Spring 2019

DMX Controlled Scenic Automation

Hannah Sisney
Tiernan O’Rourke
J. V. Ating

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UNDER MY SUPERVISION BY

Hannah Sisney, Tiernan O’Rourke, J.V. Ating

ENTITLED
SwiftScene
DMX Controlled Scenic Automation

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Timothy Hight, Thesis Advisor  6/4/19

David Sword, Thesis Advisor  06/11/19

Michael Taylor, Thesis Advisor  6/11/19

Drazen Fabris, Department Chair  6/13/19
SwiftScene
DMX Controlled Scenic Automation

By
Hannah Sisney, Tiernan O’Rourke, J.V. Ating

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical Engineering

of
SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Mechanical Engineering

Santa Clara, California

Spring 2019
Abstract

SwiftScene DMX Control is a safe, simple, and low-cost solution to automated scenery marketed to educational level and low-income theaters. The module is an 18” x 18” electrical enclosure that attaches to the underside of a stage platform and is fully controlled wirelessly via a light board. This is a scaled down prototype meant as a proof of concept and product viability. It is capable of rotational motion and limited linear motion. This prototype meets expectations of traveling at 1 ft/s with acceleration and deceleration at 0.5 ft/s², but speed and acceleration can be varied based on desired functionality. An actual product will be able to carry a higher load and perform closer to ideal specifications.
Acknowledgements

Thank you to our advisors Dr. Timothy Hight, Dr. Michael Taylor, and David Sword, Technical Director Extraordinaire for their help and guidance through this challenging project. We would also like to thank our sponsors Parlights, Inc., MPA Lighting, and Doug Fleenor Design for their generosity and willingness to help us get off the ground. Finally, we would like to thank the Santa Clara University School of Engineering for their funding and support.
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1. Introduction
1.1 Background

The art of theater has always been a part of society. The earliest forms of theater that we know of date back to 2000 B.C.E [1]. From ancient Egypt to Elizabethan England to modern Broadway, humans have been entertaining one another. As time has progressed, so has the technology used for theatrical spectacle. Ancient Romans used an elaborate system of capstans, cables, ramps, hoists, and counterweights beneath the Colosseum to make scenery and animals appear in the stadium as if by magic (see Figures 1 and 2) [2]. Today, elaborate scene changes can be completed at the touch of a button.

The first theater was performed as part of the festival of Dionysus in Athens, Greece. Euripides, Aristophanes, and Aeschylus, among others, wrote and performed art pieces intended to send messages to society using comedy and tragedy [1]. These foundational concepts became the basis for modern theater. The Greeks, however, went so far as to include machinery in order to aesthetically improve performances in what is the first recorded scenery for theatrical production [1]. They could wheel characters in on platforms or lift them in the air with cranes, but most importantly from the beginnings of theater, scenery and scenic changes have been key to the success of a production [1]. In the thousands of years since the Greeks invented theater, technology has matched theatrical innovation to create automated and dynamic motion.

Figure 1. Elevators to the Colosseum floor (used without permission) [2].
1.2 Introduction to SwiftScene DMX Control

SwiftScene DMX Control was intended as a more affordable alternative to today’s entertainment technology for automated scene changes. In order to compete with Broadway level productions, educational and community theaters look to automating scene changes, but need to do so at a fraction of the cost. Most automation systems cost tens of thousands of dollars, whereas the goal of SwiftScene was to create an automation device for a cost at or below $2,000. For educational and regional theater the budget for an entire season may be less than $50,000. The cost of automation is also often only for a rental product not for permanent use. So SwiftScene not only is a much lower percentage of budget, but it would be a one-time investment in the future of the theater. SwiftScene DMX Control was designed to provide an accessible solution for these theaters by allowing them to move their set pieces with an inexpensive driver and control technology that they already have on hand. Figures 3 and 4 illustrate the design to final prototype journey of this project.
The basis for our project was an idea from Santa Clara University Technical Director, David Sword. He wondered if it was possible to create a reusable device capable of moving different pieces of scenery for different shows with repeatability. After some initial design discussions, we began in earnest determining the best methods for moving large pieces of equipment. As we realized the challenge of moving hundreds of pounds or more, and found the limitations of our team size, we scaled the project to a proof-of concept and intended to design the first iteration of what would be a much more challenging project.

Figure 3. Initial sketch of SwiftScene DMX Control (attributed to JV Ating).

Figure 4. Final prototype of SwiftScene.
1.3 Project Background

Currently, educational and community theaters with limited budgets complete scene changes by hand. Stage crew members (usually dressed in black) will move set pieces during a blackout (when all lights are off), when the curtain is closed, or even during a scene (as is pictured in Figure 5). The waiting time required for a scene change, in addition to the possibility of seeing crew members greatly tests the audience’s suspension of disbelief.

