

Virtual or Physical Prototypes? Development and Testing of a Prototyping Planning Tool

Mr. Christopher Lewis Hamon, The University of Texas at Austin

Dr. Matthew G. Green, LeTourneau University

Dr. Matthew G. Green is an associate professor of Mechanical Engineering at LeTourneau University-Longview. His objective is to practice and promote engineering as a serving profession. His focus includes remote power generation, design methods for frontier environments, enhanced engineering learning, and assistive devices for persons with disabilities.

Mr. Brock Dunlap, University of Texas, Austin

Brock is a second year master's student at the University of Texas at Austin. His work focuses on prototype strategy development. He is also involved in Active Learning Module development for engineering students.

Mr. Bradley Adam Camburn, University of Texas, Austin

Dr. Richard H. Crawford, University of Texas, Austin

Dr. Richard H. Crawford is a Professor of Mechanical Engineering at The University of Texas at Austin and is the Temple Foundation Endowed Faculty Fellow No. 3. He is also Director of the Design Projects program in Mechanical Engineering. He received his BSME from Louisiana State University, and his MSME and Ph.D. from Purdue University. He teaches mechanical engineering design and geometry modeling for design. Dr. Crawford's research interests span topics in computer-aided mechanical design and design theory and methodology. Dr. Crawford is co-founder of the DTEACH program, a "Design Technology" program for K-12, and is active on the faculty of the UTeachEngineering program that seeks to educate teachers of high school engineering.

Dr. Daniel D. Jensen, U.S. Air Force Academy

DR. DAN JENSEN is currently a Professor of Engineering Mechanics at the U.S. Air Force Academy. He received his B.S. in Mechanical Engineering, M.S. in Engineering Mechanics and Ph.D. in Aerospace Engineering from the University of Colorado at Boulder. He has worked as a practicing engineer for Texas Instruments, Lockheed Martin, NASA, Lawrence Berkeley National Labs and MSC Software Corp., as well as various consulting and expert witness positions. He also held a faculty position at University of the Pacific and is an adjunct faculty member at University of Texas, Austin. He has received numerous professional awards including a NASA Post-Doctoral Fellowship, ASEE Best Paper Awards, the ASME Most Innovative Curriculum Award, the Ernest L. Boyer - International Award for Excellence in Teaching, the US Air Force Academy Seiler Award for Excellence in Engineering Research and the Outstanding Academy Educator Award. He has published over 100 technical articles and generated approximately \$3.5 million of research; all at institutions with no graduate program. His research includes development of innovative design methodologies and enhancement of engineering education. The design methodology research focuses on development and testing of strategies to enhance effectiveness of prototyping, improve design flexibility and advance reverse engineering and redesign processes. The educational research focuses on development and assessment of active learning (particularly hands-on) approaches to enhance education in engineering.

Virtual or Physical Prototypes?

Development and Testing of a Prototyping Planning Tool

Abstract

A new prototyping planning tool guides designers in choosing between virtual vs. physical prototyping strategies based on answers to Likert-scale questions. We developed this tool to augment prior work in design methods seeking to facilitate prototyping strategy development. This new tool was tested with a pilot experiment in which engineering students were tasked with optimizing the design of a four-bar linkage to be used to draw a specific shape. The students were then instructed to use the new prototyping planning tool to decide whether to create a virtual **or** physical prototype of a four-bar linkage, with the goal of maximizing the performance metric detailed in the design problem statement. This paper describes the new prototype strategy planning tool, the pilot experiment, and results and conclusions. The very encouraging pilot results provide a template and strong motivation for conducting a larger scale experiment for generic prototyping applications.

1 Introduction

An engineering *prototype* (physical or virtual) is an initial manifestation of a design concept, either a scale 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 prototype(s), usually between concept generation and design verification stages. 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.

Prototypes may be 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. In contrast, *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 in the product development process. 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 with motion analysis, finite element analysis, manufacturability evaluations, and/or computational fluid dynamics (CFD.) A lack of tangible interaction and evaluation distinguishes virtual prototypes from physical prototypes¹. Both virtual and physical prototypes may be developed for an entire system or a specific subsystem.

