants in the experimental group (who used the decision making tool) compared to the control group, this difference is not statistically significant. This chapter discusses the statistical analysis employed and implications of the results.

6.1 Test of Two Proportions Analysis

With two distinct choices of prototyping techniques available to participants in this experimental study, their selections of virtual versus physical prototyping represent a binomial distribution. The prototyping choices of participants among each test group are analyzed using the comparison of two population proportions to test the hypothesis that two samples are from the same population. For the purposes of this work, it is assumed that any value for p less than 0.05 will suffice to reject the null hypothesis with statistical significance for the test of two population proportions.

Using multiple *two-tailed* tests for the null hypothesis that there is no significant difference between 32 of 40 (80%) choices of virtual prototyping among the experimental group compared to 28 of 40 (70%) among the control group, the null hypothesis cannot be rejected. For example, two population proportions tests yield the following:

- Z-test ➞ $p = 0.303$
- Pearson Chi-Square ➞ $p = 0.305$
- Fisher Exact ➞ $p = 0.439$

Furthermore, similar *one-tailed* tests of the null hypothesis that the proportion of optimal choices among the experimental group is not significantly *higher* than that of the control group also support the null hypothesis (e.g., z-test ➞ p = 0.15; therefore, there is only an 85% chance the experimental group proportion is higher). The fortuitously convenient proportions of 80% and 70% are only significantly different for sample sizes, $N \geq 150$ (z-test).

6.2 Performance Metrics Statistical Analysis

Throughout the following sections, the Student's t-test is employed for hypothesis testing where a performance measure and thus resulting difference of means can take on variable values. For the purposes of this work, it is assumed that any value for p less than 0.05 will suffice to reject the null hypothesis with statistical significance for the Student's t-test.

In the experimental group and control group, virtual prototypers produced higher performance metric ratios in less time on average relative to physical prototypers, and performance across test groups was comparable for both types of prototypers. For example, the average $\Delta x/\Delta y$ and *completion time* for physical prototypers in the experimental group were just 6% and 9% higher, respectively, compared to those for physical prototypers in the control group; accordingly, neither of these performance metric differences are statistically significant. Performance ratios obtained by participants as a function of *completion time* for physical prototypes (Figure 31) and virtual prototypes (Figure 32) for both test groups are shown below.

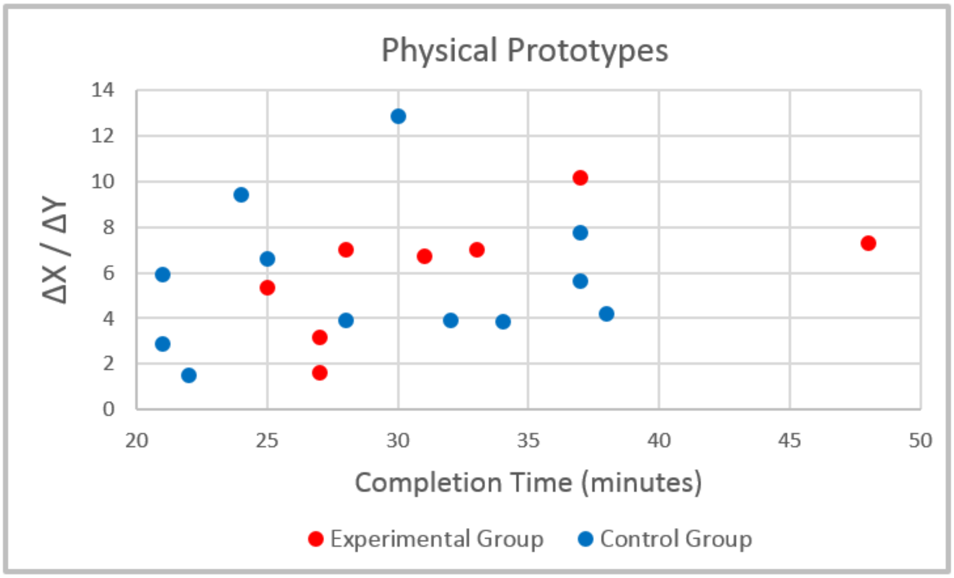


Figure 31: Performance Ratios vs. Completion Times for Physical Prototypes Built by Both Test Groups