![In the background of this photo of SCU’s production of Legally Blonde it can be seen that actors are in process of moving scenery.](image)

Figure 5. In the background of this photo of SCU’s production of Legally Blonde it can be seen that actors are in process of moving scenery [3].

Professional theaters with large budgets have the luxury of technologies that automate scene changes, or in some cases can build theater structures specifically around one production (as shown in Figure 6). Set pieces appear to move by magic before the audience’s eyes, and the performance can continue seamlessly without breaking focus. SwiftScene DMX Control was designed to bring some of this magic to patrons who may not have the means to attend big-budget, Broadway style shows, and at a reasonable size and price for small theaters.
1.4 Core Technologies

The primary core technology used in SwiftScene DMX Control is, as the name implies, DMX512. DMX, as it is more commonly known, is a digital data transmission standard created by the United States Institute for Theatre Technology (USITT) to be compatible with entertainment technology across different manufacturers [5]. DMX stands for digital multiplex, and it is the only standardized control signal in the theater industry; all others are proprietary. The FAQ page on USITT’s website provides basic information about creation and use of DMX. When it was originally invented in the 1980’s DMX was intended to be the method of data transmission between controllers and lighting fixtures for the lowest common denominator of equipment [5]. DMX “covers electrical characteristics (based on the EIA/TIA–485 standard), data format, data protocol, and connector type” [5]. A diagram of basic data transmission over DMX can be seen in Figure 7. The system itself is not intended for any hazardous applications, as it does not have strong error detection.

What made DMX the best choice for SwiftScene was its ability to integrate seamlessly across many types of theatrical spaces. Almost every theater in the U.S. uses DMX already as a standard part of operation. Using an existing and well known protocol for communication helps to ensure that SwiftScene functions--it is much more challenging to develop a new communication channel. Furthermore, current research into the usage of DMX suggests that there are some unexplored applications for wireless DMX. We found that using wireless DMX was a simple solution to ensuring that SwiftScene could move across a stage unencumbered.
The US Patent for Lighting Control Network states, “theatrical lighting control network which incorporates a local area network for communication among a number of node controllers and control consoles or devices employed in establishing lighting or other effects levels in a theater” [7]. This patent supplies all of the basic information we need and was the basic guideline for our integration, as the control network is the basis for the design of SwiftScene.
Figure 8. From the patent Lighting Control Network this figure shows how the network basics are connected (used without permission) [7].

Figure 8 shows the setup for a lighting control network on DMX. SwiftScene is a device that can be added to the node controller shown at the top of the figure. SwiftScene simply drops into an already existing control network, like the one shown above, without changing a single thing. The DMX address of the device is the only piece that needs changing before the module is operable. Utilizing this basic and already understood technology allowed us to create a device that is simple to work with.

The other core technology that makes up SwiftScene DMX Control is the stepper motor. The stepper motor allowed for specific position control without needing encoders for
positioning. This allowed us to lower the overall cost of the device, while maintaining the core ideas that started the project. Standard NEMA motor sizes were chosen and tested for ease of purchase, and the associated drivers for the motors were purchased once the proper loading had been calculated and the necessary currents were known--this process is explained in more detail in the Drive section of this report.

As a part of this review of relevant materials and literature, we reviewed the information found in *Mechanical Design for the Stage* by Alan Hendrickson [8]. The text applies physics and the basics of engineering to applications for stage equipment like rigging systems and turntables. In order to best understand how we might apply our product to stage equipment like wagons, we turned both to this book and to our advisor David Sword, who walked us through the basic needs of a technical director both in the fall and later in the spring during THTR 130, Technical Design [9]. Furthermore, Derek Duarte--lighting professor at Santa Clara--walked through the particulars of using DMX for staging applications in his class THTR 132, Production management [10]. This led to the patent search above, and resulted in our decision to use DMX for SwiftScene.