2 Background

Prototyping is a vital phase of the product design process as a whole. A *prototyping strategy* refers here to *the set of choices guiding development of prototype(s)*². 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.”) Most currently published structured prototyping approaches (strategies) focus on management logistics aspects such as lead times, budgets, and project efficiency³. However, Otto and Wood⁴ provide a foundation for an engineering approach to prototyping strategy in the form of a basic method for designing physical prototypes and guidelines for prototype development. Additionally, Otto and Wood cover analytical (virtual) and physical prototyping techniques and appropriate testing procedures to ensure that physical models satisfy design requirements. The authors acknowledge that virtual modelling 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.

Recently a diverse research team presented work towards generalized methodologies for developing *project-specific prototyping strategies*⁵. 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 derive 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 Moe⁶, Christie⁷, and Viswanathan⁸. This prototyping strategy formation method provides a systematic framework to translate independent context variables into dependent prototyping strategy variables in the following four steps (Figure 1):

1. Predict how many iterations each concept requires to satisfy design requirements (in light of: designer’s experience, design requirement difficulty, and design requirement rigidity.)
2. Determine appropriate prototype scaling, subsystem isolation, and functional relaxation for each iteration of each concept (diagrammatic flowcharts aid this step.)
3. Determine which concepts to prototype in parallel, based on available budget and time.
4. Document the resulting prototyping strategy.

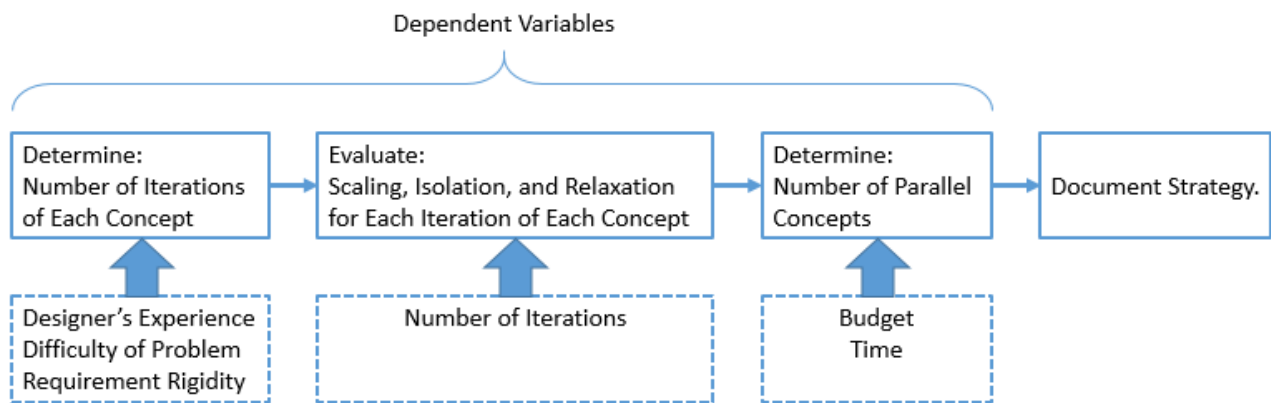


Figure 1: Flowchart of Prototyping Strategy Method⁵

The above methodology was previously experimentally evaluated in a controlled design environment using primarily mechanical engineering students⁵. The published experiment 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 paper.

The research reported here supplements the above prototyping strategy formation method by adding a new prototyping decision – whether a prototype will be virtual or physical. The goal of this study is development and evaluation of a systematic decision tool that guides the choice between virtual or physical prototyping for generalized design problems.

No research was located addressing a structured method aiding engineering designers in deciding between virtual and physical prototyping. However, Ulrich and Eppinger⁹ detail the usefulness of considering virtual versus physical prototyping in a generalized description of the prototyping process. By charting prototyping decisions in two dimensional space (Figure 2), they provide a graphical decision making tool based on the relative accuracy and expense of virtual versus physical prototypes.