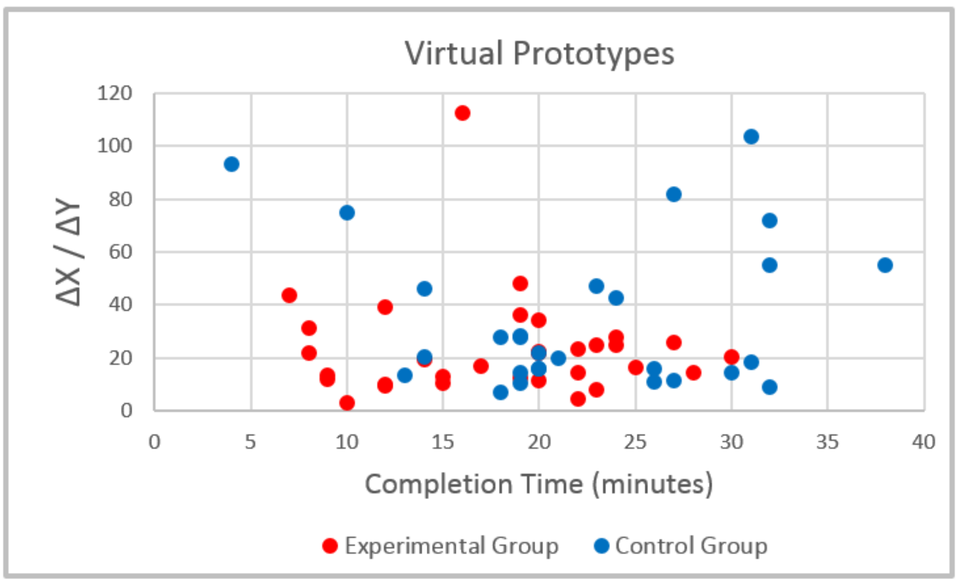


Figure 32: Performance Ratios vs. Completion Times for Physical Prototypes Built by Both Test Groups

The large amount of variance in prototype performance coupled with relatively small sample sizes provides quantitative reasoning for the lack of statistically significant differences for $\Delta x/\Delta y$ across test groups, while the inherent subjectivity associated with virtual and physical prototyping (e.g., software modeling/building experience, dexterity, personal motivation) in conjunction with noise (e.g., random/sampling error) offers a practical explanation for accepting the null hypothesis that there is no difference in mean performance ratios obtained by virtual and physical prototypers across test groups.

Although differences in $\Delta x/\Delta y$ for each type of prototyper were not statistically significant in comparison of the test groups, virtual prototypers in the control group spent over 25% more time prototyping than those in the experimental group, which represents a significant difference with a Student's *t*-test at $p = 0.015$ (Table 12 below). One possible explanation for this difference in *completion time* is that participation was incentivized with bonus points on an exam for the 40 recruits in the control group, whereas 32 participants in the experimental group received bonus points on an assignment and eight were paid $15 (Section 5.2). Thus, a reasonable conclusion is that participants in the experimental group, who were compensated with cash or bonus points on an assignment, felt less inclined to spend more time prototyping than participants in the control group, who may have thought that exam bonus points were contingent on prototype performance ratio. During administration of both experimental trials, it was never stated or implied that compensation was dependent upon obtaining $\Delta x/\Delta y$ of any magnitude; however, participants in the control group may have had more motivation to optimize their prototypes for the sake of improving their scores on an exam versus an assignment.

	P-values (*T*-test)	
Experimental vs. Control Group	ΔX / ΔY	Completion Time
Physical Prototypes	0.801	0.368
Virtual Prototypes	0.069	0.015
All Prototypes for Each Group	0.240	0.049

Table 12: *P*-values of Performance Metric Differences for Experimental Group vs. Control Group (95% Confidence Interval)

The control group as a whole (physical and virtual prototypers) spent 18% more time prototyping versus the experimental group as a whole, which is statistically significant with a Student's *t*-test at $p = 0.049$ (Table 12). This difference in *completion time* may be attributed to the different compensation provided to participants in each test group, as previously mentioned. Another possible explanation is that the experienced gained by the author in running the first trial with the experimental group influenced the subsequent administration of the second trial with the control group. While conducting the second trial, the author likely presented the design problem and answered participants' questions more effectively than during the first trial, although every attempt was made to replicate the initial trial. In addition, the author became more proficient in GIM® software during the eight month hiatus between the two experimental trials. Consequently, participants in the control group possibly had an advantage in terms of information provided and guidance in prototyping, which may explain why they spent more time perfecting their prototypes.

6.3 Survey Responses Statistical Analysis

Differences in mean participant responses to the initial and exit surveys for both test groups are also compared via Student's *t*-test using a 95% confidence interval.

Analysis of responses to the Likert-scale decision tool, which was utilized exclusively by participants in the experimental group, is detailed previously in Section 5.5. Average responses to each statement in the initial and exit surveys for virtual and physical prototypers are itemized in Table 13 below along with the *p*-values calculated for mean differences between responses from the experimental versus the control group. Note: the exit survey statement "Likert-scale was useful in choosing virtual or physical prototyping" is omitted from Table 13, as the control group was not presented this statement. The resulting *p*-values show no statistically significant differences in survey responses for each type of prototyper across test groups; hence it can be concluded that virtual prototypers in both the experimental and control groups come from the same population, and physical prototypers in both test groups are from the same population, in terms of survey responses.

