Design, Kinematics, and Prototyping of transFORM:

A Room-Scaled Reconfigurable Environment for an Urban Public Space

Alexander Bernard, Student

Dr. Keith Green, Project Advisor

Architectural Robotics Lab

Sibley School of Mechanical and Aerospace Engineering

5/23/2018

Alexander Bernard
Sibley School of Mechanical and Aerospace Engineering
Masters of Engineering Report

1 Abstract

This Masters of Engineering (M.Eng) project with the Cornell Architectural Robotics Lab (ARL) focused on the design, kinematics, and physical prototyping of transFORM, a room-scaled, reconfigurable environment for an urban public space. Specifically, the project developed a new type of kirigami-inspired robotic mechanism. Notably, the joints of the various transFORM hinged panels are modeled with the same mathematics used to describe the position and orientation of robotic arms. The digital prototype was characterized in a MATLAB script capable of modeling the device's internal forces and displaying the transFORM device in any arbitrary configuration. The digital model was used to verify that the large-scale physical prototype was not only geometrically possible at a large-scale, but that its actuation was possible even using relatively inexpensive, off-the-shelf linear actuators. The design and kinematics efforts of the project were reported in a technical paper (see appendix) submitted to the IEEE CASE (The International Conference on Automation Science and Engineering), a benchmark conference for mechatronics and automation. Following submission of the technical paper, the M.Eng project turned to the fabrication of a medium-fidelity physical prototype of the central mechanism of transFORM. The full arc of the project therefore explored the theory, mathematics, and simulation of the novel kirigami model as well as its translation to a functioning, room-scaled, physical prototype. The mechanism and the prototyped artifact are novel contributions to kinematics and mechatronic systems. (The M.Eng project initially focused on a human-machine design tool at room-scale; contributions to this project are included in this reports index).

2 Table of Contents

3 Introduction

Over the course of the 2017-2018 school year, Alexander Bernard's Masters of Engineering (M.Eng.) Project contributed to two different projects in the Architectural Robotics Lab (ARL) within the School of Design and Environmental Analysis (DEA). The body of this report documents contributions to transFORM – specifically the brainstorming (Section 6), modeling (Section 7), and building (Section 8) of a new type of device based on the classic four-bar mechanism and kirigami. Contributions to the COMPREHEND Project, that predates transFORM, are documented in the Appendix (Section 10.3)

4 Acknowledgments

Alex would like to thank the following people:

- Keith Green for all of his encouragement and guidance over the course of this year.
- The contributors to the transFORM and Library Cubed projects: Carlos Aguiar, Gilly Leshed, Camille Andrews, Jon McKenzie.
- Andy Ruina and Bob Connelly for conceptual guidance when developing the transFORM digital prototype.
- Alex Steelman for help with transFROM physical prototype fabrication.
- The staff of the Digital Design and Fabrication Studio.
- The contributors to the COMPREHEND Project: Yixiao Wang, Ross Knepper, and Teng Teng.

5 transFORM Overview and Methodology

transFORM is an evolution of the Library Cubed Project within the ARL. The Library Cubed Project is a cross-disciplinary approach to developing a "cyber-physical library module for communities having inadequate or no library access" (2018). In order to explore the possible functions of a device meeting the aims of the project, DEA doctoral student Carlos Aguiar has been developing the system through a method he calls Co-Design At Scale (CoDAS) where scale models of a larger system are manipulated by a number of participants to generate a final design. The scale models used for this process are available in Figure 1.

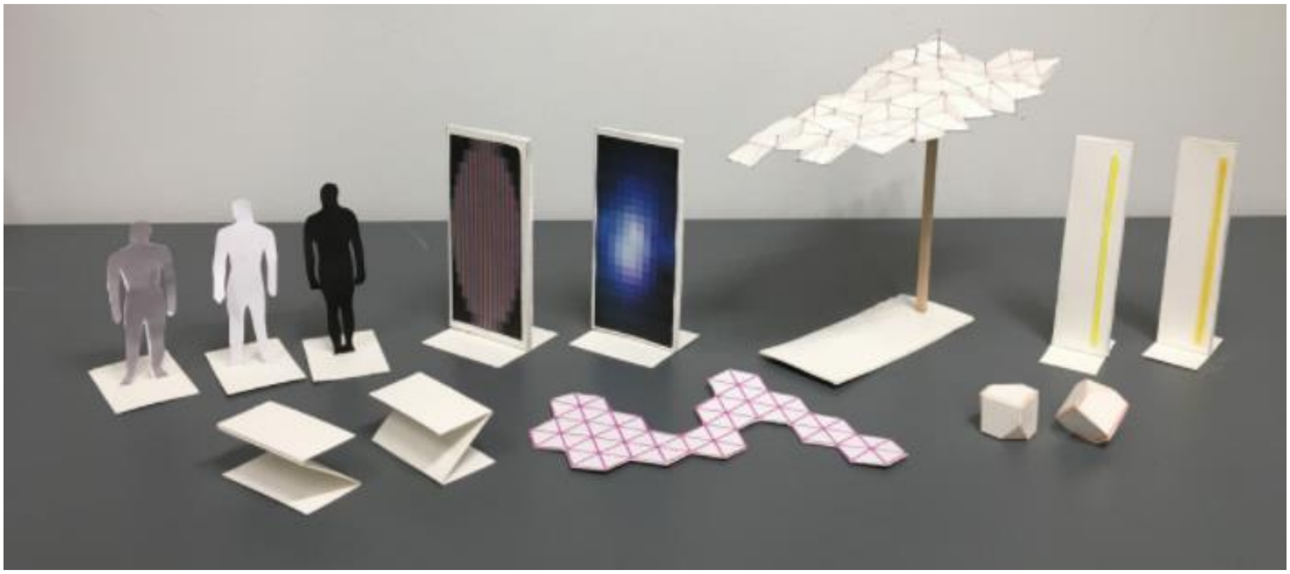

Figure 1 – Scale models of larger Library Cubed system used for Carlos' CoDAS design methodology. This picture comes from a paper recently submitted to the 2018 Conference on Computer-Supported Cooperative Work and Social Computing

Alex joined the project to help develop the physical form that the Library Cubed system would assume in the real world. Therefore, this prototype needed to be able to support the functions that Carlos was exploring through the CoDAS process. Alex generated a few small-scale cardboard models before being introduced to a design based on pop-up origami. Alex authored a paper on the kinematics and structural mechanics of origami at room-scale, and also built a physical prototype which will be used by Carlos for further development of the Library Cubed project. This device has been named "transFORM" due to its reconfigurable nature.

6 transFORM Early Brainstorming

Carlos' CoDAS methodology, as applied to functional components of the Library Cubed system, focuses on how users expect to interact with 6 main elements:

1. Lighting
2. Ceiling
3. Bench Seating
4. Chair Seating
5. Screen Displays (and computers to power them)
6. Flooring

Carlos' research is concerned with how potential users envision themselves accomplishing certain tasks using the 6 main elements. These tasks, or "gerunds", are as follows:

1. Reading
2. Learning
3. Writing
4. Resting
5. Observing Others
6. Working
7. Sketching/Drawing
8. Surfing the Internet
9. Social Media
10. Exploring the Surroundings
11. Playing Video Games

In order to understand all of the possible relationships between the 6 elements, Alex attempted to map out every possible combination. After realizing there were 2450 possible configurations, Alex instead decided to build a small cardboard model of a device which incorporated all 6 elements while maintaining the ability to be *reconfigurable* – that is, to be able to pick and choose which elements are active at any given moment. This way the proposed design would be able to accomplish many of the 2450 possible configurations without intentionally designing for each and every combination.

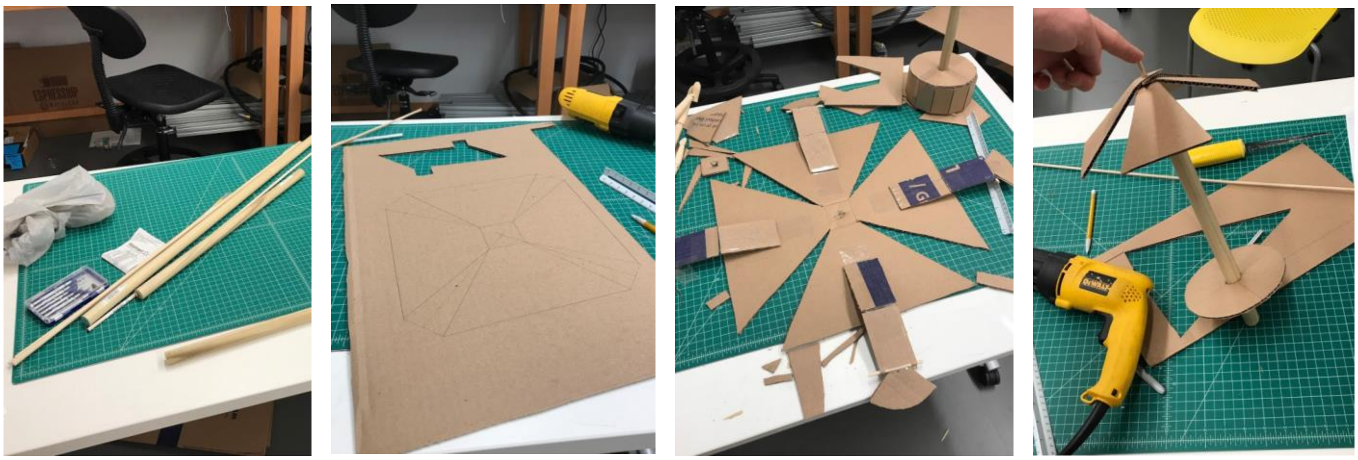

Figure 2 – Brainstorming Build Day – Work in Progress

Figure 3 – Brainstorming Build Day – Finished Product Shown Staged with Wooden Models

Carlos also brainstormed a potential design, motivated by popup-book style origami, something Dr. Green holds as an exciting realm of mechanical design. Carlos' design is available in Figure 4. Results of several iterations of naming conventions used in analysis and final fabrication are available in Figure 5 and Figure 6.

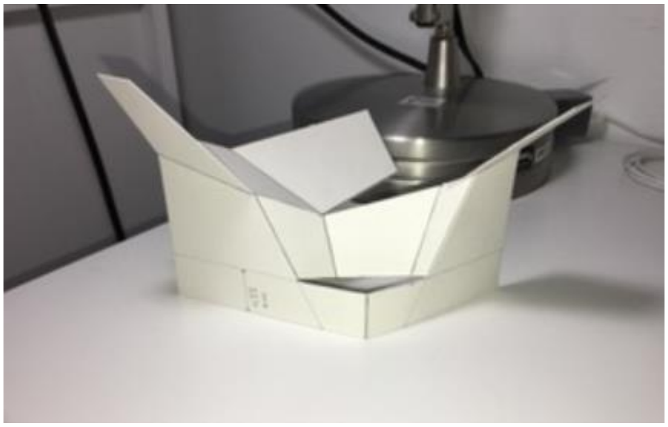

Figure 4 – Carlos' Initial Design for the transFORM device.

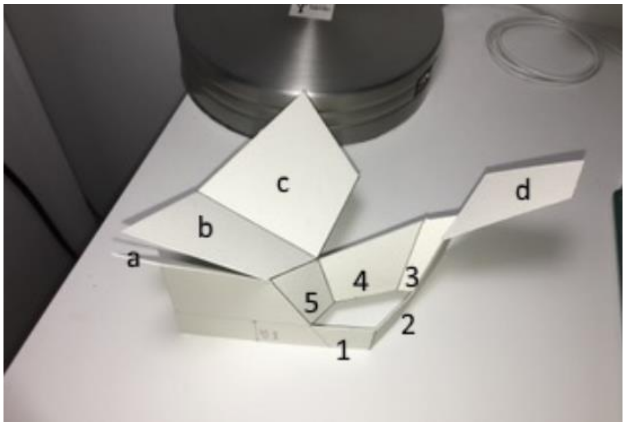

Figure 5 – First naming convention for the transFORM device.

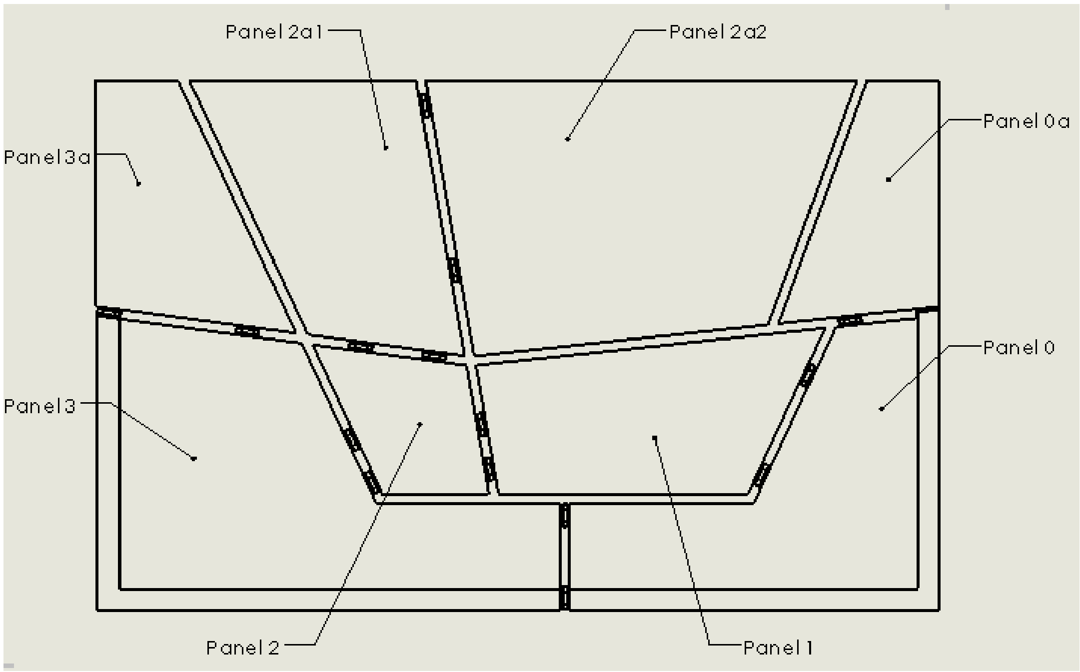

Figure 6 – Final naming convention for panels in the transFORM device.