1.5 Team Goals

When we began this project, we also made it a priority to outline three main goals. The goal was set to finish the proof of concept and create an automated moving device by the design conference. It was also important that the safety of the device was always kept in mind and vital to the success of SwiftScene. And finally, it was set out that the project be used to further the breadth of information in lighting control systems and scenic automation, in an effort to start the trickle down of scenic motion to smaller theater spaces.
2. Research and Background

2.1 Project Rationale

The theory behind SwiftScene was one of accessibility. In order to bring scenic automation to low-budget theaters, our design had to be low cost. Our emphasis was, again, on lowering the overall percentage of cost for a season as well as ensuring that this product was reliable over-and-over so that it would be only a one time purchase, not a recurring cost. If we could create a product that when purchased was under 10% of a typical season budget, then we would be successful. In order for our design to be low cost, it had to make use of equipment already in those low-budget theaters. Thus, SwiftScene was designed with widely used-theatrical technologies in mind. A traditional light board was chosen as the programming tool for SwiftScene because every theater already has a light board. DMX technology was chosen as the control protocol for SwiftScene because every theater is already equipped to communicate using DMX. If SwiftScene were a fully developed product, it could be brought into any theater to be programmed and used immediately.

SwiftScene DMX Control comprises a physical driving module and its control system. The driving module is attached to the underside of a standard platform (seen in Figures 9 and 10) that already has wheels. The control board is out of the way of actors and running crew, either placed at a desk offstage or in the light booth. One person operates SwiftScene at this control desk and oversees the movement of the driving module during rehearsals and performances. A scenario in which SwiftScene would be appropriate is illustrated in Figure 11.

Figure 9. Standard Platform (used without permission) [1].
2.2 Customer Needs

The market for SwiftScene DMX Control is theater companies with low budgets like educational and community theaters. In order to understand this customer base, interviews were conducted with professionals in the theater industry. A technical director for an educational theater, a director for an educational theater, a student studying stage management, and a professional stage manager of Broadway shows were consulted. The following questions asked the responses of each participant can be found in Appendix A.

Each subject felt that SwiftScene DMX Control would be beneficial a product for the target market. Those in educational theaters stated that a product like this could be used once or twice each season (per school year in essence), while the one person from Broadway thought that
it could be used as often as small set pieces were necessary in a small scale theater. The theater department at SCU currently uses advanced entertainment technology mostly in the realm of lighting, whereas set movement still uses standard pulley systems or stage crew to pull pieces on and off stage. This product would be welcome in SCU’s theater department because it would bring more automation to the theater to make scene changes more predictable and alleviate foot traffic onstage, as well as potentially offering more flexibility of motion than human beings. In professional theater, lessening stage crew lowers cost. The professional stage manager pointed out that she would be more likely to use the product if it can be a cost effective way to lower the manpower needed.

The following customer needs, in no particular order, were determined:

- The product is structurally sound
- The product is visually integrable into set pieces
- The product can handle the weight and movement of humans
- The product provides a service that human stage crew cannot
- The product is simple to use
- The product can do the work of multiple humans
- The product is stoppable and moveable without intricate programming
- The product is accurate in its position
- The product holds charge for a reasonable amount of time
- The product is easy to integrate into existing set pieces
- The product is simple to program
- The product can move in multiple directions
- The product is affordable
- The product is usable by customers of all experience levels
- The product is safe

From this list, three main areas of need emerged: Safety, Simplicity, Integrability. Safety is the number one priority for this project, and will therefore was given the most consideration. Exact needs are summarized in Table 1.
Table 1. Customer Needs Breakdown (1 is most important, 5 is least important).

<table>
<thead>
<tr>
<th>#</th>
<th>Area</th>
<th>Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Safety</td>
<td>has a reliable braking/parking system</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Integrable</td>
<td>can visually “disappear” into sets</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Safety</td>
<td>Can handle the weight and movement of humans</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Performance</td>
<td>Can outperform human stage crew</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>Simple</td>
<td>Has user friendly controls</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Simple</td>
<td>Can be used by customers of all experience levels (coding wise)</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Safety</td>
<td>Can be stopped or moved out of the way quickly and easily</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Performance</td>
<td>Accurate position control</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>Integrable</td>
<td>Holds charge for a reasonable amount of time</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>Integrable</td>
<td>Can be charged while its installed</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>Integrable</td>
<td>Can be easily installed onto set pieces</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>Simple</td>
<td>Easy to program</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>Performance</td>
<td>Can move in multiple directions</td>
<td>5</td>
</tr>
<tr>
<td>14</td>
<td>Cost</td>
<td>Affordable for low budget theaters</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>Safety</td>
<td>Does not exceed a dangerous speed</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>Safety</td>
<td>Will stop in a reasonable time/manner</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>Safety</td>
<td>Physical components cause no harm (i.e. not burst into flames)</td>
<td>1</td>
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Common concerns that came up among the subjects were how much physical load could be supported by the system and its ability to stop correctly. The technical director and the stage manager wanted to know how reasonable it would be for this system to support an actor or any particularly heavy piece of scenery. All subjects voiced some type of concern with the stopping mechanism of the product, such as how it would stop, how accurately it could stop, or how quickly it could stop. Thus an emergency stop system emerged as an important consideration in the design.
The production of SwiftScene greatly benefited from the insight of potential customers. From these interviews, it was determined that latent needs include the ability to work with the product in versatile and new scenarios, the ability to hold its charge or be charged while installed, and the ability for multiple drivers to be used simultaneously. Customer insight told us that SwiftScene needed to defy expectations of what a normal stage crew could accomplish, along with handling the weight and movement of actors on the sets it would support. There is an eager market for our system, but it became clear that this product needed to be user friendly, safe, versatile, and inexpensive in order to fully appeal to customers. The technical director of a production would ultimately work with SwiftScene the most, so meeting technical specifications—particularly safety—was the primary design focus.