		Virtual Prototypers			Physical Prototypers		
	Sample size:	**32**	**28**		**8**	**12**	
	Strongly Disagree (-2) → Strongly Agree (+2)	**Exp Group**	**Control Group**	***P*-value**	**Exp Group**	**Control Group**	***P*-value**
Initial Survey	I have an understanding of four-bar linkages	0.9	0.6	**0.087**	0.8	0.7	**0.789**
Initial Survey	I have experience using computer simulation software	1.1	1.1	**0.879**	0.8	0.7	**0.811**
Initial Survey	I prefer to design using software vs. building models	0.2	0.0	**0.424**	-0.6	-0.5	**0.663**
Initial Survey	I have experience building physical models	0.9	0.7	**0.292**	1.1	0.8	**0.106**
Exit Survey	VP is the best technique for designing four-bars	1.5	1.6	**0.672**	0.6	0.9	**0.458**
Exit Survey	GIM is a useful tool for VP four-bars	1.6	1.7	**0.473**	0.3	0.2	**0.669**
Exit Survey	I will consider using VP in future designs	1.7	1.6	**0.718**	1.5	1.3	**0.274**
Exit Survey	I chose the best technique for my prototype	1.4	1.7	**0.085**	-0.9	-0.5	**0.444**

Table 13: Student's *T*-test Calculated *P*-values for Mean Survey Responses across Test Groups for Virtual and Physical Prototypers

6.4 VIRTUAL VS. PHYSICAL GENERALIZED HEURISTICS

As previously mentioned in Section 3.1, no heuristics relating specifically to *virtual-vs-physical* prototyping decisions were found. While most recent product design literature makes the distinction between types of prototypes and recommends that designers should consider using virtual models in the prototyping process (Schrage, 2000; Otto & Wood, 2001; Thomke, 2003; Drezner, 2009), these works offer only minimal guidance in the decision making process of selecting one type of prototype over the other. Therefore, generalized heuristics to aid designers in choosing physical and/or virtual prototyping amalgamated from the findings of this thesis are suggested as follows:

- For low fidelity models consider physical prototyping, and for high fidelity models consider virtual prototyping.
- Use virtual prototyping early in the design process when multiple design concepts are being considered to rule out infeasible concepts and identify potential design flaws, especially if CAD models are required.
- Physical prototypes may be beneficial if only one design concept is being pursued, especially if hands-on evaluation is required for design verification.
- Consider virtual prototyping when highly complex models will require many iterations.
- Physical prototypes may be beneficial if few design iterations will be required.
- Build virtual models initially when complex/expensive materials and fabrication methods are required for prototypes, if virtual modeling software can accurately simulate material properties and kinematics.

- Final prototypes must be in physical form when required by safety and legal regulations (e.g. automobile crash testing), or if the final product will experience extreme environments or operating conditions (e.g. space exploration). However, virtual models may be useful in early stage prototypes.
- If scaling is required to build physical prototypes, or if scaling laws are not sufficiently accurate, consider virtual prototyping initially.
- For integrated subsystems consider physical prototyping; for isolated subsystems consider virtual prototyping.
- For rigid design requirements consider physical prototyping; for flexible design requirements consider virtual prototyping.
- When initially redesigning an existing product virtual prototyping may be beneficial; disruptive new products will likely require physical prototyping ultimately.
- If budget and time permit, prototype virtually and physically to best understand the potential functionality, flaws, usability, aesthetics, and ergonomics of the final product.

6.5 SUMMARY

It is not the intention of this pilot study to make statistical claims, but rather to demonstrate the viability of the experiment and provide a foundation and compelling motivation to conduct it on a larger scale, possibly using more generalizable prototyping scenarios.

Ideally, the proportion of participants who chose the optimal prototyping technique using the Likert-scale decision tool would be significantly higher than the proportion of those who did not use the tool, statistically, and the performance metric differences ($\Delta x/\Delta y$ and *completion time*) between the experimental and control groups would not be statistically significant (i.e. both groups are from the same population). However, neither of these results were obtained. In addition, differences in average initial and exit survey responses for each type of prototyper across test groups are not statistically significant. Finally, generic heuristics for *virtual-vs-physical* prototyping decisions are proposed based on relevant literature and results of this pilot study.