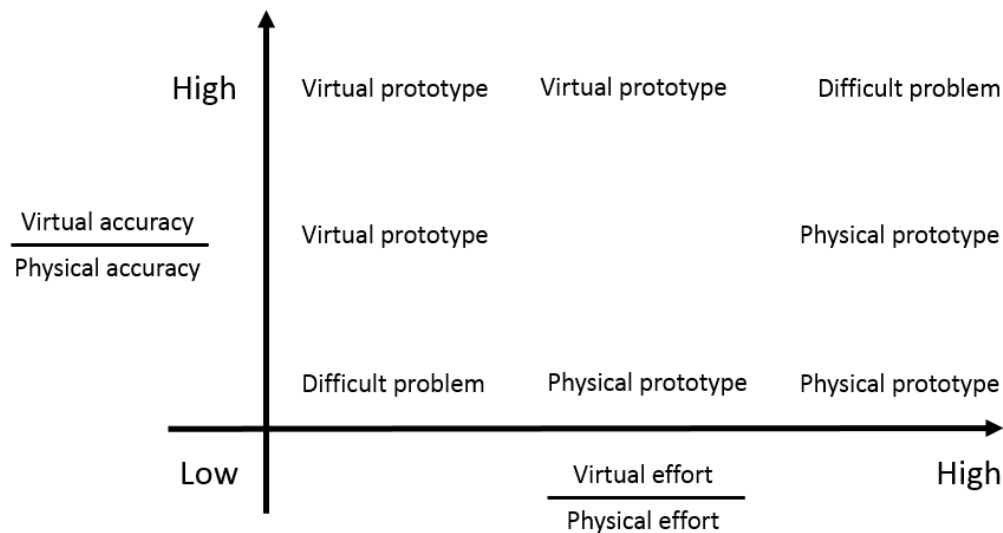


Figure 2: Decision Trade-off between Virtual and Physical Models (Adapted from Ulrich and Eppinger⁹)

Ulrich and Eppinger’s only caveat is that comprehensive virtual prototypes are generally not feasible. However, there are some instances when physical prototypes are prohibitively expensive. For example, Northrop Grumman¹⁰ has virtually modeled an entire aircraft carrier with over three million parts. This complex virtual model 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.

3 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 will be a useful addition to the prototyping strategy formation tool developed by Camburn et al.⁵ described above. A major contribution of this work is the use of a heuristics-based approach, rather than the strictly quantitative approach of the prior work. The new virtual-vs-physical module of the prototyping strategy formation method includes a newly developed tool employing Likert-scale questions (described below, and shown in Appendix A.)

The pilot experimental study reported here tests this heuristics-based, Likert-scale tool. 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.

All forty participants in this pilot experiment were junior or senior mechanical engineering students, with at least basic familiarity with four-bar linkage design. Each participant worked individually. 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. Next, Grashof's Law¹¹ was presented in order to inform participants of the condition necessary to achieve continual rotation of the shortest link in a four-bar linkage, i.e., the sum of the shortest and longest links must be less than the sum of the other two links.

Participants were then instructed to complete an initial Likert-scale survey (Appendix A), 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. Next, creating a virtual four-bar linkage using GIM^{12, 13} software was briefly detailed. The free (with registration) GIM software provides an easy interactive environment for the design and simulation of simple linkages (Figure 3.) GIM allows users to quickly create and modify links and joints, and animate the resulting linkage.