2.3 Product Research

SwiftScene is a unique design, but other, similar products do exist. Below are some examples of similar products currently in use, a summary of which can be found in Table 2.

Figure 12. DMX Scenery Rotator (used without permission) [11].

The Rose Brand DMX Scenery Rotator is a DMX controlled piece of technology used for spinning set pieces. This rotator can support up to 110 lbs vertically and up to 22 lbs horizontally [11]. Operation is expected to lie within 16-bit DMX precision and 6 channels of DMX control [11].
The Wahlberg DMX Track Runner is a DMX controlled piece of equipment used for translating set pieces. The runner can support up to 220 lbs, and also operates with 16-bit DMX precision on 6 DMX channels [12].

The Wahlberg Remote Controlled Platform is used for moving actors and set pieces in all directions across a stage. This platform can support up to 441 lbs, and has maximum operation times of 1.5 hours for driving and 10 hours for standby [13]. Controlled by traditional RC, the platform has a transmission range of 328 feet [13].
Table 2. Similar Products Summary.

<table>
<thead>
<tr>
<th>Product</th>
<th>Main Function</th>
<th>Control Type</th>
<th>Price</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenery Rotator</td>
<td>To rotate 360°</td>
<td>DMX</td>
<td>$1,450</td>
<td>DMX controlled, supports heavy pieces</td>
<td>Movement constricted to rotational</td>
</tr>
<tr>
<td>Track Runner</td>
<td>To translate</td>
<td>DMX</td>
<td>$2,525</td>
<td>DMX controlled, supports heavy pieces</td>
<td>Movement constricted to translational</td>
</tr>
<tr>
<td>Remote Controlled</td>
<td>Two wheel drive in any direction</td>
<td>RC</td>
<td>$2,870</td>
<td>Supports heavy pieces, can drive in any direction</td>
<td>More expensive, needs to be customized by Wahlberg</td>
</tr>
</tbody>
</table>

2.4 Product Requirements

According to advisor David Sword, the ideal, full scale version of SwiftScene would be able to move 200 lbs of scenery, no more than 40 ft of distance at a time, at an average velocity of 1 ft/s, with a 1 second range of stopping. At an eighth scale model, the proof of concept created needed to accomplish the same but at 25 pounds weight. Table 3 is the final list of product design specifications for the proof of concept prototype created. The metrics used in determining product design specifications and our original benchmark chart from Fall can be seen in Appendix B.

Table 3. Final Product Design Specifications for SwiftScene Prototype.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Units</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Datum (RC Platform)</td>
</tr>
<tr>
<td>Top Speed</td>
<td>ft/s</td>
<td>4.07</td>
</tr>
<tr>
<td>Acceleration</td>
<td>ft/s²</td>
<td>unknown</td>
</tr>
<tr>
<td>Load Capacity</td>
<td>pounds</td>
<td>441</td>
</tr>
<tr>
<td>Operating Time</td>
<td>hours</td>
<td>1.5/10</td>
</tr>
<tr>
<td>Braking Time</td>
<td>seconds</td>
<td>unknown</td>
</tr>
<tr>
<td>Directional Control</td>
<td>N/A</td>
<td>Any direction</td>
</tr>
</tbody>
</table>
Designs for SwiftScene DMX Control were improved upon throughout the fall and winter. Our very first concept for a physical module can be seen in Figure 3. This is obviously quite different from the final design selected. With a product as complex as SwiftScene, many design options were considered. The three subsystems involved are the housing, the drive system, and the control/safety system. Specific considerations are explored more thoroughly in each respective section of this report, however for the overall system the main considerations were the orientation of the wheels and the subsequent housing that could contain them.