Chapter 7: Conclusion and Future Work

This thesis documents the development of a heuristics-based decision making tool to guide a designer's choice between virtual or physical prototypes, based in part upon published prototyping strategies, as well as the design, implementation, and results of a pilot experimental study used to test this virtual-vs-physical decision-making tool for prototypes.

Although prototyping is an integral phase in the development of new products, relatively few methodologies have been published on structuring prototyping activities compared to other aspects of the product design process. Additionally, most recently published attempts to organize prototyping activities focus on management logistics aspects, such as lead times and budgets (Christie et al., 2012). However, a novel, heuristics-based approach for formulating prototyping strategies (Dunlap et al., 2014) provides the foundation and direction for the continuing evolution of an engineering framework for prototyping.

We developed a heuristics-based tool that guides designers in choosing physical or virtual prototypes based on answers to Likert-scale questions in conjunction with the prototyping strategy methodology pioneered by Dunlap et al. (2014). Using this heuristics-based approach, designers take into consideration the relative accuracy and effort of virtual models with respect to physical models to provide guidance in the selection of the most appropriate prototyping technique. In order to test this Likert-scale decision-making instrument, we designed a pilot experiment in which participants are given the choice of either virtually or physically prototyping a four-bar linkage. This pilot experiment features a design problem with the objective of prototyping a four-bar linkage that maximizes the length of a line drawn in one dimension, while minimizing length in the orthogonal dimension. With the goal of the design problem being that the optimal choice between types of prototype is not obvious, we chose GIM® software for four-bar linkage virtual prototyping along with foam-board and detachable pins for physical prototyping in this experiment.

The 80 undergraduate mechanical engineering students that volunteered for this pilot experiment were given the choice of physically or virtually prototyping a four-bar linkage. Forty participants in this pilot study were instructed to use the Likert-scale instrument to choose their prototyping technique, and an additional 40 participants, who did not use the instrument, served as a control group for evaluating the effectiveness of the instrument.

Performance metric ratios, $\Delta x/\Delta y$, were measured manually for physical prototypes and extracted from GIM® software models for virtual prototypes. Analysis of performance metrics undeniably shows that virtual prototyping is the optimal technique for this design problem, as virtual prototypers achieved $\Delta x/\Delta y$ ratios almost five times higher in about one-third less time than physical prototypers on average across both test groups. With the aid of a heuristics-based decision-making tool, 10% more participants in the experimental group picked the best technique versus those who did not use the tool in the control group (32 of 40, and 28 of 40, respectively). The prototyping choices of participants among each test group were analyzed using the comparison of two population proportions to test the hypothesis that two samples are from the same population. Results from a two-tailed Z-test yielded $p = 0.303$; thus, the null hypothesis cannot be rejected with statistical significance for the test of two population proportions.

Survey responses indicate a consensus among all participants that virtual prototyping is the ideal choice in this instance, and those who used the Likert-scale in making their choice generally agreed that it was useful. Although the difference in choice of the optimal prototyping technique between test groups of this pilot study is not statistically significant, it serves as a preliminary model for a systematic approach that incorporates consideration of type of prototype as a strategic decision. Although the findings of this four-bar linkage study cannot be extrapolated to a generic prototyping process, this work provides a paradigm for thinking critically about virtual vs. physical prototyping decisions using a heuristics-based, structured prototyping strategy. The encouraging pilot results provide a template and strong motivation for conducting a larger scale experiment for generic prototyping applications.

7.1 Future Work

Additional research should seek deeper understanding of what designers learn from tactile engagement while building physical prototypes (such as fit and form), in contrast to the virtual experience of software manipulations. Incorporating the importance of human-prototype interaction as a heuristic in decision making may enhance prototyping strategies.

Haptic interfaces have enhanced hands-on engagement in virtual prototyping applications, and could provide a heuristics-based approach for studying human-prototype interaction. Studies have documented the effectiveness of utilizing haptic interfaces in simulating real-world force response feedback in case studies involving the design of a washing machine knob (Ha et al., 2009) as well as an automotive power-window switch and turn-signal switch (Morioka et al., 2008; Erdelyi & Talaba, 2010).

Future work can broaden the experiment detailed in this paper to more generic design problems. Testing this method with new design problems, in which the choice between virtual and physical models is less obvious, can provide more generalizable results. Potential design problems must use simple and readily-available computer software for practical reasons.