Carlos provided Alex with a copy of a Paul Jackson's *Cut and Fold Techniques for Pop-Up Designs*, which inspired Carlos' early transFORM design. Alex decided to generalize the designs within this book in the form of kinematic equations, which lead to the digital prototype described in Section 7, which together motivated the physical prototype presented in Section 8.

7 transFORM Digital Prototype

Carlos' initial design for the transFORM device (Figure 4) was envisioned as a large-scale device, replacing paper and folds with large panels and hinges. The transFORM device is, at its core, a kinematic loop consisting of four revolute joints – more familiarly known as "hinges" since the device connects panels rather than bars. These joints allow rotational motion about one axis while constraining rotational and translational motion in all other directions.

Alex was asked to take the origami design Carlos created and identify whether it was feasible for full-scale construction. He was initially concerned the material properties of paper allow for the motion of the origami device, and that these geometric constraints would not scale well to "room-scale" (building the device to the height of a ceiling).

Alex began searching for a suitable software package to model the geometry and internal forces of a large-scale piece of this "popup origami." While a CAD package like Solidworks can simulate motion between parts, it is very poor at estimating internal forces, since it needs finite element analysis to do so. Finite element analysis is not a strong suit for Solidworks. Finite element analysis programs like Ansys do a great job with deformations and internal pressures, but cannot handle relative motion between parts. Alex looked into origami toolboxes for MATLAB, but found the only options available were for geometries created using folds only – and the transFORM device contains a cut through two folds. However, having recently studied robotic manipulator arms, Alex decided to model the joints of the transFORM device with the same mathematics used to describe the position and orientation of robotic arms. The mathematics and theory of this process are documented in the 2018 CASE paper, available in the Appendix (Section 23). Examples of the hand calculations that contributed to this effort are available in Figure 7.

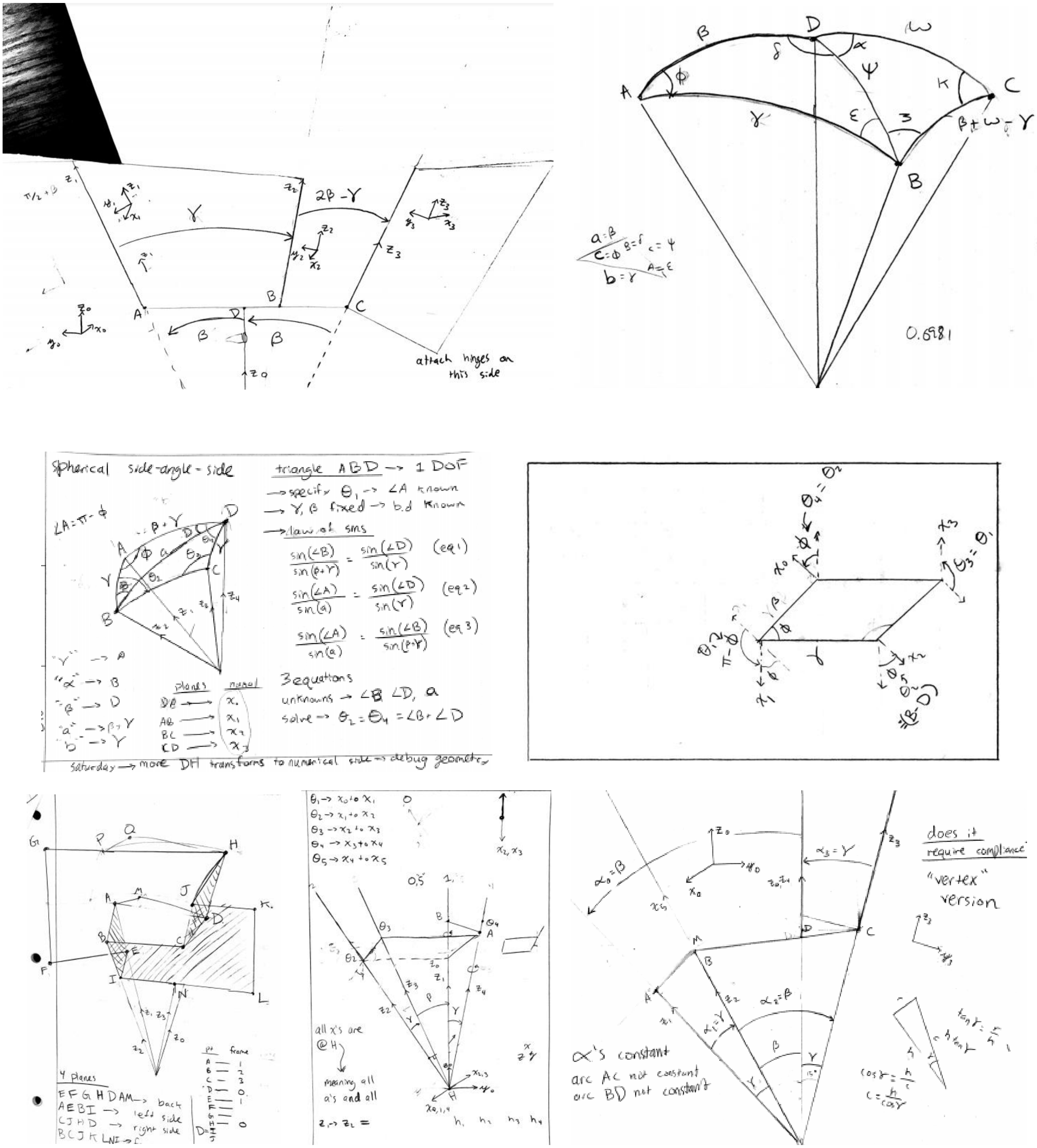

Figure 7 – Selected hand calculations and diagrams contributing to the digital prototype. These images demonstrate some of the work put into describing the geometry of the mechanism – which involved both spherical trigonometry as well as 3D kinematic chains.

The “digital prototype” emerged as a MATLAB script capable of modeling the device’s internal forces and displaying the transFORM device in various configurations. Through this model, Alex was able to verify that the prototype was not only geometrically possible at a large-scale, but that actuation is possible even using relatively cheap off-the-shelf linear actuators. Figure 8 shows the digital prototype’s output onto the screen after calculating internal forces in two different configurations. The digital prototype also allowed Alex to identify the limit of motion (see Figure 9).

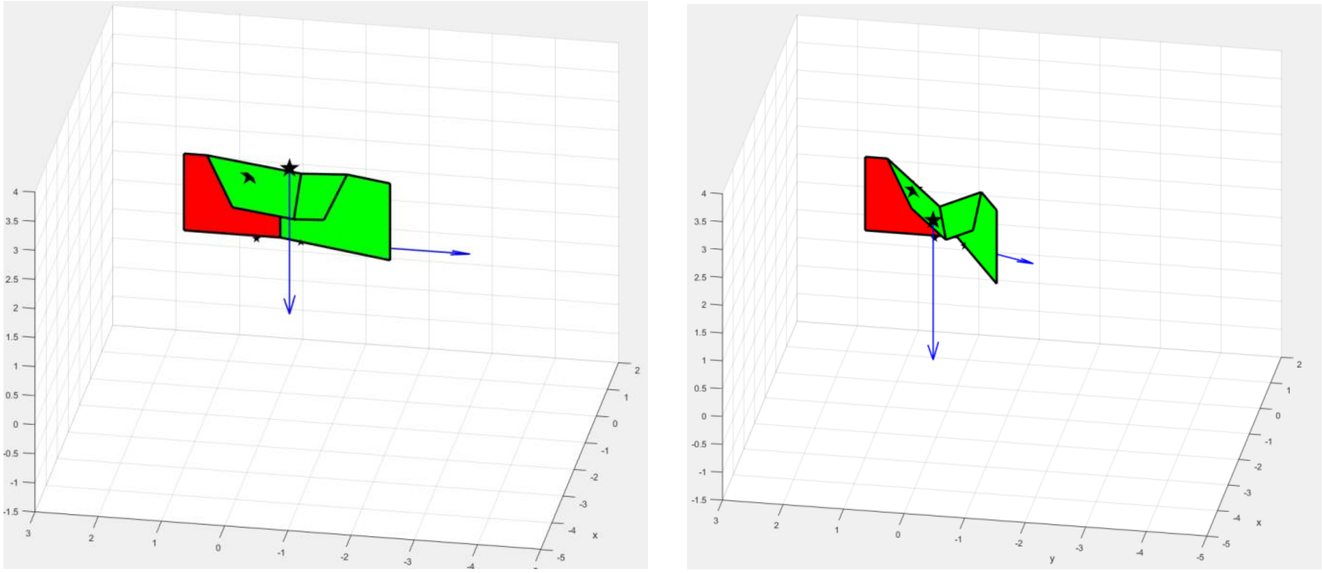

Figure 8 – Digital Prototype output displayed in two different configurations. Blue arrows represent relevant internal forces (gravity and actuation). Stars represent centers of gravity. Red denotes fixed to ground, while green denotes constrained only by hinges.

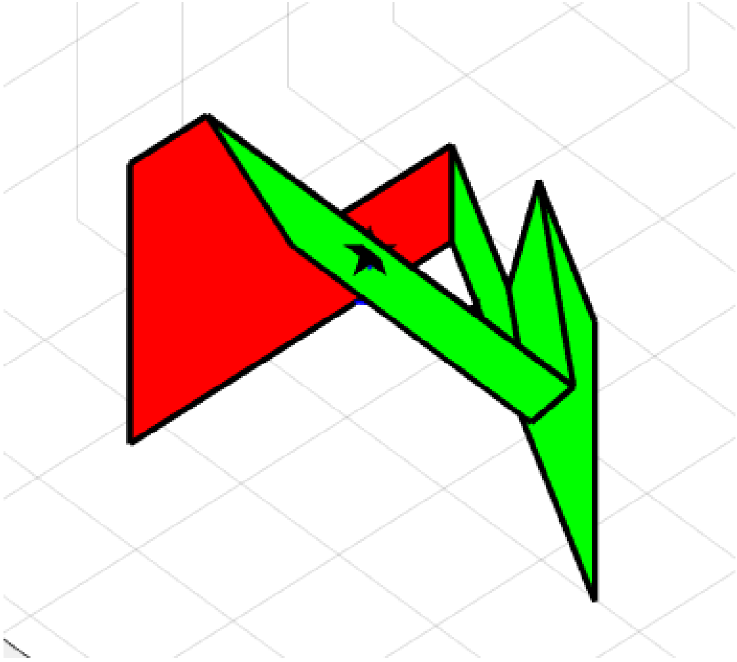

Figure 9 – transFORM limit of motion due to interference.

8 transFORM Physical Prototype

After verifying the feasibility of a physical prototype through the digital prototype, and after authoring a paper for IEEE CASE 2018 conference (see appendix), Alex began developing a physical prototype of the transFORM device. The prototype delivered is substantially complete: it was decided that the lab only needed the lower half of transFORM device fabricated at this time. This was sufficient for verifying the research developed in pursuit of the digital prototype, since the digital prototype was also only a model of the bottom part of the transFORM mechanism.

8.1 Physical Prototype Design Requirements

The ARL desired a prototype of the transFORM device to test user reception to a reconfigurable space. Alex's interest in the prototype extended to verification of the model created for the conference paper. The prototype needed to also accommodate the dimensions of the fabrication equipment in the Human Ecology Building's Wood Shop. To these ends, the prototype needed to meet the following requirements.

1. All panels must be smaller than 50" x 100" because that is the available cutting surface for the laser cutter
2. Stand under its own weight
3. Electrically actuate from flat closed (see Figure 11) to open (see Figure 12)
4. Maintain the relative dimensions of the device specified in the conference paper (see Figure 8)

The prototype was not intended to be very high tech or complicated. Rather, the physical prototype serves as a proof of concept of the spherical four-bar mechanism developed in the paper and modelled in the digital prototype, while also providing a platform on which Carlos' CoDAS methodology can continue to be pursued.

8.2 Physical Prototype B.O.M.

COMPONENT	SOURCE	PRICE	QUANTITY	TOTAL
LINEAR ACTUATOR	Amazon	$ 64.00	1	$ 64.00
HINGES	McMaster Carr	$ 12.06	16	$ 192.96
MDF, 0.75X48X96	JLC Supply	$ 46.00	3	$ 138.00
BRACES	McMaster Carr	$ 15.00	4	$ 60.00
ELECTRONICS BOX	Amazon	$ 7.81	1	$ 7.81
MOMENTARY DPDT SWITCH	Amazon	$ 14.45	1	$ 14.45
PLYWOOD FOR BASE	Wood Shop Inventory	$ 25.00	1	$ 25.00
CASTER WHEEL	Amazon	$ 7.25	1	$ 7.25
FASTENERS	Home Depot	$ 71.93	1	$ 71.93
			Total:	**$ 581.40**

Table 1 – Bill of Materials for the transFORM physical prototype – prices are shown after tax.