Through a concept selection and scoring matrix, found in Appendix D, it was determined that a triangular wheel orientation (what is commonly referred to as a Kiwi-drive) in a rectangular housing would be best suited for the needs of SwiftScene. This design had no negative qualities according to the concept selection matrix and scored the highest of all possible concepts in the concept scoring matrix. The three wheels in a triangular orientation allow for rotational movements as well as lateral movements easily, whereas four wheels in a rectangular orientation make rotational movement more difficult. A rectangular housing was thought simple to build, while a triangular housing would have posed a unique manufacturing challenge.

2.5 System Level Design and Functional Analysis

The design specifications for SwiftScene expected the physical driver to carry a 25 lb load, have a reasonably sized housing footprint, and use three omniwheels no larger than 5” in diameter. In addition, it was expected that stepper motors would be used and that they would be controlled by DMX-to-Stepper-Motor conversion controllers (later referred to as DMX2STP). Programming of the module was designed to be achieved wirelessly from any light board or cue building software. The module prototype was designed to be powered by a series of 9.6 V batteries, with the assumption that power will be consolidated to one single source in future iterations of the project.

The primary function of SwiftScene overall was to drive the platform to which it is attached in lateral and rotational directions. These signals to move were sent from the operator with a light board via DMX technology (explained in the controls subsystem section of this report) to the driving module. The DMX2STP card was the communication checkpoint between the light board and the driving module. SwiftScene is an open loop system control system. The controls were meant to be easy to use and be a similar interface to other products used for theatrical productions, thus open loop control became inherent to the design of the project. A flow chart summarizing SwiftScene’s operation can be seen in Figure 15.
2.6 Patent Research

SwiftScene DMX Control was a project aimed at bringing scenic automation on a small scale to educational and community theatres. The premise of the project is using DMX technology to control a multi-directional, wireless robot that is meant to drive heavy pieces of scenery. If patented, the inventors would be listed as JV Ating, Tiernan O’Rourke, and Hannah Sisney under sponsorship of Santa Clara University.

If patented, SwiftScene DMX Control would remain the title. A more accurate descriptor would be “DMX based scenic robot”. The general purpose of the robot is to move wagons with affixed set pieces/scenery wirelessly. The control for this robot’s motion would come from a light board, cue software, or any other controller that can output a DMX signal. The technical features that give this product an advantage is that it is multi-directional and DMX controlled simultaneously, making it unique in the current market. The current market only has products that are multi-directional, or DMX controlled, but not yet both. Possible variants of the product include: using the robot outside of a theatrical setting for moving non-scenic objects, using the same physical robot with a different control system, or using the same control system but with a slightly different physical layout of the robot.

Similar competing technologies come from Rose Brand and Wahlberg, companies which sell DMX controlled scenic actuators and RC controlled multi-directional robots for scenic purposes, respectively (see Product Research section of this report). If our product were to be
commercialized, we believe that there would be a positive market reception. Our product would be relatively inexpensive compared to the custom automation systems some theatres use to achieve scenic automation.

We believe that SwiftScene could fit into patent classifications A63J, G05B, and possibly B62D, H04L, and H04B. Relevant patents to SwiftScene include the theatrical lighting network mentioned in the introduction to this report, Motorization System for Scenic Environment (Patent No. FR3038522A1), Automation and Motion Control System (Patent No. US8768392B2), and Battery Powered Wireless DMX LED Lighting System (US8581513B1). Selections from these patents are found in Appendix C.
3. Control and Safety

3.1 Roles and Responsibilities

The control of SwiftScene is what separates this product from others in the market currently. No other scenic automation company uses DMX to move full staging on the ground. Proprietary systems are expensive and, while effective, they require operators to learn to use an unfamiliar program and require specific training sessions and certifications. These are pluses for safety, but create a large overhead cost for manufacturers and that cost trickles down to the end user and their costs increase. Our goal was to choose a control system that exists currently rather than attempt to control SwiftScene with a newly created protocol. DMX was the logical choice because it is an existing protocol that is standard for almost every theater across the country.

The control subsystem is responsible for creating the movement of SwiftScene. This subsystem consists of several components to create a wireless transmission pathway for DMX control. The onboard components of the system are housed in the 18” by 18” by 8” electrical housing unit that makes up the majority of the device. Though we chose to use a Cognito2 light board for our final testing and for operation, the control system is design to be implement with any DMX capable device [14]. The conversion cards used in SwiftScene are manually addressed before operation and are simply patched into an available universe for use.

Similarly, when recognizing that control needed to be wireless, the City Theatrical ShowBaby was clear and away the right choice because many theaters already use these as their primary wireless DMX transceivers. The ShowBabies come ready to function out of the box, and as such fulfill ease of use requirements [15].