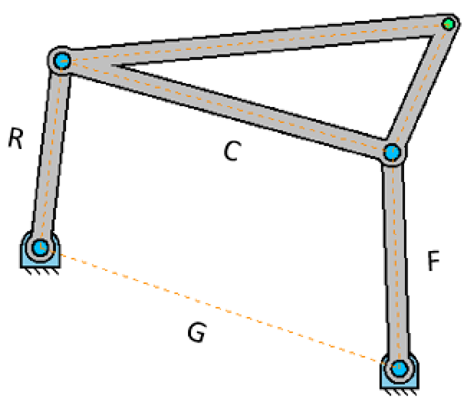
Appendix A: Experiment Worksheet (Experimental Group)

Name: ___________________________ **Date**: ________________

Four-Bar Linkages
Prototyping Experiment

1. Introduction to four-bar linkages:

- Grashof's Law: (shortest link + longest link) < (sum of remaining 2 links)
- Virtual Prototype - a computer simulation (CAD model, motion analysis, FEA, CFD, etc.) of a product that can be analyzed, tested, and modified.
- Physical Prototype – a tangible, physical model of a product that can be analyzed, tested, and modified.



R = rocker link
G = ground link
F = follower link
C = coupler link

2. Fill out initial survey:
Based on your experience, complete this survey.

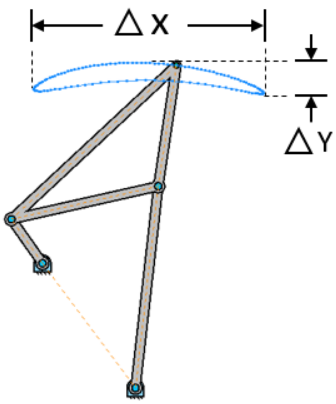
		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly agree.
		-2	-1	0	+1	+2
a)	I have an understanding of four-bar linkages.					
b)	I have experience using computer simulation software (e.g., CAD, FEA, etc.).					
c)	I prefer to design using software, rather than building physical models.					
d)	I have experience building physical models.					

3. Introduction to GIM software

4. Prototype four-bar linkage: [~ 30 minutes]

Design Problem:

- Design a continuously rotating four-bar linkage to draw the longest possible horizontal shape.
- Goal: maximize the ratio of ΔX / ΔY
- Complete Likert-scale below and choose to virtually **or** physically prototype a four-bar linkage.
- There is no limit to the number of times you may modify your design.
- Record your Starting and Completion Time below.



Starting Time:

Completion Time:

4. b) Complete Likert-scale:

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	+1	+2
a)	Virtual prototyping will require less time than building physical prototype(s).					
b)	Virtual prototyping will be sufficiently accurate to model critical physics or dynamic motions.					
c)	Prototyping a four-bar linkage will require many iterations.					
	Use the sum of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive sum would suggest pursuing virtual prototyping).	← Physical				Virtual →

5. Fill out exit survey:

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly agree.
		-2	-1	0	+1	+2
a)	Virtual prototyping (vs. physical prototyping) is the best technique for designing four-bar linkages.					
b)	GIM software is a useful tool for virtually prototyping four-bar linkages.					
c)	The Likert-scale above was useful in choosing between virtual and physical.					
d)	I will consider using virtual prototyping in future designs.					
e)	I chose the best technique for my prototype.					

f) Why did you choose virtual or physical prototyping?

6. Submit your physical prototype,

or save your virtual prototype file (FirstName_LastName.gim) to the desktop**.**

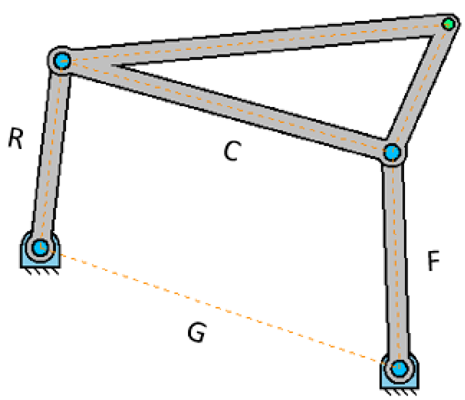
Appendix B: Experiment Worksheet (Control Group)

Name: ___________________________ **Date**: ________________

Four-Bar Linkages
Prototyping Experiment

1. Introduction to four-bar linkages:

- Grashof's Law: (shortest link + longest link) < (sum of remaining 2 links)
- Virtual Prototype - a computer simulation (CAD model, motion analysis, FEA, CFD, etc.) of a product that can be analyzed, tested, and modified.
- Physical Prototype – a tangible, physical model of a product that can be analyzed, tested, and modified.