8.3 Physical Prototype Design

The first step of fabrication was translating the geometry from the digital prototype to a precise CAD model. Solidworks was chosen due to Alex's prior familiarity with the software package. Through the modeling process, Alex identified constraining dimensions with respect to the 50" x 100" cutting surface constraint.

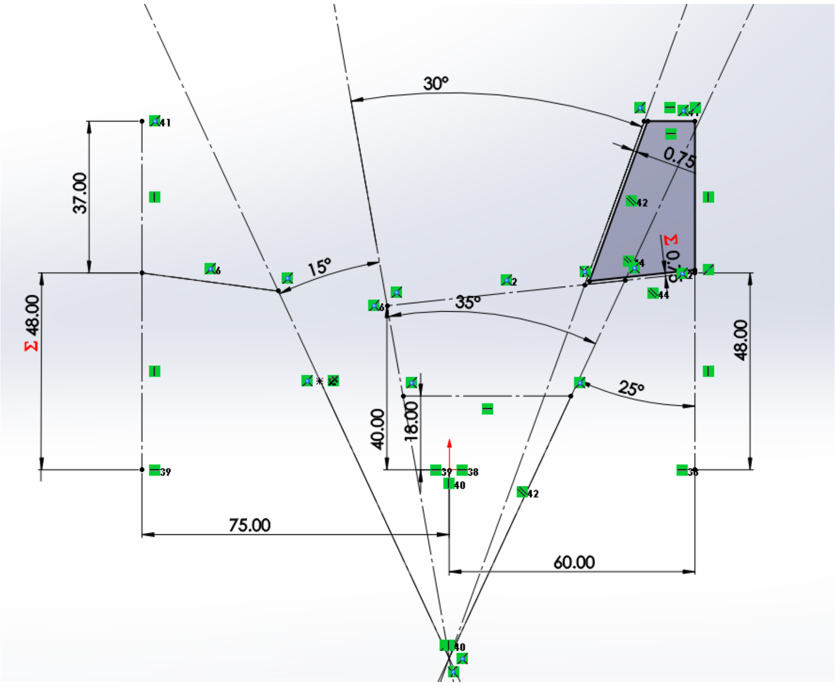

Figure 10 – A demonstration of the constraints necessary to recreate the precise geometry necessary for spherical four-bar mechanism defined in the CASE 2018 conference paper (see Section 10.2)

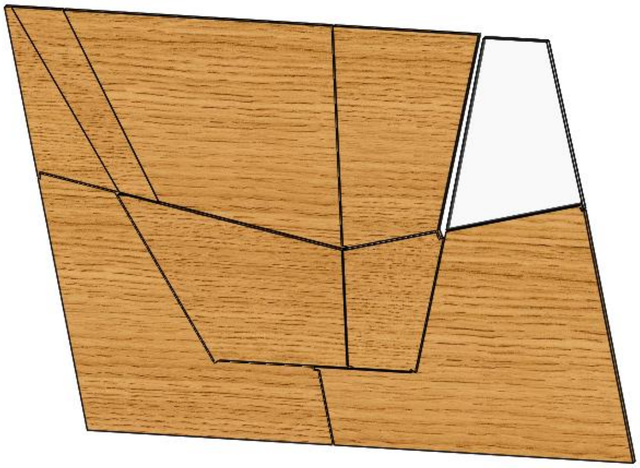

Figure 11 – Flat "closed" configuration of the transFORM device. This comes from an early CAD model of the transFORM device which did not yet incorporate the strap hinges that were incorporated later (see Figure 13).

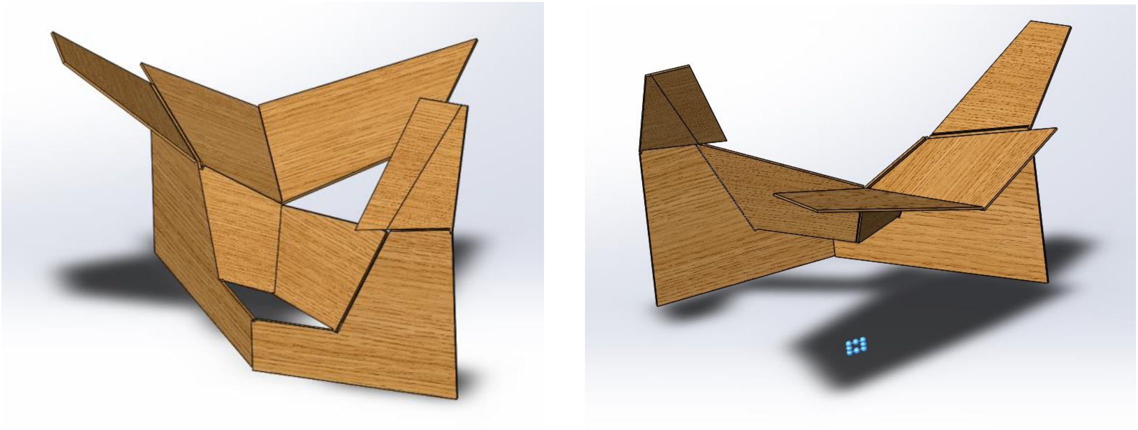

*Figure 12 – Working "open" configuration. While this is not the absolute **limit** of motion (for this, see Figure 9), the represents the desired working limit of the device, and is defined by the configuration where the side of edge panel 2a1 is parallel with the top edge of panel 3 (see Figure 6 for panel naming definitions).*

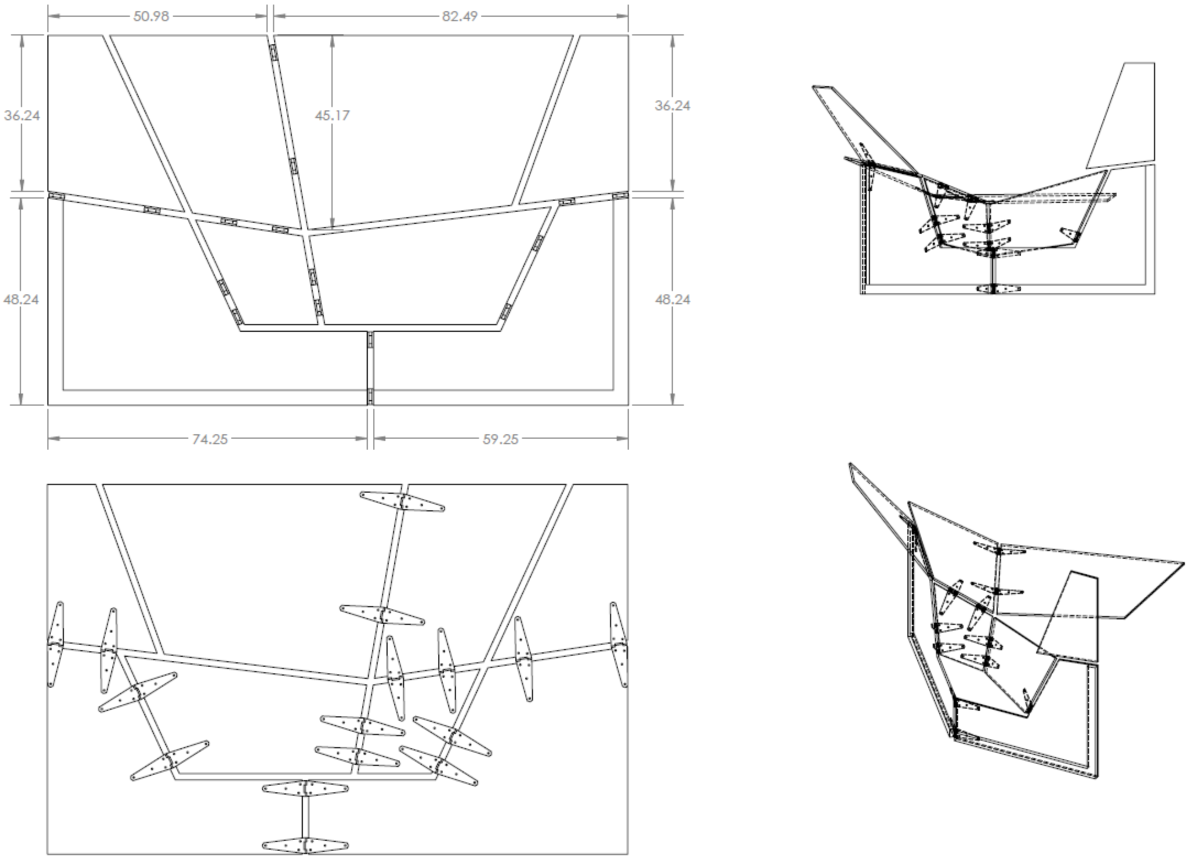

Figure 13 – Model of transFORM with strap hinges incorporated.

Although the device was now designed in CAD as prescribed by Carlos' original design (see Figure 4), it could not stand on its own, especially when in the "flat configuration" (see Figure 11). Therefore, a "foot" was designed to provide stability when transFORM is in its fully flat configuration. Support brackets were chosen from the McMaster Carr website for stability. Please see Figure 14 and Figure 15.

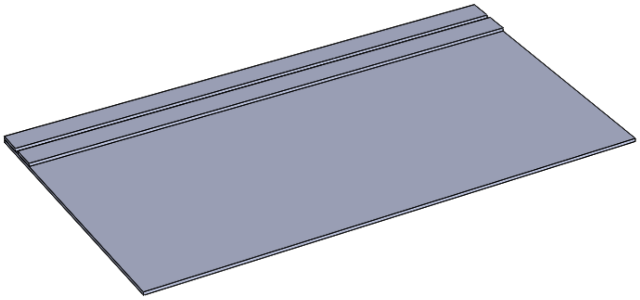

Figure 14 – "Foot" for the transFORM device which provided stability. It is a simple platform with a slot for panel 3 to slide into. Four brackets attach the foot to the device.

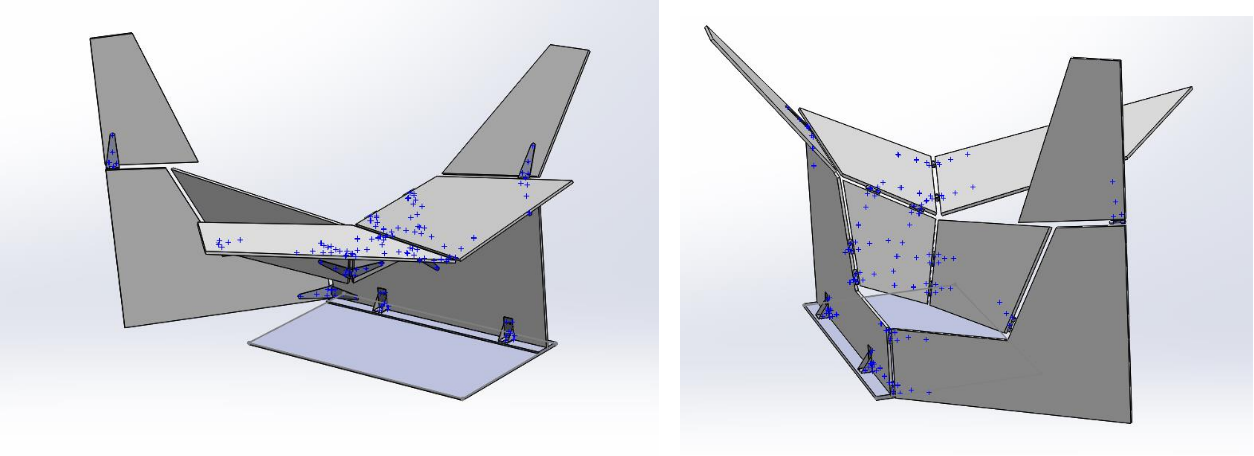

Figure 15 – transFORM CAD model with foot installed, including the brackets.

Engineering undergraduate Alex Steelman helped design the mounting surfaces for the linear actuator (see Figure 16). Alex (Bernard) helped Alex Steelman understand Solidworks and design the dimensions of the actuator's mounting surfaces given the geometric constraints of the device.

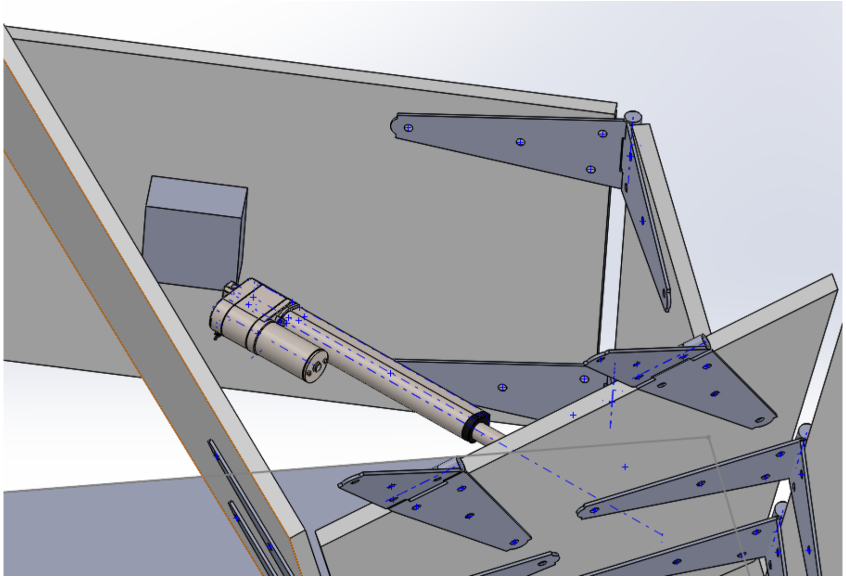

Figure 16 – Linear actuator mounting designed by Alex Steelman

The system is meant to be actuated by electrical components. Therefore, Alex had to design a simple, robust electrical system to supply 12 V to the linear actuator. A "double pole, double throw" (DPDT) switch was necessary because the linear actuator changes direction by reversing polarity. A DPDT switch can reverse polarity on a constant voltage power supply without causing a short circuit (see Figure 17). Alex selected a generic DPDT switch. He also wired the switch into a plastic hobby box in order to avoid ugly wire terminations and provide a way to rigidly attach the switch to the transFORM device.