There are also two safety features that were designed for the control of SwiftScene. The first is an edgefinding system that uses a light sensor to detect distance to the ground below the device and uses this distance to control the enable pin on all motors. When the distance is too great the wheels will not turn. The second safety device built in was the “big red button,” otherwise known as an emergency stop.

3.2 Design

3.2.1 Possible Controllers

The appeal of SwiftScene DMX Control is its ease of use. By incorporating familiar controllers into the system, operators would be able to learn how to drive SwiftScene quickly and easily. In addition, the prototype that was built for this year’s iteration of the project was supposed to move in more than one direction at a minimum, so the controller must accommodate movement in multiple directions. The four concepts considered were a standard light board, a newly designed joystick (including building an interface ourselves), the ETC Mosaic Show Controller in conjunction with Mosaic Designer Software, and an ETC Mosaic touch panel. After careful consideration using the selection and scoring matrices (shown in Table 4, the others in Appendix D), we determined the best controllers theoretically to use for SwiftScene DMX were controllers from ETC’s Mosaic series. The touch screen (seen in the model pictured in Figure 16) affords the most flexibility as it is programmable ahead of time to the needs of any
end user such that the correct allocation of motor power is arranged ahead of time to move the device in the desired direction.

Table 4. Concept selection matrix for the control system, where concepts A and B are ETC Mosaic controllers, concept C is a joystick, and concept D is a light board.

<table>
<thead>
<tr>
<th>Control Subsystem</th>
<th>Concepts</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection Criteria</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Can control movement for multiple directions</td>
<td>minus</td>
<td>plus</td>
<td>plus</td>
<td>minus</td>
</tr>
<tr>
<td>Reliable stop and go controls</td>
<td>plus</td>
<td>zero</td>
<td>plus</td>
<td>plus</td>
</tr>
<tr>
<td>Visually appealing</td>
<td>zero</td>
<td>plus</td>
<td>minus</td>
<td>zero</td>
</tr>
<tr>
<td>User friendly</td>
<td>plus</td>
<td>plus</td>
<td>zero</td>
<td>zero</td>
</tr>
<tr>
<td>User friendly for all experience levels</td>
<td>plus</td>
<td>zero</td>
<td>zero</td>
<td>minus</td>
</tr>
<tr>
<td>Exists such that the system can stop or move quickly and easily</td>
<td>plus</td>
<td>zero</td>
<td>plus</td>
<td>zero</td>
</tr>
<tr>
<td>Can control movement for multiple speeds</td>
<td>zero</td>
<td>plus</td>
<td>zero</td>
<td>plus</td>
</tr>
<tr>
<td>Ease of installation</td>
<td>zero</td>
<td>zero</td>
<td>minus</td>
<td>plus</td>
</tr>
<tr>
<td>Emergency stop incorporated</td>
<td>minus</td>
<td>minus</td>
<td>plus</td>
<td>zero</td>
</tr>
<tr>
<td>Affordable</td>
<td>zero</td>
<td>zero</td>
<td>zero</td>
<td>zero</td>
</tr>
<tr>
<td>Sum +</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Sum 0</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Sum -</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Net Score</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Rank</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Continue with concept?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Maybe</td>
</tr>
</tbody>
</table>

Figure 16. ETC Mosaic Touchscreen (used without permission) [16].
The difficulty of using the Mosaic software is that a Mosaic Show Controller (MSC) is required along with a touchscreen, along with access to the local network for uploading and communication. In our case, the MSC was shipped non-functional and we only discovered this as we went into testing. However, we were able to rely on our selection matrix to know that a standard light board would function as a controller for SwiftScene well enough to test the device to our standards. The department of theater and Dance at Santa Clara University was kind enough to lend our project a Cognito2, a product of Pathway Connectivity. This lightboard was specifically designed for a primarily DMX system, however, in the process of testing we also used a Strand GLX. This console was manufactured in the early 1990s and is considered obsolete, but still outputs DMX and worked equally to the Cognito as a means of controlling SwiftScene. We did not test the preprogramming features of either console because they require recording cues, rather than creating buttons for forward, reverse, and circle.

The one-line diagram for the final design of the control system is shown in section 6.1. The components shown are the controller, the Show Babies, an Arduino, the DFD DMX2STP control cards, the “Big Easy” stepper motor driver from SparkFun and a breadboard.

### 3.3 Supporting Analyses

Our control system required analysis of the individual components and their functionality with specific testing before the entire system could be subject to testing. The components could not be modeled so they were tested for function prior to the integration. Before integrating the entire system as one, with the drive and housing, we tested control individually to ensure that we were handling the equipment properly and to prove that this form of motor control would result in the type of motion we expected. To test this equipment the control system was laid on a test bench and each part was tested first individually and then in concert with others. The motors were tested on a DC power supply directly connected to one of the stepper motor drivers. The DMX2STP controllers (see Figure 17) were tested first with a DC power supply to ensure functionality. When placed in conjunction with the rest of the subsystem, however, the DMX2STP did not work as expected.