R = rocker link
G = ground link
F = follower link
C = coupler link

2. Fill out initial survey:
Based on your experience, complete this survey.

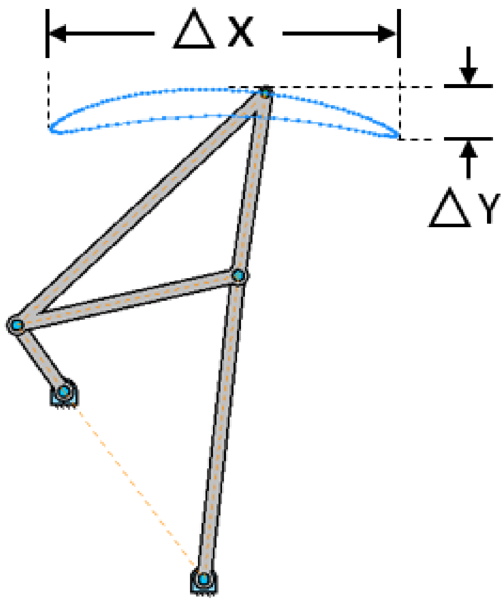
		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly agree.
		-2	-1	0	+1	+2
a)	I have an understanding of four-bar linkages.					
b)	I have experience using computer simulation software (e.g., CAD, FEA, etc.).					
c)	I prefer to design using software, rather than building physical models.					
d)	I have experience building physical models.					

3. Introduction to GIM software

4. Prototype four-bar linkage: [~ 30 minutes]

Design Problem:

- Design a continuously rotating four-bar linkage to draw the longest possible horizontal shape.
- Goal: maximize the ratio of ΔX / ΔY
- There is no limit to the number of times you may modify your design.
- Record your Starting and Completion Time below.



Starting Time:

Completion Time:

5. Fill out exit survey:

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly agree.
		-2	-1	0	+1	+2
a)	Virtual prototyping (vs. physical prototyping) is the best technique for designing four-bar linkages.					
b)	GIM software is a useful tool for virtually prototyping four-bar linkages.					
c)	I will consider using virtual prototyping in future designs.					
d)	I chose the best technique for my prototype.					

e) Why did you choose virtual or physical prototyping?

6. Submit your physical prototype,

or save your virtual prototype file (FirstName_LastName.gim) to the desktop.

Appendix C: Experiment Data for Experimental Group

Individual Participant Data:

	Participant #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	Virtual or Physical	P	P	P	P	P	P	P	P	V	V	V	V	V	V	V	V	V	V	V	V
Initial Survey	I have an understanding of four-bar linkages	2	0	1	1	1	1	0	0	1	0	0	1	1	1	1	1	0	2	1	1
Initial Survey	I have experience using software	0	1	0	1	1	1	1	1	1	1	-1	1	2	1	1	2	1	1	2	1
Initial Survey	I prefer to design using software	0	-2	0	-1	-1	0	-1	0	1	0	-1	2	1	1	-1	2	0	-1	2	0
Initial Survey	I have experience building physical models	2	1	1	1	1	1	1	1	1	1	0	0	-1	-1	2	1	2	2	0	1
Likert Scale	VP will require less time than PP	1	-1	-1	-1	0	-1	-1	-1	1	2	1	2	0	1	1	1	0	1	1	1
Likert Scale	VP will be sufficiently accurate	0	0	0	1	-1	0	1	1	0	2	1	-1	2	1	1	2	2	1	2	1
Likert Scale	Prototyping a four-bar linkage will require many iterations	-1	-1	1	-1	1	0	1	-1	1	-1	0	-1	1	1	1	1	2	1	1	1
	Subtotal	0	-2	0	-1	0	-1	1	-1	2	3	2	0	3	3	3	4	4	3	4	3
Exit Survey	VP is the best technique for designing four-bars	-1	1	1	-1	2	1	1	1	0	1	2	1	2	2	2	2	2	0.5	2	1
Exit Survey	GIM is a useful tool for VP four-bars	0	1	0	0	0	0	0	1	1	1	2	1	2	2	1	2	2	2	1	2
Exit Survey	Likert Scale was useful in choosing VP or PP	0	0	0	1	0	-1	1	1	0	0	2	1	1	0	0	1	2	1	0	2
Exit Survey	I will consider using VP in future designs	2	1	2	1	2	1	2	1	1	2	2	2	2	2	1	2	2	1	2	1
Exit Survey	I chose the best technique for my prototype	-2	-1	0	1	-2	-1	-1	-1	0	0	0	1	2	2	2	2	2	1	2	1
Metrics	**Time to Complete (minutes)**	**25**	**27**	**48**	**37**	**31**	**33**	**27**	**28**	**22**	**30**	**10**	**16**	**20**	**19**	**20**	**22**	**23**	**9**	**12**	**28**
Metrics	**Performance Ratio (ΔX / ΔY)**	**5.2**	**1.7**	**7.3**	**9.7**	**6.8**	**7.1**	**3.2**	**6.6**	**4.5**	**20.3**	**3.2**	**112.4**	**34.2**	**12.7**	**22.1**	**14.5**	**24.6**	**13.6**	**10.1**	**14.6**