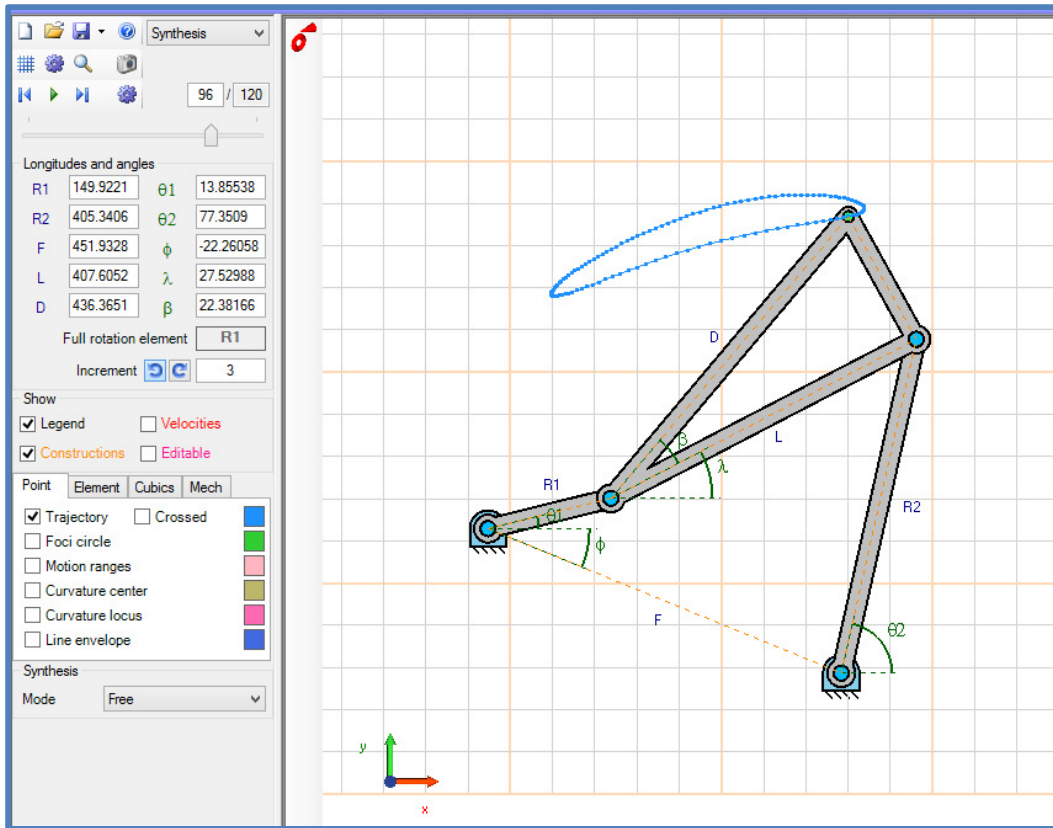


Figure 3: GIM Software User Interface

After a brief demonstration of the GIM software, participants were presented with the following materials and tools (Figure 4) to potentially construct a physical four-bar linkage:

- Four precut foam board pieces
- Four detachable pins
- Hole-punch (for installing detachable pins)
- Scissors (for cutting foam board to the desired length)
- Pencil and paper (for marking the trajectory of a four-bar linkage)

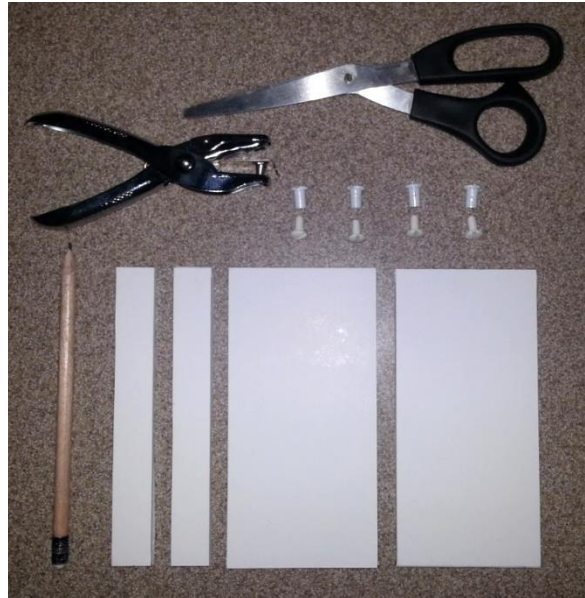


Figure 4: Materials for Four-bar Linkage Physical Modelling, Excluding Paper

Participants were then presented with the problem of designing a continuously rotating four-bar linkage to draw the longest possible horizontal shape (the closest approximation of a straight line). The design objective is to maximize $\Delta X / \Delta Y$ (Figure 5.) Participants were permitted an unlimited number of modifications within a recommended 30 minute time limit, with 48 minutes being the longest time taken.