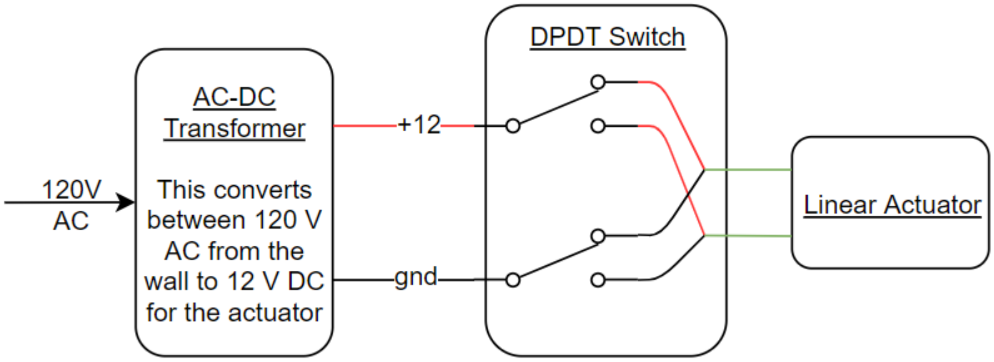

Figure 17 – transFORM electrical diagram showing the general idea behind a DPDT switch.

8.4 Physical Prototype Materials and Components

Medium Density Fiberboard (MDF) was selected as the desired material for the panels of the transFORM device because it can be easily and precisely laser cut. Alex ordered the sheets of MDF after packing the panels onto three 4' x 8' sheets to minimize waste (see Figure 18). A thickness of ¾" was selected for the MDF due to the large size of the prototype (see dimensions in Figure 13) and needing more structural integrity than the originally suggested ¼" thickness.

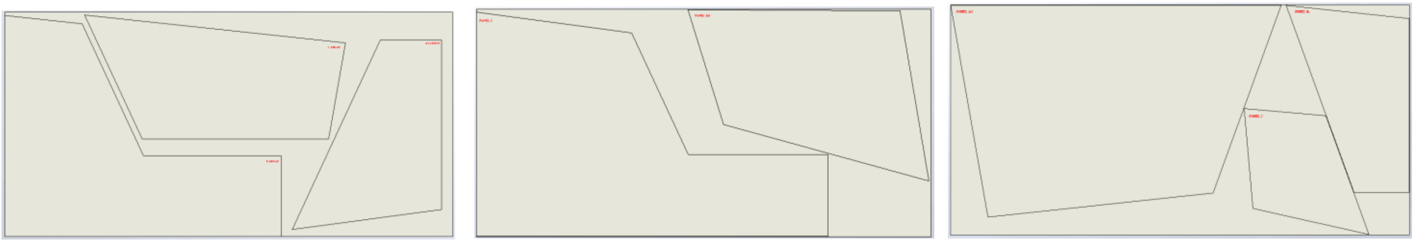

Figure 18 – Solidworks drawing of laser cutting guides, arranged in tight packing on three 4'x8' sheets to accommodate both the maximum available MDF sheets as well as the maximum dimensions of the laser cutter.

Hinges were selected to fit the constraints that ¾" thick panels put on the joints. Due to the large thickness (compared to the original paper folding this is modelled after), gaps were required between the hinges to facilitate full range of motion without interference (see Figure 19). After extensive testing on Solidworks, Alex determined a 1.5" gap was necessary between each panel. There are very few off-the-shelf hinges which have a more than 0.75" between the centerline and first fastener hole. Therefore, Alex decided that strap hinges were a good, cost effective fit that were also available off-the-shelf from McMaster-Carr (see Figure 20).

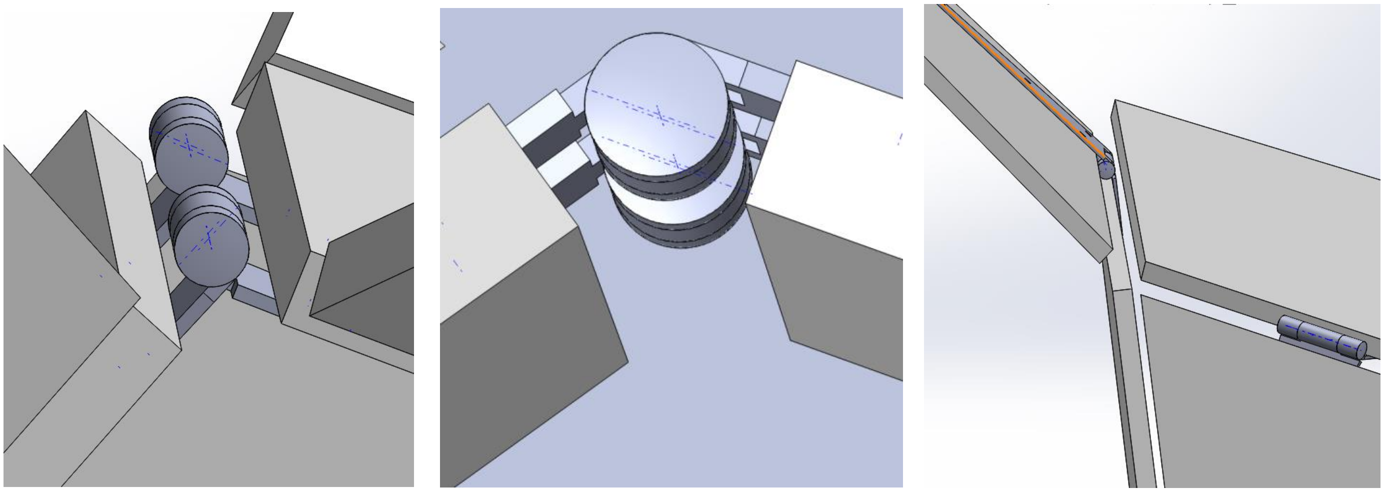

Figure 19 – Final Solidworks model select screenshots to highlight the process used to validate panel gap and hinge compliance.

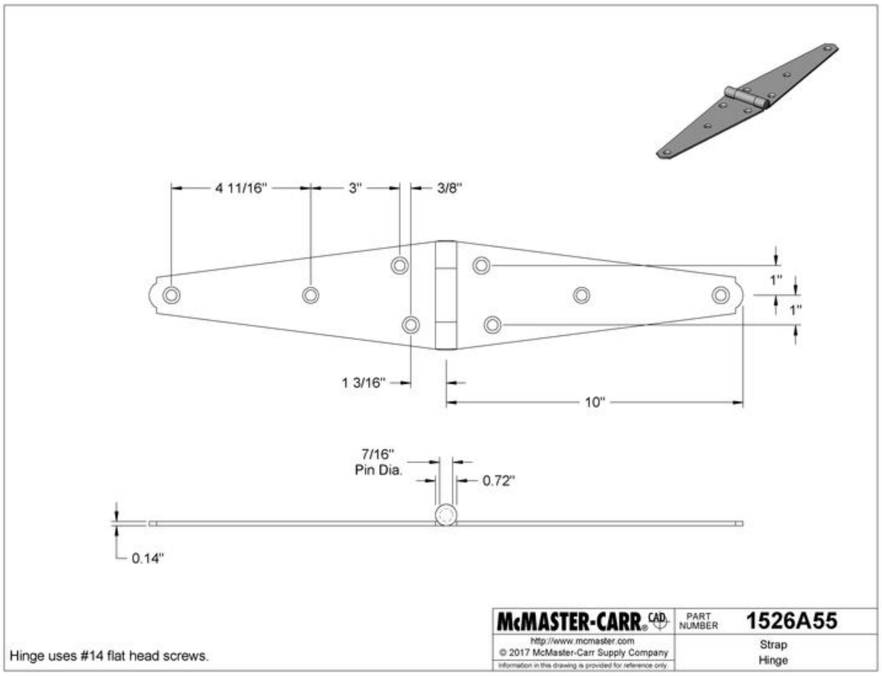

Figure 20 – Dimensioned drawing of McMaster-Carr strap hinge used in the physical prototype.[1]

The linear actuator needed to withstand approximately 180 lbs of force (see Figure 22). Multiplying by a factor of safety of 2, that is 360 lbs of force. This put a force requirement on the linear actuator. Alex analyzed the desired range of motion of the transFORM device using the Solidworks model. The digital prototype can calculate forces for the full range of motion of transFORM device – from flat closed (see Figure 11) to full limit of motion (see Figure 9). However, the device only needs to actually move from flat closed to working open (see Figure 12). Therefore, the full range of motion shown in Figure 22 is not necessary. After doing some basic trigonometric hand calculations, Alex determined that the linear actuator needed to have a 12” stroke, at a minimum. After searching online, Alex identified an actuator was chosen (see Figure 21), which has a 330 lb maximum force (reasonably close to 360 lbs) and 14” stroke (just to be safe).

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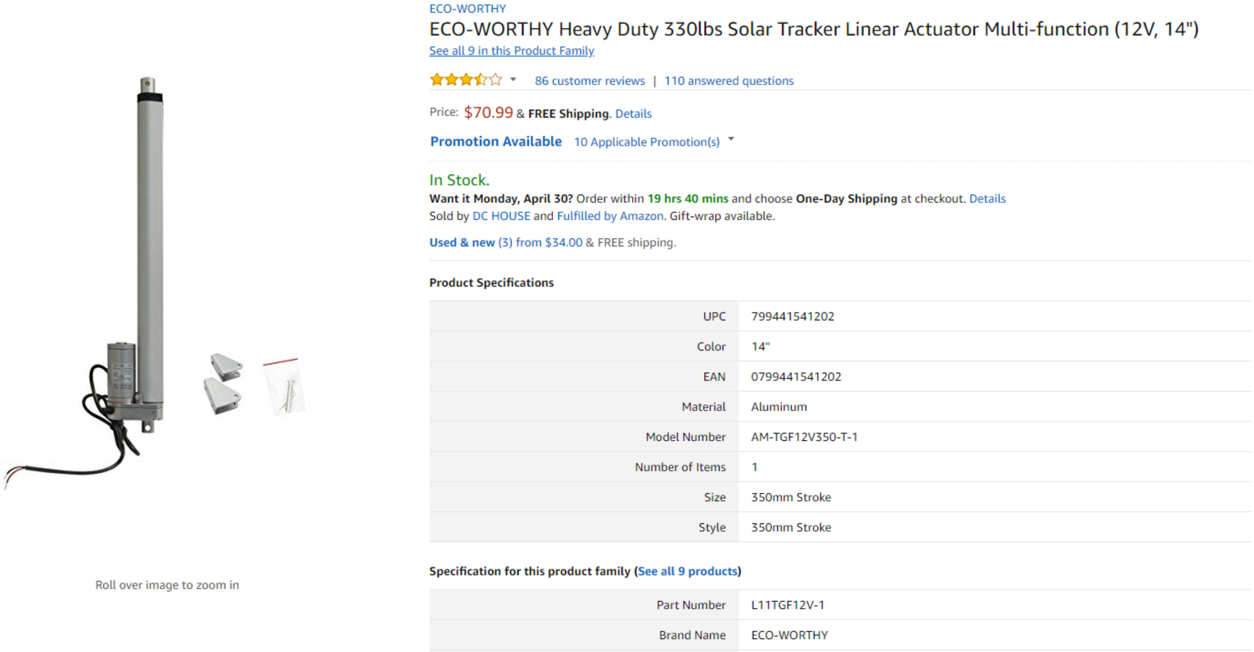
[1] Please see McMaster-Carr Part No 1526A55 at https://www.mcmaster.com/#1526a55



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Color	14"
EAN	0799441541202
Material	Aluminum
Model Number	AM-TGF12V350-T-1
Number of Items	1
Size	350mm Stroke
Style	350mm Stroke

Specification for this product family (See all 9 products)

Part Number	L11TGF12V-1
Brand Name	ECO-WORTHY

Figure 21 – Linear actuator chosen for physical prototype.