	Participant #	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
	Virtual or Physical	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
Initial Survey	I have an understanding of four-bar linkages	1	1	1	2	1	-1	1	1	1	2	0	1	1	1	1	1	1	1	0	1
Initial Survey	I have experience using software	1	1	1	1	1	1	1	1	2	2	1	2	1	1	1	1	2	0	1	0
Initial Survey	I prefer to design using software	0	-2	1	0	0	1	0	0	0	1	1	0	0	0	-1	-1	0	1	-1	0
Initial Survey	I have experience building physical models	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	0	1	1
Likert Scale	VP will require less time than PP	2	1	2	1	0	2	1	1	-1	1	2	1	2	1	1	1	2	2	-1	2
Likert Scale	VP will be sufficiently accurate	2	1	1	1	1	1	2	1	1	1	2	1	1	2	1	1	1	0	2	1
Likert Scale	Prototyping a four-bar linkage will require many iterations	2	2	2	1	1	1	2	2	1	0	1	1	1	1	2	1	1	2	2	1
	Subtotal	6	4	5	3	2	4	5	4	1	2	5	3	4	4	4	3	4	4	3	4
Exit Survey	VP is the best technique for designing four-bars	1	2	2	1	1	1	2	2	1	1	2	2	2	2	1	2	2	1	2	2
Exit Survey	GIM is a useful tool for VP four-bars	1	1	2	2	1	1	2	2	1	2	2	2	2	1	1	2	2	2	2	2
Exit Survey	Likert Scale was useful in choosing VP or PP	1	1	1	0	1	1	2	1	0	1	1	2	1	1	0	2	1	0	1	0
Exit Survey	I will consider using VP in future designs	2	2	2	1	2	1	2	2	2	2	2	2	1	1	1	1	2	2	1	2
Exit Survey	I chose the best technique for my prototype	2	1	2	1	0	1	2	2	1	1	2	2	1	2	1	2	2	2	2	2
Metrics	**Time to Complete (minutes)**	**27**	**15**	**24**	**23**	**9**	**15**	**20**	**14**	**20**	**12**	**19**	**25**	**8**	**17**	**19**	**7**	**12**	**8**	**22**	**24**
Metrics	**Performance Ratio (ΔX / ΔY)**	**25.7**	**10.7**	**28.1**	**8.2**	**12.1**	**12.8**	**11.6**	**19.3**	**22.2**	**39.2**	**36.1**	**16.3**	**31.3**	**16.9**	**48.2**	**43.9**	**9.7**	**21.9**	**23.1**	**24.7**

<u>**Appendix C - Aggregated Data (Experimental Group):**</u>

		Average: Virtual	Std Deviation: Virtual	Average: Physical	Std Deviation: Physical	Average Delta (V-P)
Initial Survey	I have an understanding of four-bar linkages	0.9	0.6	0.8	0.7	0.1
	I have experience using software	1.1	0.6	0.8	0.4	0.3
	I prefer to design using software	0.2	0.9	-0.6	0.7	0.8
	I have experience building physical models	0.9	0.7	1.1	0.3	-0.3
Likert Scale	VP will require less time than PP	1.1	0.8	-0.6	0.7	1.7
	VP will be sufficiently accurate	1.2	0.7	0.3	0.7	0.9
	Prototyping a four-bar linkage will require many iterations	1.1	0.8	-0.1	0.9	1.2
	Subtotal:	3.4		-0.5		3.9
Exit Survey	VP is the best technique for designing four-bars	1.5	0.6	0.6	1.0	0.9
	GIM is a useful tool for VP four-bars	1.6	0.5	0.3	0.4	1.4
	Likert Scale was useful in choosing VP or PP	0.9	0.7	0.3	0.7	0.6
	I will consider using VP in future designs	1.7	0.5	1.5	0.5	0.2
	I chose the best technique for my prototype	1.4	0.7	-0.9	0.9	2.3
Metrics	**Time to Complete (minutes)**	**17.8**	**6.3**	**32.0**	**7.1**	**-14.2**
	Performance Ratio ($\Delta X / \Delta Y$)	**23.4**	**19.3**	**6.0**	**2.5**	**17.4**