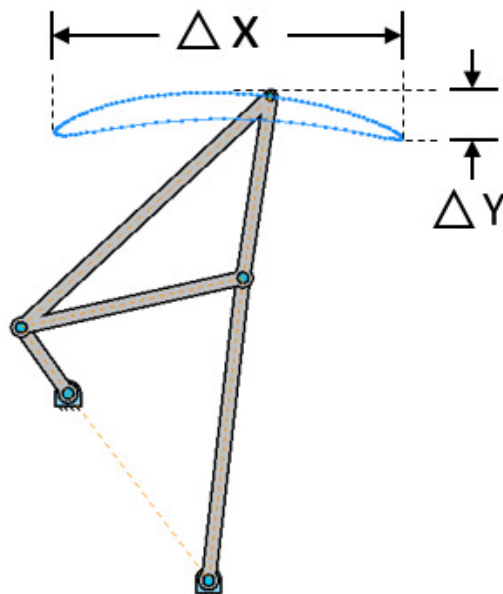


Figure 5: Depiction of Performance Metric: Maximize $\Delta X / \Delta Y$

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 (Figure 6.) Based on the sum of their survey responses (bottom of Figure 6), participants then chose to either virtually or physically prototype a four-bar linkage in order to achieve the design objective.

		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	

Figure 6: Likert-scale Survey for Informing Choice between Virtual and Physical Prototyping

The Likert-scale in Figure 6 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. Question (a) addresses participants’ perception of the ratio of accuracy between virtual and physical models, and question (b) addresses the ratio of effort between virtual and physical models. Question (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 their prototyping start and end times.

Finally, after completion of either a virtual or physical prototype, all participants completed an exit survey. The exit survey recorded participants’ opinion of the choices they made and of the Likert-scale as a decision making tool.

4 Results

Eight out of the forty participants in this pilot study chose to create a physical prototype of their four-bar linkage, and Figure 7 pictures an example being used to draw a pencil line on paper.

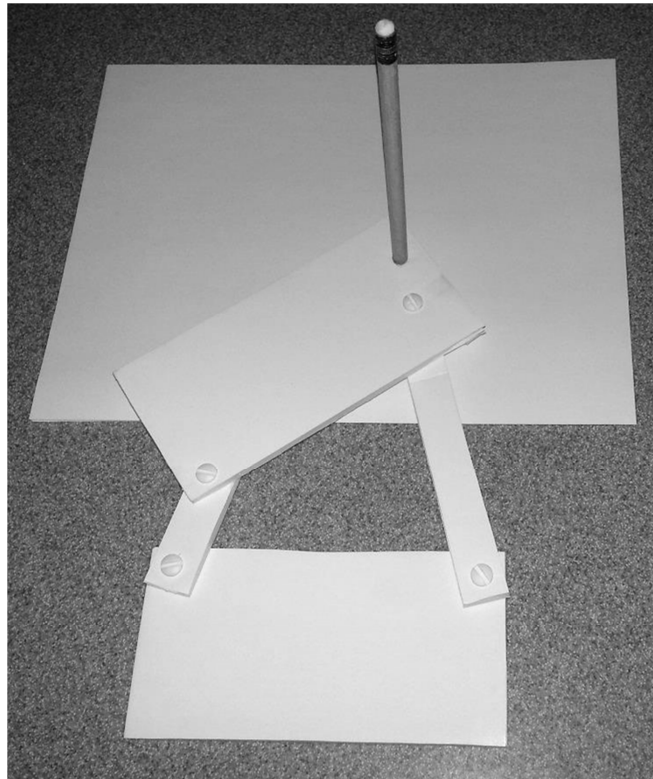


Figure 7: Example of Four-bar Linkage Physical Prototype, with Pencil to Draw a Line on Paper

Table 1 summarizes the 40 trials in this pilot experimental study, including the performance metrics of $\Delta X / \Delta Y$ ratio and time to finish. Likert scale responses range from -2 to +2, with a +1 indicating “agree” and +2 “strongly agree.” Appendix B presents more detailed data.