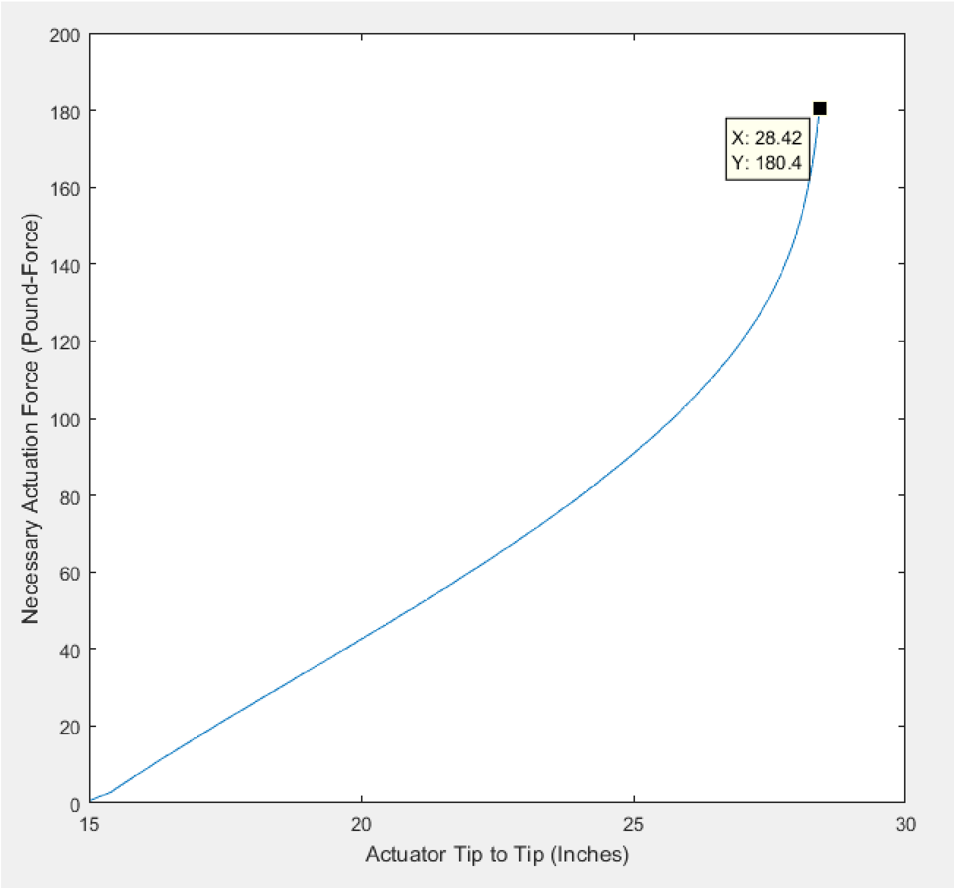

Figure 22 – Plot of necessary linear actuator force against linear actuator length. This was generated using the internal force model developed for the digital prototype of the transFORM device. This shows that a linear actuator will need approximately 180 lbs of force to actuate the transFORM device.

8.5 Physical Prototype Fabrication and Assembly

Although the panels were designed to be cut with the laser cutter (this was the source of the 50”x100” constraint), the laser cutter available was not powerful enough to cut through ¾” of MDF. Therefore, the laser cutter simply scored the MDF and a guided circular saw was used to finally cut the MDF panels (see Figure 23).

Figure 23 – Cutting the MDF panels using a circular saw.

Engineering undergraduate Alex Steelman assisted with assembling the panels (see Figure 24).

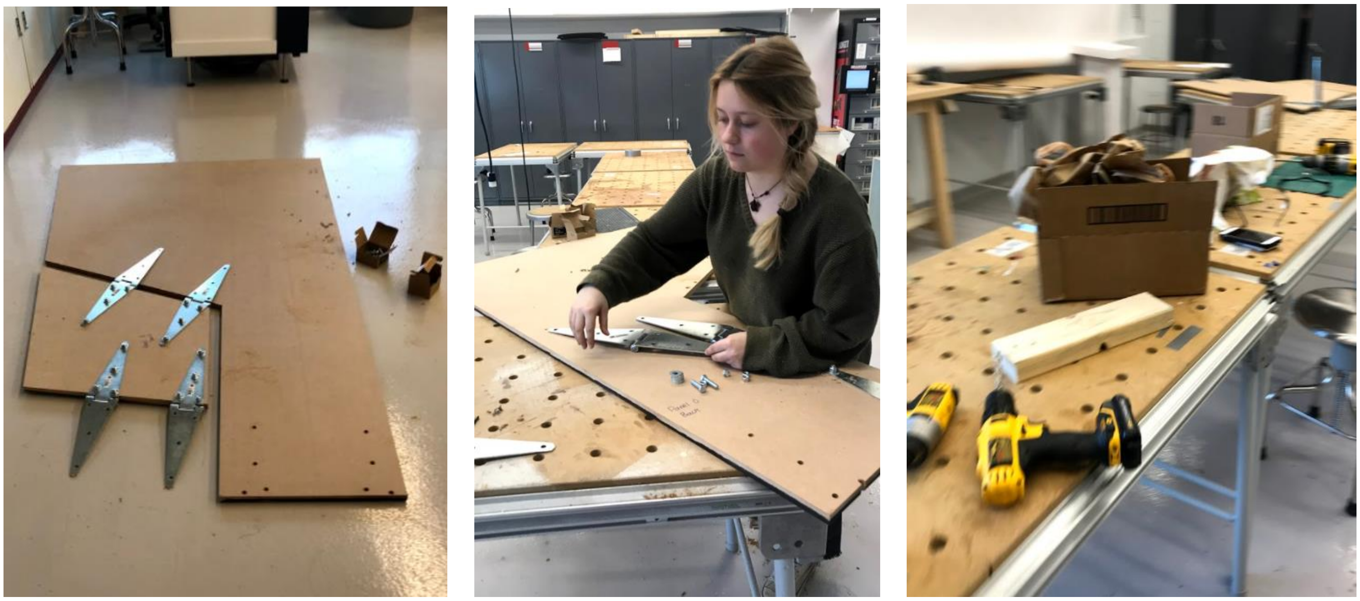

Figure 24 – Assembly of the MDF panels using bolts and strap hinges. Alex Steelman shown helping with assembly in the top middle photo.

Figure 24 (cont'd) – Assembly of the MDF panels using bolts and strap hinges. Alex Steelman shown helping with assembly in the top middle photo.

The foot was fabricated from plywood and attached to the base of panel 3 (see Figure 25).

Figure 25 – Foot fabrication from construction-grade plywood.

Alex Steelman assisted with the fabrication and assembly of the linear actuator mounting surfaces. Alex Bernard then attached electronics to the mechanism body (see Figure 26). At this point, the prototype was complete (see Figure 27).

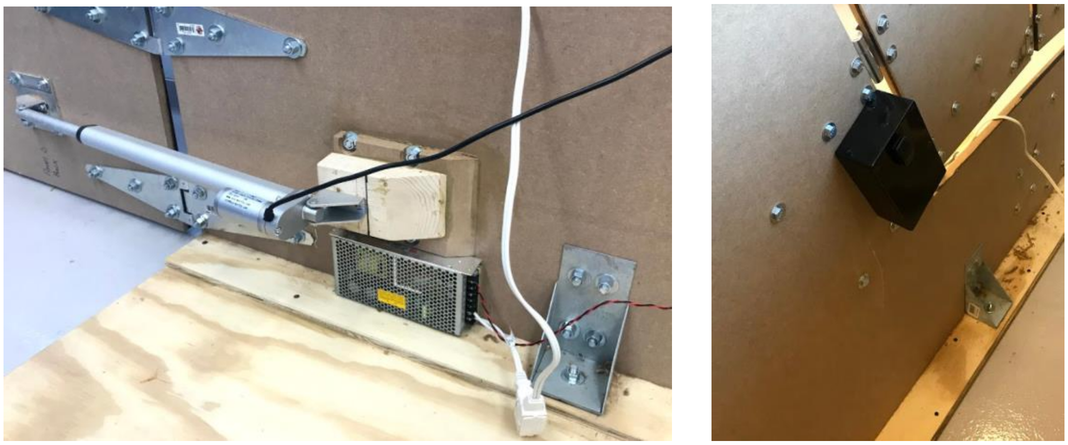

Figure 26 – Fully mounted electrical components.

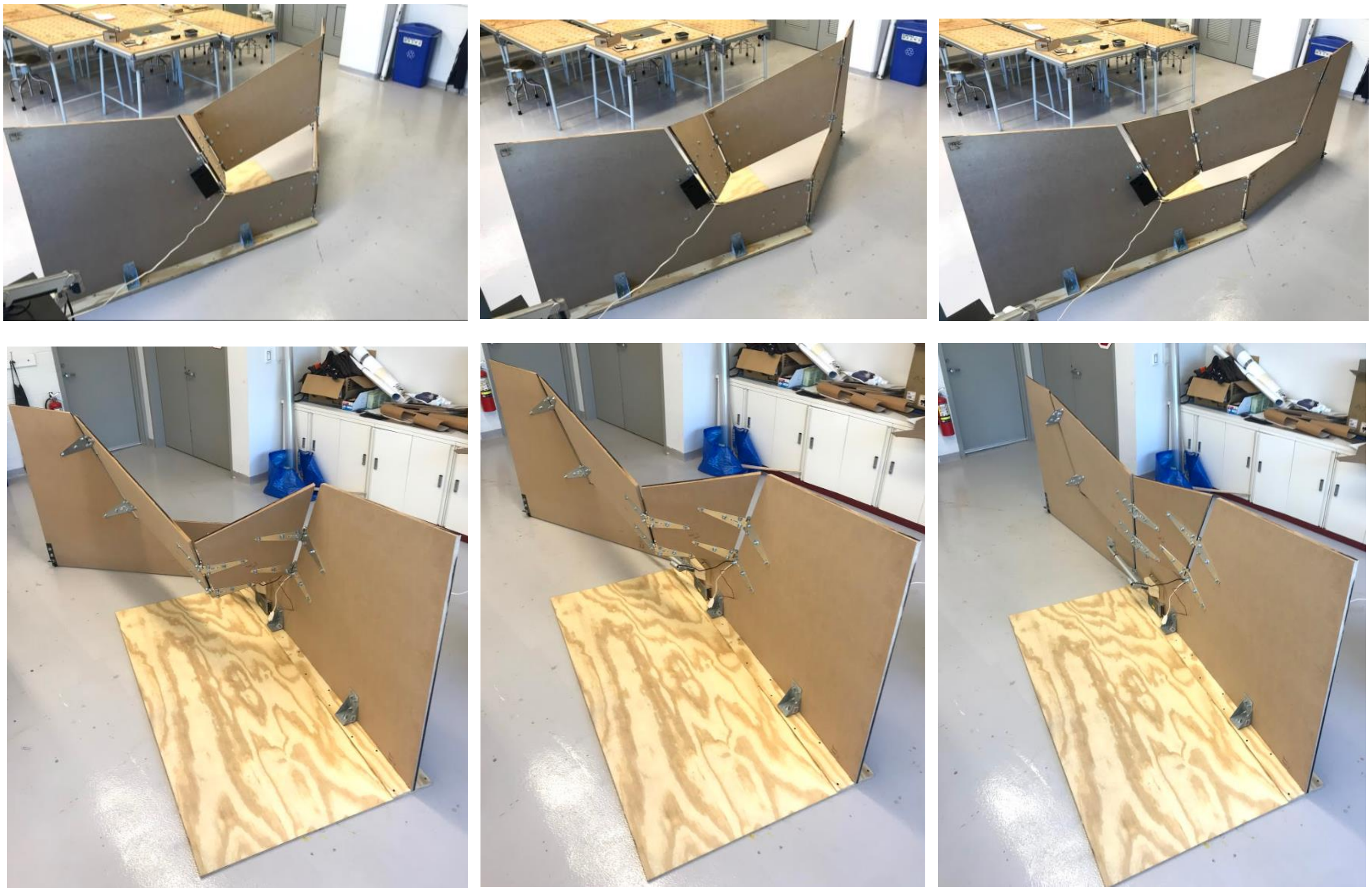

Figure 27 – Finished prototype in various states of open/closed, from two angles

8.6 Physical Prototype Conclusion and Recommendations

The physical prototype is successful and operates as expected. However, there are a few shortcomings in the design which should be improved in future iterations (bold type for emphasis):

1. **The upper panels: The state of the physical prototype at the end of Alex's M.Eng. project is *only* panels 0, 1, 2, and 3. Panels 0a, 2a1, 2a2, and 3a have not been attached.**
2. **Rigidity of panel material: The panels are currently made of fiberboard, which is too flexible to serve as a robust structural material for everyday use over the anticipated lifetime of the device.**
3. **Electrical fire hazard: The electrical connection to wall power (see Figure 26) is not currently grounded. This poses a major hazard for fires and should not be left plugged in unattended.**
4. **Electrocution hazard: The electrical connection to wall power (see Figure 26) has exposed wires with live, 120V AC power running through them. This connection must be handled with care to avoid electrocution of users.**

In order to avoid accidents, the following sign is posted on the prototype at the time of Alex's departure (see Figure 28).

Figure 28 – Warning label affixed to the physical prototype to avoid accidents due to electrical system.

Alex recommends the following future work (when funding is available):

1. **Replace MDF panels with an extruded aluminum skeleton. These are fairly easy to modify in a machine shop, more rigid, and more durable.**
2. **Replace the power supply with something that protects users from electrocution while still allowing for ventilation of the power supply for fire protection. This should work, and is legal to leave plugged in. https://www.amazon.com/Signcomplex-Supply-Transformer-Switching-Adapter/dp/B075R3RW6J. It is meant for strips of LED lights, but it provides 12V up to 8A, which is the correct voltage and *plenty* of current for the linear actuator. It is not grounded with a third prong, but *it is UL listed,* which is all we really need. This signifies that the electricity supply is approved for use in consumer products and does not violate insurance policies.**

9 M.Eng. Project Conclusion

This M.Eng project with the Cornell Architectural Robotics Lab (ARL) focused on the design, kinematics, and physical prototyping of transFORM, a room-scaled, reconfigurable environment for an urban public space. Specifically, the project developed a new type of kirigami-inspired, robotic mechanism. Alex's M.Eng. project imparted both professional and academic lessons while also contributing to the work of ARL.