There were two separate pins as seen above that needed to be functional for the cars to properly transmit the data to control motion. The enable pin on the DMX2STP must be held low in conjunction with the enable on the stepper motor controller for the motors to turn. We chose to ground this particular I/O because this way we could control the enable only on the “big easy” via an arduino that we connected to our distance sensor.

The DMX2STP also required a limit switch routine upon startup. To mimic this routine, we connected the limit switch to an arduino output pin, set to go between 0 and 5V in succession. We used a voltmeter to test the outputs before connection and found that the arduino was outputting the correct pattern of voltage. Similarly, we used the voltmeter in conjunction with an Adafruit VL6180x light emission device. This device uses I2C communication to test the time it takes and range from the light emission source, which we then used to control an output pin between 0 and 5V again. This output pin controlled the enable function of the big easy driver,
and thus created our edgefinding, automated stop system. The code for both of these Arduino functions can be found in Appendix F.

3.4 Testing and Results

The testing for SwiftScene control was broken into two categories. The first was a series of tests to confirm that the system was running and that DMX was, in fact, controlling the motion of the wheels. The second set of testing data was to test for the benchmarks that we set for the device in early fall. We aimed to answer several questions for part one, shown in the table below.

Table 5. Control Testing Results Part 1.

<table>
<thead>
<tr>
<th>Does it turn on?</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output DMX?</td>
<td>Yes</td>
</tr>
<tr>
<td>Output voltage</td>
<td>Yes</td>
</tr>
<tr>
<td>Rotate correct number of times?</td>
<td>Yes</td>
</tr>
<tr>
<td>Rotate at correct speed?</td>
<td>Yes</td>
</tr>
<tr>
<td>Stop with edge finder?</td>
<td>Yes</td>
</tr>
<tr>
<td>Stop with E-stop?</td>
<td>No</td>
</tr>
</tbody>
</table>
The only area where the basic control of the device failed is the emergency stop. This e-stop was designed to cut all data transmission to the device, and our understanding of the DMX2STP was that if data was lost the device would stop all motion. However, it has been shown that power must also be cut, and because the system is powered with 9.6V RC batteries, there is no central way to cut power and therefore the emergency stop system is non-functional as designed. Future iterations of the project will include a central battery and an emergency switch circuit that will cut power if data is lost.

The second set of criteria are somewhat control dependent and somewhat dependent on other parts of the device. Those criteria are shown in Table 6, with those tested for control highlighted.

Table 6. Benchmark Testing Parameters, Control Specified.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Units</th>
<th>Parameters</th>
<th>Datum (RC Platform)</th>
<th>Target Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Speed</td>
<td>ft/s</td>
<td>4.07</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Acceleration</td>
<td>ft/s²</td>
<td>unknown</td>
<td></td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>Load Capacity</td>
<td>pounds</td>
<td>441</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Operating Time</td>
<td>hours</td>
<td>1.5/10</td>
<td></td>
<td>1/10</td>
</tr>
<tr>
<td>Braking Time</td>
<td>seconds</td>
<td>unknown</td>
<td></td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>Directional Control</td>
<td>N/A</td>
<td>Any direction</td>
<td></td>
<td>forward/back/rotate</td>
</tr>
</tbody>
</table>

The results of our testing can be found in Table 7 in section 6.3. It is clear that SwiftScene passed all but one of the basic tests that we were able to perform, as well as meeting several of the benchmarks set out.

3.5 Conclusion

Though we have yet to reliably control the linear motion, we have shown that our product does function as we believed it might, and is a valid proof of concept for DMX controlled scenic automation. We intend to continue testing the linear motion, as well as utilize these results to further our product and develop future iterations. Though the DMX controllers work, they function such that they limit the operations we can complete. When testing, we found that the wheels must rotate to the target location in one direction entirely before changing directions. We were looking for a product that can be continuously rotated, but we were able to make these specific cards work.
4. Drive
4.1 Roles and Responsibilities

The drive subsystem of SwiftScene included the motors and wheels of the physical module. Customer needs research indicated the need for the module to drive in multiple directions, and to reasonably attain a desired position onstage. Thus, the primary requirement of the drive subsystem was a multi-directional drive with accurate position control. The secondary requirements of the drive subsystem were that it be simple to use and integrate into the project. DMX technology is one-directional, so the system overall was already decided to be open-loop, which invalidated the need for encoders.