Participants choosing virtual prototyping achieved $\Delta X / \Delta Y$ ratios averaging almost four times better than participants using physical prototypes. One additional participant not included here was assigned (rather than given a choice) to physically prototype, and outperformed the physical prototypers average in this study by 60% (achieving a $\Delta X / \Delta Y = 9.5$, 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.

Final analysis of the experimental data 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. 80% of all participants chose to build a virtual prototype and these virtual prototypers “agree” (+0.9 on a Likert from -2 to +2) that the heuristics-based, Likert-scale tool “was useful ...”, suggests the usefulness of the tool presented here. Future work will further investigate the usefulness of this tool by comparing these results with a “control” group of

participants who must choose between virtual and physical prototyping without the aid of the Likert-scale tool.

Responses to the “initial survey” indicate participants choosing physical prototyping had more experience building physical models and less experience using software for design (compared to the virtual group), and most physical prototypers expressed a preference for a “hands-on” approach to design. Responses to the “exit survey” indicate a consensus among both groups that virtual prototyping is the best technique for this four-bar linkage design problem. In addition, the virtual group as a whole reported that they believe they chose the best prototyping technique, whereas the physical group disagreed that they had made the best choice.

Table 1: Summary of Experiment Data

		Virtual Group	Physical Group	
Sample size:		32	8	
Strongly Disagree (-2) → Strongly Agree (+2)		Average	Average	Delta (V-P)
Initial Survey	I have an understanding of four-bar linkages	0.9	0.8	0.1
	I have experience using software	1.1	0.8	0.3
	I prefer to design using software	0.2	-0.6	0.8
	I have experience building physical models	0.9	1.1	-0.3
Likert Scale	VP will require less time than PP	1.1	-0.6	1.7
	VP will be sufficiently accurate	1.2	0.3	0.9
	Prototyping a four-bar linkage will require many iterations	1.1	-0.1	1.2
Exit Survey	VP is the best technique for designing four-bars	1.5	0.6	0.9
	GIM is a useful tool for VP four-bars	1.6	0.3	1.4
	Likert Scale was useful in choosing VP or PP	0.9	0.3	0.6
	I will consider using VP in future designs	1.7	1.5	0.2
	I chose the best technique for my prototype	1.4	-0.9	2.3
Metrics	Time to Complete (minutes)	17.8	32.0	-14.2
	Performance Ratio ($\Delta X / \Delta Y$)	23.4	5.9	17.5

*Legend: VP = virtual prototyping, PP = physical prototyping, “Initial Survey” and “Likert Scale” completed before prototyping, “Exit Survey” completed after prototyping.

5 Conclusions and Future Work

This pilot study, itself a prototype for future experiments, provides insight into development of a tool aiding designer choice between virtual and physical prototypes. This paper presents a Likert-scale guide to choosing virtual vs. physical prototyping, which can be a useful addition to a larger prototyping strategy formulation method such as that proposed by Camburn et al⁵. It is

not the intention of this pilot 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 and with varied conditions (such as a control group, a physical-prototype-directed group, and a virtual-prototype-directed group.) 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.

Future work will 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, will provide more generalizable results. Potential design problems must use simple and readily-available computer software for practical reasons.

Finally, additional research will seek deeper understand 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.

Finally, future work may explore correlations among participant MBTI type, preference for virtual vs. physical prototyping, and performance outcomes. Such findings could enable a richer, heuristic-based tool, which more intelligently directs users to the best method for them according to their MBTI type.

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Appendix A: Experiment Worksheet