Alex made tangible contributions toward the goal of the ARL – to combine robotic precision and interactivity with architectural design and the built environment. Through the digital and physical prototypes of transFORM, Alex helped advance research in origami-based mechanism design as well as collaborative design methodologies. Alex gained experience designing computational tools through the digital prototype for the transFORM device, including standards for robotic manipulation in three dimensions.

The transFORM project also challenged Alex's fabrication skills. The physical prototype exercised Alex's fabrication and CAD modeling skills as well as communications skills. Alex had to communicate part dimensions to the shop staff because he did not have the necessary training to operate the saws and machining equipment.

Finally, the transFORM project culivated Alex's paper-writing skills. Having never authored an academic paper, Alex learned LaTeX over the course of one week in order to fit the CASE 2018 conference paper to the required format.

Moving from the COMPREHEND project early in the year to the transFORM project provided Alex an experience with rapidly changing requirements and how to quickly pivot when project assignments change, which was good practice in remaining professionally flexible.

In conclusion, the M.Eng. project has prepared Alex to be a better engineer in an industrial role where priorities span across disciplines, deadlines, and projects.

10 Appendices

10.1 References

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NOTE: Many more references for the transFORM device are listed in the CASE 2018 paper (Section 10.2)

10.2 Full Text of IEEE CASE 2018 Conference Paper

Model for a Rigid, 3D Mechanism Inspired by Pop-Up Origami, and its Application to a Re-configurable, Physical Environment

Alexander Bernard,[1] Carlos de Aguiar[2] and Keith Evan Green, *Senior Member, IEEE*[3]

***Abstract*— Origami has had wide-ranging application in mechatronics, robotics, design, and aerospace engineering. This paper offers a model for a rigid, three-dimensional mechanism inspired by "pop-up" origami (i.e., kirigami). In pop-up origami, a cut is introduced to the folded sheet to expand formal possibilities. We present vertex and parallel pop-up origami mechanisms, model the former using the Denavit-Hartenberg Convention, and present a case study that we are actively developing that harnesses the capacity of origami to fold and unfold on demand. We explore this case, calculating its actuation forces, while recognizing that the model presented here has potential to generalize widely.**

I. INTRODUCTION

Origami is the ancient art of folding a single sheet of paper to create a three-dimensional sculpture. In recent years, origami has received attention from researchers in mechatronics and robotics as a potential for applications at very small physical scales. For example, [10] presents a sheet, 1.7 cm square, that self-folds into a functional 3D robot that can walk, swim, and then dissolve in liquid. At the other end of the physical scale, origami structures have served as the basis for habitable, physical environments. The Miura Ori pattern of origami has, for instance, been applied to form the structural envelope of a chapel building [1]. Origami has also served as the basis for a variety of mechanical systems [16], from nano-devices to retinal implants, heart stents, air bags, inflatable masts for satellites, solar panels, and mirrors [15].

While origami is mostly recognized as a three-dimensional sculpture formed by folding a sheet of paper, a variation of origami called kirigrami, otherwise known as "pop-up" origami, introduces a single, internal cut into the folded sheet of paper to expand the formal possibilities of the resulting form [17] [2] [18]. In this paper, we characterize and explore the potential of pop-up origami for mechanical systems of wide-ranging applications at wide-ranging physical scales.

One property of origami (including the pop-up variant) that benefits mechanical systems is its capacity to fold and unfold on demand. It is this property that we harness in our own design of a suite of physically re-configurable outdoor furniture to be installed in a public, urban square which, for this paper, serves as a case study.

A. *From Pop-Up Books to Mechanical Systems*

Paul Jackson's *Cut and Fold Techniques for Pop-Up Designs* [8] provides a comprehensive introduction to the art of creating pop-up (origami) books using folded paper. Jackson describes the most basic elements of any pop-up origami mechanism and the techniques for creating one using paper. Generalizations of the designs from Jackson's book provided the foundation and inspiration for the models produced in this paper.

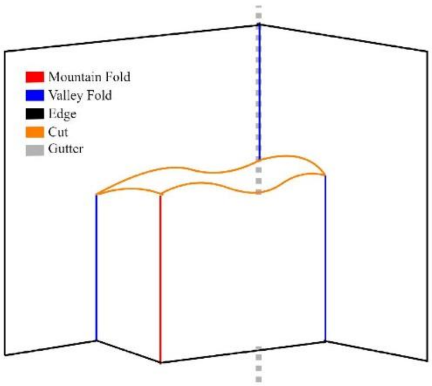

Fig. 1: Parallel pop-up mechanism in open configuration

We describe pop-up origami mechanisms using accepted terminology found in Jackson's book. These mechanisms are briefly explained here and visualized in Figure 1. Folds are described as either *mountain* or *valley* depending on whether the fold is meant to be viewed as convex or concave, respectively [17] [8]. Any configuration can be inverted by changing all mountains to valleys and all valleys to mountains [8]. Each pop-up mechanism has an axis of symmetry which is known as a *gutter* [17] [8]. In order to be classified as a "pop-up," a paper mechanism must meet the following criteria:

- The mechanism is created from one paper sheet.
- The mechanism must have exactly four straight folds.
- The mechanism possesses two flat-folding configurations, "open flat" (Fig. 2) and "closed flat," such that

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This work performed by the Architectural Robotics Lab, Cornell University, Ithaca, NY 14853 USA

[1] Alexander Bernard is a Masters of Engineering Student with the Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY `arb392@cornell.edu`

[2] Carlos de Aguiar is a PhD student in the department of Design & Environmental Analysis, Cornell University, Ithaca, NY 14853 USA `ca449@cornell.edu`

[3] Keith Evan Green is professor in the department of Design & Environmental Analysis and the Sibley School of Mechanical and Aerospace Engineering, Cornell University, Cornell University, Ithaca, NY 14853 USA `keg95@cornell.edu`

a book could be fully opened or fully closed without violating the mechanism's range of motion.

- One or both of the center folds must be co-linear with the gutter.
- The mechanism must contain exactly one cut which is entirely on the interior of the paper.
- All folds begin at the cut and terminate at the edge of the paper.
- The cut begins and ends at the start of the two outermost folds, and need not be a straight line.

These criteria allow for eight different fold locations, each with two different fold types, for a total of 1120 different folding patterns. Of these, only 8 patterns are physically realizable (i.e. it is not possible to create a mechanism where all folds are mountain type). Jackson elaborates these valid configurations in *Cut and Fold Techniques for Pop-Up Designs* [8].

B. The Engineering of Larger-Scale Pop-Up Mechanisms

When considering the applications of pop-up design at a larger physical scale (e.g. our case study), the mechanism must meet the following amended criteria. The amendments primarily recognize the engineering limitations of a large-scale pop-up such as replacing paper folds with mechanical joints.

- The mechanism is constructed of exactly four flat panels, attached by four revolute joints.
- The neighboring edges panels are straight and parallel to the shared joint's axis of rotation.
- The mechanism has at least one flat-folding configuration.

The main difference between paper and large-scale construction is the thickness of materials. At paper-scale, thickness is negligible and building materials are highly flexible, but large-scale construction introduces greater opportunity for collision as panel thickness increases, and materials are more rigid.

II. GENERAL FORMS OF POP-UP ORIGAMI MECHANISMS

Jackson's pop-ups fall into two broad categories, referred to in this paper as "vertex" and "parallel" type mechanisms, which Winder et al. describe as one-piece, single-slit planar and one-piece single-slit spherical mechanisms, respectively. These mechanisms each constitute one degree-of-freedom, four-bar mechanisms [17]. These two cases are characterized by the relationship between the folds of the mechanism, and allow for rigid, three-dimensional motion without buckling or locking.

A. Vertex Mechanism

The vertex mechanism type (Fig. 2) demonstrates spherical motion about a fixed point (vertex) in space. Instead of the parallel fold axes shown in Fig. 1, these axes converge at a point on the gutter. This has been shown to allow for motion by creating a spherical four-bar mechanism [17].

B. Parallel Mechanism

The parallel mechanism (Fig. 1) is a special case of the vertex mechanism where the vertex point is infinitely far from the intersection of the cut and the gutter. However, it is easier to express this as its own type since it behaves as a planar, four-bar mechanism.

III. GEOMETRIC MODELS OF THE VERTEX POP-UP MECHANISM

For this paper, the vertex pop-up mechanism is chosen to explore further, given that it has application to the author's use case (which will be elaborated further in Section V).

In order to solve for the structural mechanics of a pop-up mechanism, it is necessary to locate points of force application in a common frame. This is accomplished by defining points relative to frames attached to each link and using a homogeneous linear transform to find those same points relative to other frames.

A. Denavit-Hartenberg Convention

The Denavit-Hartenberg (D-H) convention [6] is a convenient way to describe kinematic transformations between coordinate frames that are related by either revolute or prismatic joints. Although normally used in robotics applications for determining the kinematic chain of a multiple degree-of-freedom end manipulator [3], these conventions are a good tool for describing the configuration of each joint of a pop-up mechanism.

Craig provides instructions for calculating robotic kinematics using what has been called "modified" D-H parameters. The definition of each parameter is shown in Table I and considered in [3].

TABLE I: D-H parameter definitions

Parameter	**Definition**
a_i	Linear distance from z_i to z_{i+1} measured in the x_i direction
α_i	Angular displacement between z_i and z_{i+1} measured about the x_i axis
d_i	Linear distance from x_{i-1} to x_i measured in the z_i direction
θ_i	Angular displacement between x_{i-1} and x_i measured about the z_i axis

B. Angle Definitions

Figure 2 shows the necessary parameters to fully define the joint axes of the pop-up mechanism. Only three independen vertex angles ($alpha$ in Table I) are required since the fourth is dependent on the other three. Figure 3 shows the placement of the link frames for each link.

In order to specify a given pose of the mechanism, the angles of each revolute joint of the mechanism must be determined. In the case of a pop-up mechanism, specifying one joint angle (θ in Table I) determines all of the angles. For a, the vertex pop-up, these angles are governed by spherical

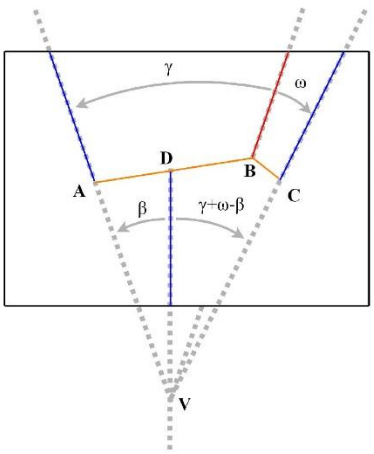

Fig. 2: Open flat configuration for vertex pop-up kinematics

trigonometry. Figure 4 defines intermediate variables that will be used to express the joint angles of the mechanism in terms of the single input angle (ϕ in Fig. 4). Spherical trigonometry provides the following relationships between the internal angles [7].

$$\delta = atan\left(\frac{sin(\phi)}{cot(\gamma)sin(\beta) - cos(\beta)cos(\phi)}\right) \tag{1}$$

$$\epsilon = atan\left(\frac{sin(\phi)}{cot(\beta)sin(\gamma) - cos(\gamma)cos(\phi)}\right) \tag{2}$$

$$\begin{aligned}\psi = acos\Big(&cos(\beta)cos(\gamma) \\ &+ sin(\beta)sin(\gamma)cos(\phi)\Big)\end{aligned} \tag{3}$$

$$\mu = acos\left(\frac{cos(\beta+\omega-\gamma) - cos(\omega)cos(psi)}{sin(\omega)sin(\psi)}\right) \tag{4}$$

$$\kappa = acos\left(\frac{cos(\psi) - cos(\omega)cos(\beta+\omega-\gamma)}{sin(\omega) * sin(\beta+\omega-\gamma)}\right) \tag{5}$$

$$\zeta = acos\left(\frac{cos(\omega) - cos(\psi)cos(\beta+\omega-\gamma)}{sin(psi) * sin(\beta+\omega-\gamma)}\right) \tag{6}$$

C. Link Frames

Given the link frames presented in Figure 3 and the angles defined in Figure 4, the D-H parameters defining the configuration of frame i are provided in Table I.

TABLE II: transFORM Link Frame D-H Parameters

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	$-\beta$	0	$\pi - \phi$
2	0	$-\gamma$	0	$\pi - (\epsilon + \zeta)$
3	0	$-(\beta + \omega - \gamma)$	0	$\pi - \kappa$
4	0	$-\omega$	0	$\pi - (\delta + \mu)$

Using the D-H parameters, it is possible to describe points on each joint in different coordinate frames. The transformation between coordinate frames is accomplished using a homogeneous transform. A point whose coordinates are expressed in frame h can be represented instead in frame k using the relationship shown in 7. The construction of the homogeneous transformation matrix is well established and, consequently, will not be presented here [3].

$${}^{k}\vec{P} = {}^{k}_{h}R\,{}^{h}\vec{P} \tag{7}$$

IV. STRUCTURAL MECHANICS TO DETERMINE ACTUATION FORCE

The practical construction of a large scale pop-up mechanism is a main goal of this project. Because a pop-up possesses a single degree of freedom, the entire mechanism can be actuated with a single input force or torque. However, sizing an appropriate motor or other actuation device is not trivial when a mechanism exhibits complicated three-dimensional motion. Therefore, a simple analytic method for solving the actuation effort is derived.