Appendix D: Experimental Data for Control Group

<u>Individual Participant Data:</u>

	Participant #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	Virtual or Physical	P	P	P	P	P	P	P	P	P	P	P	P	V	V	V	V	V	V	V	V
Initial Survey	I have an understanding of four-bar linkages	0	0	1	1	0	1	1	1	0	1	2	0	1	0	1	1	1	1	1	0
Initial Survey	I have experience using software	1	1	1	-1	-1	1	1	2	1	0	1	1	0	1	1	1	2	1	1	1
Initial Survey	I prefer to design using software	0	-1	0	-1	-1	0	-1	0	-1	0	-1	0	-1	0	0	-1	0	2	-1	1
Initial Survey	I have experience building physical models	1	1	1	0	0	1	1	1	1	1	1	1	1	1	-1	1	0	0	1	1
Exit Survey	VP is best technique for designing four-bars	0	0	1	1	0	1	1	1	2	2	1	1	1	2	1	2	2	2	2	1
Exit Survey	GIM is a useful tool for VP four-bars	0	0	0	1	0	0	0	0	0	1	0	0	1	2	1	2	2	2	2	2
Exit Survey	I will consider using VP in future designs	1	1	1	1	1	1	1	2	2	1	2	1	0	2	1	2	2	2	1	2
Exit Survey	I chose the best technique for my prototype	0	1	-1	-1	-1	0	-1	2	-1	-1	-1	-2	1	2	1	2	2	2	2	2
Metrics	**Time to Complete (minutes)**	**32**	**38**	**34**	**28**	**37**	**30**	**22**	**21**	**37**	**21**	**24**	**25**	**18**	**13**	**32**	**31**	**27**	**24**	**31**	**32**
Metrics	**Performance Ratio (ΔX / ΔY)**	**3.9**	**4.2**	**3.9**	**3.9**	**5.6**	**12.8**	**1.5**	**2.9**	**7.7**	**5.9**	**9.4**	**6.6**	**7.0**	**13.4**	**8.8**	**103.4**	**11.4**	**42.5**	**18.3**	**71.7**

	Participant #	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
	Virtual or Physical	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
Initial Survey	I have an understanding of four-bar linkages	1	0	0	-1	1	1	1	1	0	1	1	1	0	0	1	-1	1	-1	2	1
Initial Survey	I have experience using software	1	1	1	1	1	2	1	2	1	1	1	2	0	1	1	1	1	1	1	1
Initial Survey	I prefer to design using software	0	0	1	1	1	-1	0	0	0	-1	0	0	1	-1	-1	1	0	0	-1	0
Initial Survey	I have experience building physical models	1	-1	0	1	0	2	1	1	1	0	1	1	1	0	1	0	1	1	1	2
Exit Survey	VP is best technique for designing four-bars	1	2	1	2	1	1	2	2	1	2	2	2	2	1	2	1	2	2	1	2
Exit Survey	GIM is a useful tool for VP four-bars	1	2	2	2	1	1	2	2	1	2	2	1	2	2	2	1	2	2	2	2
Exit Survey	I will consider using VP in future designs	2	2	2	2	1	1	2	2	1	1	2	2	2	1	1	2	2	1	2	2
Exit Survey	I chose the best technique for my prototype	2	2	1	2	1	1	2	2	2	2	2	2	2	1	2	1	2	2	2	1
Metrics	**Time to Complete (minutes)**	**38**	**19**	**32**	**10**	**26**	**19**	**18**	**27**	**19**	**26**	**23**	**30**	**4**	**21**	**20**	**20**	**20**	**19**	**14**	**14**
Metrics	**Performance Ratio (ΔX / ΔY)**	**55.1**	**14.5**	**54.9**	**74.7**	**10.9**	**27.7**	**27.8**	**82.0**	**10.5**	**15.9**	**47.4**	**14.5**	**93.1**	**19.7**	**16.1**	**22.0**	**16.2**	**28.6**	**20.6**	**46.1**

Appendix D - Aggregated Data (Control Group):

		Average: Virtual	Std Deviation: Virtual	Average: Physical	Std Deviation: Physical	Average Delta (V-P)
Initial Survey	I have an understanding of four-bar linkages	0.6	0.7	0.7	0.6	-0.1
	I have experience using software	1.1	0.5	0.7	0.8	0.4
	I prefer to design using software	0.0	0.8	-0.5	0.5	0.5
	I have experience building physical models	0.7	0.7	0.8	0.4	-0.2
Exit Survey	VP is best technique for designing four-bars	1.6	0.5	0.9	0.6	0.7
	GIM is a useful tool for VP four-bars	1.7	0.5	0.2	0.4	1.5
	I will consider using VP in future designs	1.6	0.6	1.3	0.4	0.4
	I chose the best technique for my prototype	1.7	0.5	-0.5	1.0	2.2
Metrics	**Time to Complete (minutes)**	**22.4**	**7.6**	**29.1**	**6.2**	**-6.7**
	Performance Ratio (ΔX / ΔY)	**34.8**	**27.4**	**5.7**	**3.0**	**29.1**

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