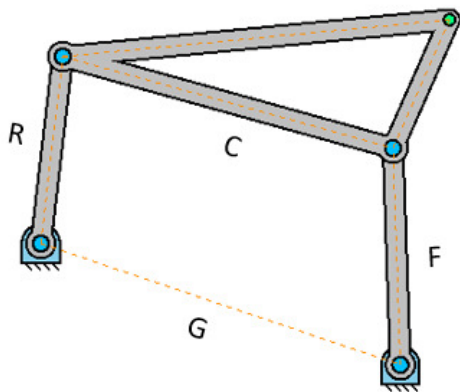
Name: _____

Date: _____

**Four-Bar Linkages
Virtual or Physical 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.

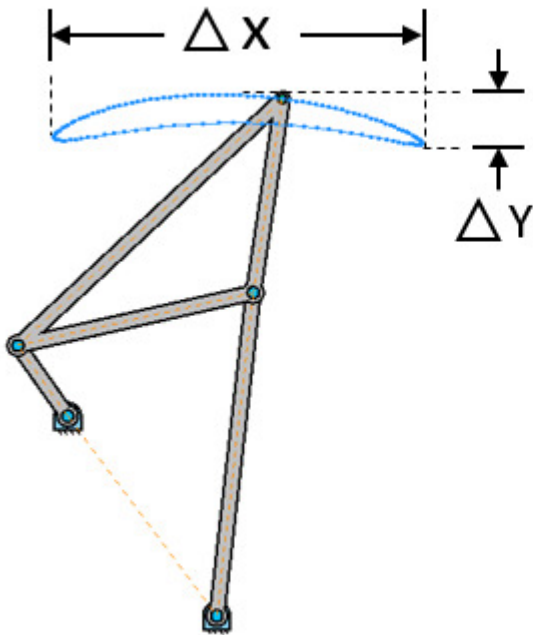
		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly agree.
		-2	-1	0	+1	+2
a)	I have an understanding of four-bar linkages.					
b)	I have experience using computer simulation software (e.g., CAD, FEA, etc.).					
c)	I prefer to design using software, rather than building physical models.					
d)	I 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 $\Delta X / \Delta Y$
- 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 email your virtual prototype file (FirstName_LastName.gim) to **[researcher email address]**

Appendix B: Experimental Data

Participant #		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40			
Virtual or Physical		P	P	P	P	P	P	P	P	V	V	V	V	V	V	V	V	V	V	V	V	V	V	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	2	0	1	1	1	1	0	0	1	0	0	1	1	1	1	1	0	2	1	1	1	1	1	2	1	-1	1	1	1	2	0	1	1	1	1	1	1	1	1	0	1		
	I have experience using software	0	1	0	1	1	1	1	1	1	1	1	-1	1	2	1	1	2	1	1	2	1	1	1	1	1	1	1	1	1	2	2	1	2	1	1	1	1	1	1	2	0	1	0
	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	0	-2	1	0	0	1	0	0	0	1	1	0	0	0	0	0	-1	-1	0	1	-1	0	
	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	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	0	1	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	2	1	2	1	0	2	1	1	-1	1	2	1	2	1	2	1	1	1	2	2	-1	2	
	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	2	1	1	1	1	1	2	1	1	1	2	1	1	2	1	1	2	1	1	1	0	2	1
	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	2	2	2	1	1	1	1	2	2	1	0	1	1	1	1	1	2	1	1	2	2	1	
	Subtotal	0	-2	0	-1	0	-1	1	-1	2	3	2	0	3	3	3	4	4	3	4	3	6	4	5	3	2	4	5	4	1	2	5	3	4	4	4	4	3	4	4	3	4		
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	1	2	2	1	1	1	2	2	1	1	2	2	2	2	2	1	2	2	1	2	2		
	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	1	1	2	2	1	1	2	2	1	2	2	2	2	2	2	1	1	2	2	2	2		
	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	1	1	1	0	1	1	2	1	0	1	1	2	1	1	0	2	1	1	0	1	0		
	I will consider using VP in future designs	2	1	2	1	2	1	2	1	1	2	2	2	2	1	2	2	1	2	1	2	2	2	2	1	2	1	2	2	2	2	2	2	2	1	1	1	1	1	2	2	1	2	
	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	2	1	2	1	0	1	2	2	1	1	2	2	1	2	1	2	1	2	2	2	2	2	
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	27	15	24	23	9	15	20	14	20	12	19	25	8	17	19	7	12	8	22	24			
	Performance Ratio ($\Delta X / \Delta Y$)	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	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			

Participant #		Average: Virtual	Std Deviation: Virtual	Average: Physical	Std Deviation: Physical	Average Delta (V-P)
Virtual or Physical						
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	1.2	-0.5	0.9	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	5.9	2.4	17.5