A. Simplifying Assumptions

The spherical, four-bar mechanism formed by the vertex pop-up has one degree of freedom. However, in an arbitrary four-link, closed-chain mechanism where the joint axes are neither parallel nor convergent on fixed point, the mechanism is over-constrained. Therefore, a few simplifying assumptions must be made in order to solve for the actuation force using the second law of motion and the Newton-Euler equations. These simplifications are provided below as well as shown as a diagram in Fig. 5 and Figs. 6 – 8.

- Joints are modelled as friction-less. Therefore, each revolute joint has only two unknown reaction moments.
- Link 0 is assumed rigidly attached to ground.
- Link 3 is assumed effectively mass-less (or otherwise supported against the force of gravity).
- The joint at point C is modelled as a ball-and-socket. Therefore, all reaction moments at this joint are zero.
- The joint at point D is modelled as free-floating in the z-direction. That is, point D supplies no reaction force along the joint axis.

B. Static Solution

With the above simplifications, free body diagrams (Figs. 6 – 8) can be constructed. There are 17 unknowns: Fa_x, Fa_y, Fa_z, Fb_x, Fb_y, Fb_z, Fc_x, Fc_y, Fc_z, Fd_x, Fd_y, Ma_x, Ma_y, Mb_x, Mb_y, Md_x, Md_y. There are three Newtonian force balance equations each for links 1, 2, and 3 – for a total of nine force equations. There are three Newtonian moment balance equations each for links 1, 2, and 3 – for a total of nine moment equations. With 18 equations and 17 unknowns, a designer is free to choose an appropriate unknown actuation effort and solve for values to create static

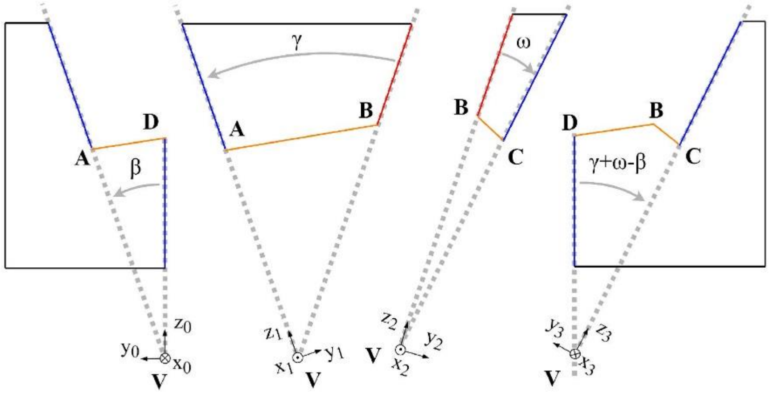

Fig. 3: Vertex pop-up link frame definitions

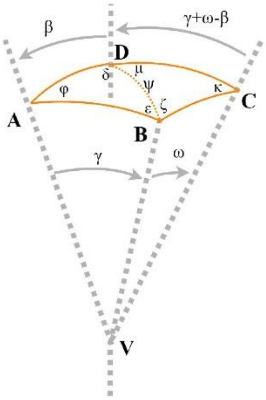

Fig. 4: Diagram for solving spherical joint angle relationships

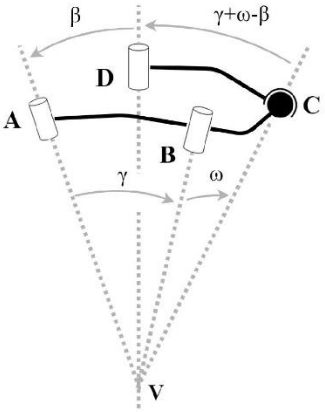

Fig. 5: Mechanical simplifications made for analyzing structural forces of vertex pop-up mechanism

equilibrium. This gives the designer an approximation, within a factor of safety, of expected necessary actuation effort for the system, and is computationally more efficient than running a full mechanical simulation.

V. USE CASE: “TRANSFORM,” A RECONFIGURABLE, CYBER-PHYSICAL ENVIRONMENT

The prior analysis on the vertex pop-up mechanism is performed as an intermediate step in a specific project that our lab is undertaking. Figure 9 shows computer renderings of three configurations (“unfoldings”) of what we call “transFORM.” The project is motivated by the emergence of social networks and apps that have reduced the importance of physical space as a locus for social interaction and place attachment [12] [13] [4] [14]. As a means to recapture the important of public outdoor spaces [5] [9], our research team proposes this reconfigurable, cyber-physical environment at room scale, installed in a public, urban square. We strive to “create fresh urban relationships, processes, and patterns that have the social and cultural qualities we seek for the twenty-first century” [11].

In practical terms, transFORM is a series of hinged, responsive panels with embedded lighting, audio, and displays that transform according to needs. A pop-up origami mechanism permits the hinged, single sheet to reconfigure (transform) into different utilitarian and evocative configurations that allow individuals and assemblages of people to lounge, meet, read, work, exchange, access information, and generate information to be archived and shared. Figure 9 shows three such configurtations, two of these daytime ones and one evening one in which the folded sheet flattens to prevent vandalism and loitering.

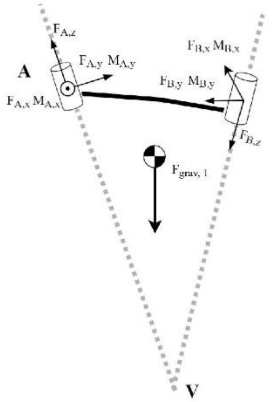

Fig. 6: Free body diagram for link 1.

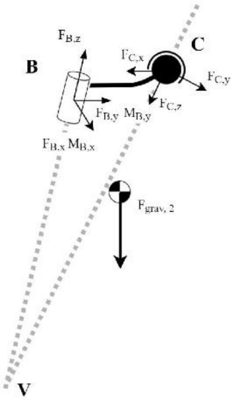

Fig. 7: Free body diagram for link 2.

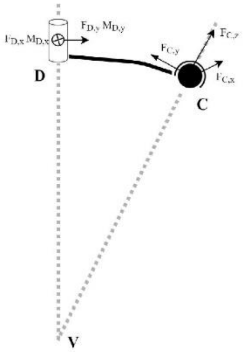

Fig. 8: Free body diagram for link 3.

A. Modelling Parameters

The D-H parameters for the transFORM mechanism are provided in Table III. It is important to note that in this application, ω and β are equal. Furthermore, the link angles θ_i are left in variable form as they are dependent on 1 – 6. Because it is one degree-of-freedom, upon specifying ϕ, all other angles can be determined.

TABLE III: Vertex Pop-up Link Frame D-H Parameters

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	$-25°$	0	$\pi - \phi$
2	0	$-35°$	0	$\pi - (\epsilon + \zeta)$
3	0	$-15°$	0	$\pi - \kappa$
4	0	$-25°$	0	$\pi - (\delta + \mu)$

B. Force Analysis Results

The actuation effort solved for in this analysis is the reaction force necessary to accomplish static equilibrium, applied at the far corner of link 3 (see Fig. 11). For this analysis, centers of gravity are estimated using a computational geometry program (Solidworks, 2017). A MATLAB script solves for the unknown force across the entire range of possible configurations, and the results are presented in Figure 10. An actuator placed at the location shown in Figure 11 would need to exert a maximum estimated reaction force of 200 Newtons or 45 lbs to keep the mechanism in equilibrium. Therefore, a motor capable of applying approximately 600 Newtons or 135 lbs of force is recommended for this mechanism.

VI. FURTHER APPLICATIONS

More broadly and beyond the transFORM project introduced here, the vertex pop-up mechanism offers a replicable and modular platform for wide-ranging applications at wide-ranging scales, as referenced earlier in this paper. At large scale, we can for instance envision pop-up origami mechanisms at the core of flat-packed emergency housing and mobile hospital units, transported by shipping container (sized 8ft x 8ft x 20ft) to provide a variety of critical resources in response to natural or human-made disasters.

ACKNOWLEDGMENT

The authors offer their thanks to Andy Ruina, professor in the Sibley School of Mechanical and Aerospace Engineering, Cornell University, for his help with this paper.

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Fig. 9: A case study of the vertex pop-up mechanism, transFORM (three configurations shown above) is 2.5m (approx. 8ft) tall in its flattened configuration (the right-most image, shown at night).

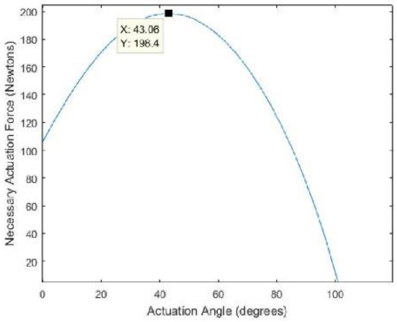

Fig. 10: transFORM actuation force solution results. Actuation angle is the defined in Fig. 11.

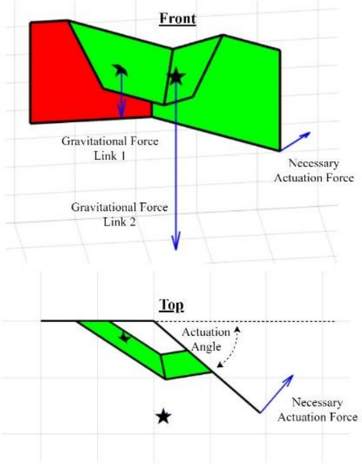

Fig. 11: transFORM loading generated by MATLAB. Stars denote centers of mass. Forces of interest shown in blue. Red panel (link 0) is rigidly attached to ground. Link 3 is modelled as mass-less.

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10.3 COMPREHEND Project

The COMPREHEND Project is a cross-disciplinary approach to National Science Foundation's National Robotics Initiative 2.0 (2018). According to the solicitation, "The focus of the NRI-2.0 program is on ubiquity, which in this context means seamless integration of co-robots to assist humans in every aspect of life." Combining talent and experience from architecture, engineering, and computer science, the ARL attempts to meet this solicitation by understanding and designing for "higher-order, thinking-and-making activities highly suited for addressing the kinds of 'wicked' problems of society" (Architectural Robotics Lab, 2017). To this end, Alex joined the team in September of 2017 to help create a physical prototype of the platform on which the COMPREHEND system could be tested and completed.

Alex worked on the COMPREHEND project between September 8th and October 6th, 2017. During this time, he helped identify the functional requirements of a physical prototype, and made plans to build a low-fidelity proof-of-concept. The main goal of the physical prototype was a flexible platform for the system as the science behind the computer aided assistant advanced throughout the project.

10.3.1 COMPREHEND Functional Requirement Exploration

Alex worked with DEA doctoral student Yixiao Wang to identify functional requirements for a final COMPREHEND system. From there, Alex worked to identify what steps in prototype development could be completed at this stage of the project.

Alex and Yixiao participated in an iterative design process, identifying scenarios in which the COMPREHEND system could be used, how it would behave, and then identifying core functionalities that the system must fulfill in order to recreate the behaviors described in the scenarios. Figure 29 shows a small portion of one such functional requirement generation design process.

Scenario I – Designer Searches for Images

Scenario	Functional Requirements	Block Diagram
(The room asks Joanna out-loud: What is your design topic today?)	Sense that designer is present	D.6 - Eyetrack Camera
	Auto-start	C.6 - Brain
	Spoken prompt to designer	D.3 - Echo
Joanna: A lamp	Audio input from designer	D.3 – Echo
	Language interpretation	C.3 – Echo API C.6 – Brain
(The room asks: Please specify what type of lamp.)	Intelligent concept narrowing[1]	C.6 – Brain
Joanna: I'm not sure	Audio input from designer	D.3 – Echo
	Language interpretation	C.3 – Echo API C.6 – Brain

Figure 29 – Functional Requirement Gathering Scenario Exercise. This figure also shows the expansion of this exercise where functional requirements are matched to corresponding blocks from the functional block diagram

Through this process, it was decided that the COMPREHEND system should be an interactive desk which uses machine learning techniques to tangibly interact with a designer's current work – adding to the designer's drawings using something like a robotic pencil, and generating complementary ideas on a set of screens in front of the designer. Furthermore, the system should be able to track a designer's eyes as they view the screens, identify interests based on viewing pattern, and display updated visuals based on the viewing pattern.

10.3.2 COMPREHEND Prototype Development

The functional requirements were broken down into high level functional blocks, and relationships between blocks were identified. Please refer to Figure 30 to see the final block diagram.

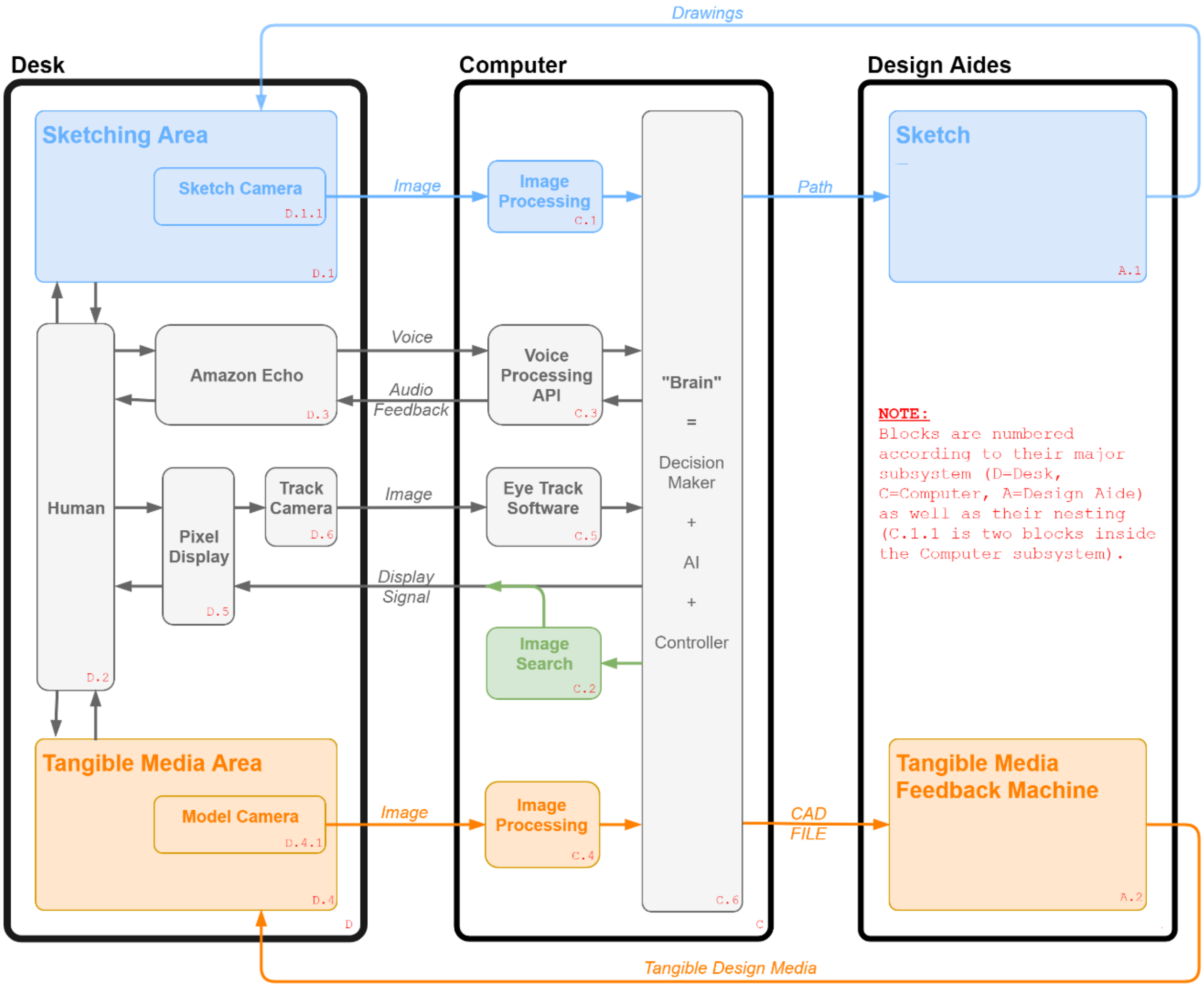
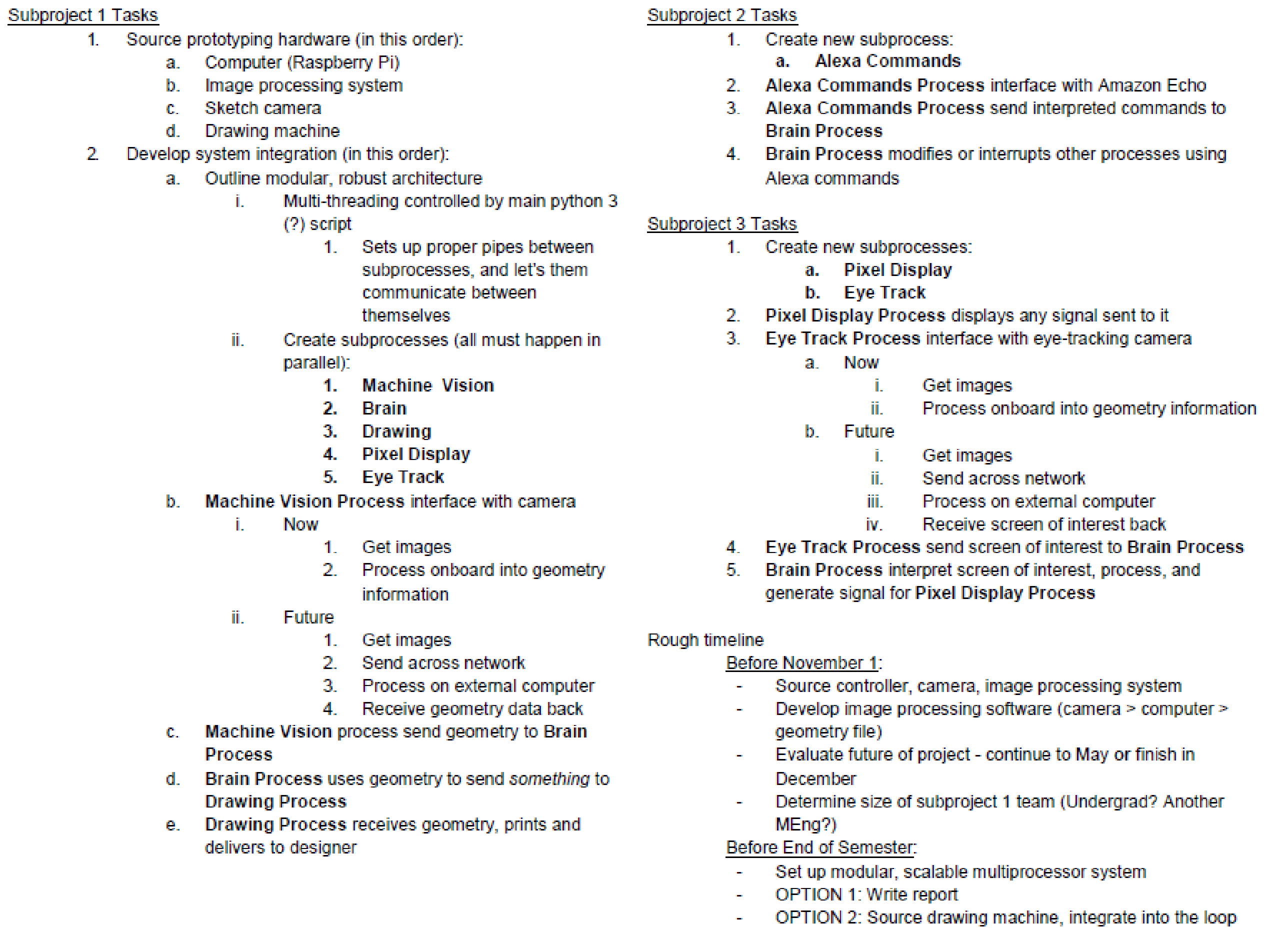


Figure 30 – Functional block diagram for the COMPREHEND system which Alex created as part of the initial ideation of the COMPREHEND Project.

At first, Alex was assigned to the “blue loop” (see the blue arrows and blocks in Figure 30). Alex briefly worked with a few undergraduate researchers in the lab to begin gathering supplies for a physical prototype. Alex developed a project outline and timeline for successful completion and hand-off of the project (see Figure 31).



Subproject 1 Tasks

1. Source prototyping hardware (in this order):
    a. Computer (Raspberry Pi)
    b. Image processing system
    c. Sketch camera
    d. Drawing machine
2. Develop system integration (in this order):
    a. Outline modular, robust architecture
        i. Multi-threading controlled by main python 3 (?) script
            1. Sets up proper pipes between subprocesses, and let's them communicate between themselves
        ii. Create subprocesses (all must happen in parallel):
            1. Machine Vision
            2. Brain
            3. Drawing
            4. Pixel Display
            5. Eye Track
    b. **Machine Vision Process** interface with camera
        i. Now
            1. Get images
            2. Process onboard into geometry information
        ii. Future
            1. Get images
            2. Send across network
            3. Process on external computer
            4. Receive geometry data back
    c. **Machine Vision** process send geometry to **Brain Process**
    d. **Brain Process** uses geometry to send *something* to **Drawing Process**
    e. **Drawing Process** receives geometry, prints and delivers to designer

Subproject 2 Tasks

1. Create new subprocess:
    a. Alexa Commands
2. **Alexa Commands Process** interface with Amazon Echo
3. **Alexa Commands Process** send interpreted commands to **Brain Process**
4. **Brain Process** modifies or interrupts other processes using Alexa commands

Subproject 3 Tasks

1. Create new subprocesses:
    a. Pixel Display
    b. Eye Track
2. **Pixel Display Process** displays any signal sent to it
3. **Eye Track Process** interface with eye-tracking camera
    a. Now
        i. Get images
        ii. Process onboard into geometry information
    b. Future
        i. Get images
        ii. Send across network
        iii. Process on external computer
        iv. Receive screen of interest back
4. **Eye Track Process** send screen of interest to **Brain Process**
5. **Brain Process** interpret screen of interest, process, and generate signal for **Pixel Display Process**

Rough timeline

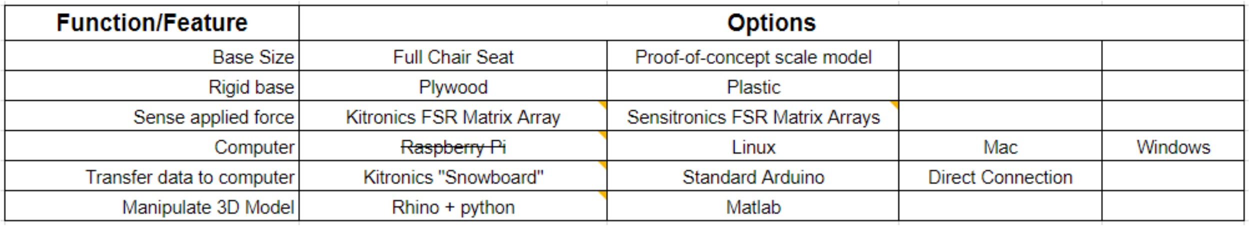
Before November 1:
- Source controller, camera, image processing system
- Develop image processing software (camera > computer > geometry file)
- Evaluate future of project - continue to May or finish in December
- Determine size of subproject 1 team (Undergrad? Another MEng?)

Before End of Semester:
- Set up modular, scalable multiprocessor system
- OPTION 1: Write report
- OPTION 2: Source drawing machine, integrate into the loop

Figure 31 – "Blue Loop" proposed work breakdown and rough timeline – 9/19/2017

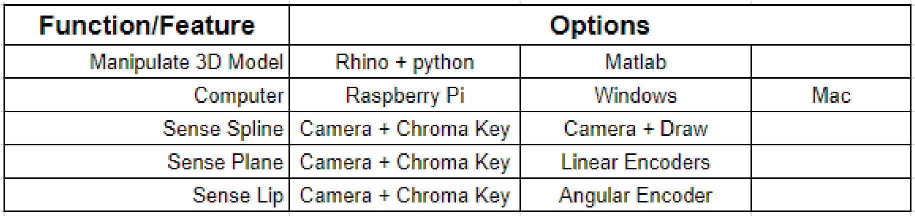
It was decided that the blue loop was not ready for a physical prototype. And so, Alex pivoted to begin working with DEA graduate student Teng Teng to develop the "tangible design" aspect of the COMPREHEND system (the "orange loop" in Figure 30). Teng is an expert in the tangible design realm – using more tactile feedback for designers than what is offered by a mouse and keyboard today. Alex was asked to explore two prototypes of tangible design aids – taking inspiration from a hypothetical designer creating a chair:

1. <u>Pressure Sensor Topography</u>: A 2d array of pressure sensors allows a designer to craft the contours of a chair seat on screen while applying tangible pressure to the device. Alex developed a morphological chart which is shown in Table 2.
2. <u>Modular Shape Definition</u>: A multi-component design aid which allows a designer to change the borders of a three-dimensional shape by bending a spline and adjusting the relative positions of several rigid components. Alex developed a morphological chart which is shown in Table 3.



Function/Feature	Options			
Base Size	Full Chair Seat	Proof-of-concept scale model		
Rigid base	Plywood	Plastic		
Sense applied force	Kitronics FSR Matrix Array	Sensitronics FSR Matrix Arrays		
Computer	~~Raspberry Pi~~	Linux	Mac	Windows
Transfer data to computer	Kitronics "Snowboard"	Standard Arduino	Direct Connection	
Manipulate 3D Model	Rhino + python	Matlab		

Table 2 – Pressure Sensor Topography Prototype Morphological Chart



Function/Feature	Options		
Manipulate 3D Model	Rhino + python	Matlab	
Computer	Raspberry Pi	Windows	Mac
Sense Spline	Camera + Chroma Key	Camera + Draw	
Sense Plane	Camera + Chroma Key	Linear Encoders	
Sense Lip	Camera + Chroma Key	Angular Encoder	

Table 3 – Modular Shape Definition Prototype Morphological Chart

Before either of these two prototypes could be started, this project was also deemed too early in development to warrant physical prototype. Alex was forced to pivot again to a new project: transFORM.

10.3.3 COMPREHEND Results and Discussion

COMPREHEND was an excellent exercise in being adaptive and eager to take on new challenges in an engineering environment. In industry, it is expected that engineers give full effort to any project they are assigned, and to not take it personally when projects get cancelled without full conclusion. Furthermore, it was very satisfying to help lay the groundwork for a multi-year project, even if the suggested prototypes are not getting built at the moment.