4.2 Design

As discussed in the product specifications section of this report, it was decided early on that SwiftScene would make use of the “kiwi-drive,” a drive layout in which three omni-wheels are positioned as an equilateral triangle (seen in Figure 18). An omni-wheel (seen in Figure 19) is a double layered wheel with rollers placed perpendicular to the main wheel’s axis of rotation. This layout is simple to accomplish and allows for a maximum range of movement. Other design options for drive layout were briefly considered (see Appendix D), but this one was ultimately chosen for its range of motion, ease of manufacture, and cost benefit.

Figure 18. Kiwi Drive (used without permission) [17].

Figure 19. An Omni-Wheel (used without permission) [18].
With the overall layout confirmed, the next step was choosing a motor. Early in the design process of SwiftScene we decided that using DC motors would be best for the project in regards to simplicity and cost. With the need for position control but the inability to implement a closed-loop feedback control system, it soon became clear that stepper motors would be the optimal type of motor. Stepper motors are a type of DC motor that rotate the shaft in steps. The number of steps is easy to control, thus position is easy to control. Analysis from section 4.3 revealed which type of stepper motor was best for the purposes of this project. The type of motor then influenced the choice of motor driver. We chose the Big Easy Driver (seen in Figure 20) for its familiarity, compatibility, and cost benefit.

As part of the kiwi-drive layout, the drive design calls for the omni-wheel to be mounted directly to the shaft of its respective motor. Much like the process for the overall layout, other designs for mounting the motors were briefly considered (see Appendix D), but direct mounting was chosen for simplicity and space considerations.

![Figure 20. Big Easy Driver (used without permission) [19].](image)

### 4.3 Theoretical Analysis

An estimate of required torque was necessary to choose the motors for SwiftScene, as weight capacity was an influence on the design. A simple analysis of the forces on one wheel (see Figure 21) of the module allowed for a conservative estimate of required stall torque. This estimate came out to approximately 142 oz-in. Calculations for torque requirements were completed under the assumption that a 25.0 pound load would be evenly distributed across seven points of contact with the ground (three wheels of the SwiftScene module, and four wheels of the platform). This assumption gave us an estimated load of 3.57 pounds (15.9 N) per wheel. The force of friction is drawn in Figure 21, but was determined to be negligible for the case of this estimate. The moment of inertia of the motor shaft was also determined to be negligible. The wheels were considered to be solid aluminum with a 2.5” (0.0635 m) radius. The desired linear speed was considered to be 1 ft/s (0.305 m/s), which translated to a rotational speed of 4.8 rad/s. The following calculations lead to the estimate of 142 oz-in (1.0 Nm) [20]:

\[
T_{\text{stall}} = F_{\text{weight}}r + T_o \\
T_o = J_{\text{wheel}}\alpha \\
J_{\text{wheel}} = \frac{1}{2}mr^2
\]

(Eq. 1)

(Eq. 2)

(Eq. 3)
\[ J_{\text{wheel}} = \frac{1}{2} (1.31 \text{ kg})(0.0635 \text{ m})^2 = 0.00264 \text{ kgm}^2 \]
\[ \alpha = \frac{\omega}{t} = \frac{4.8 \text{ rad/s}}{0.5 \text{ s}} = 9.6 \text{ rad/s} \]
\[ T_{\text{stall}} = (15.9 N \times 0.0635 \text{ m}) + 0.0253 \text{ Nm} = 1.03 \text{ Nm} \]
\[ T_{\text{stall}} \approx 1.0 \text{ Nm} = 142 \text{ oz \cdot in} \]

With this estimate, a NEMA 23 stepper motor, the torque-speed curve of which can be seen in Figure 22, was chosen. The actual motor can be seen in Figure 23.

![Figure 21. Forces considered on one wheel of SwiftScene (attributed to Hannah Sisney).](image)

![Figure 22. NEMA 23 Torque-Speed Curve (used without permission) [21].](image)
4.4 Testing and Results

Due to unforeseen obstacles (detailed in the Team and Project Management section of this report), we were unable to complete thorough testing of the drive subsystem before its assembly into the full prototype. We did test the ability of each stepper motor, paired with each motor driver, to step and micro-step in clockwise and counterclockwise directions. Each motor and each motor driver were able to step and micro-step in both directions without issue.

In order to test the motors (and motor drivers) for their ability to step and microstep in clockwise and counterclockwise directions, we used power from a standard adjustable DC power supply and an Arduino microcontroller. The test set up can be seen in Figure 24. The test code was taken from SparkFun Electronics, the supplier of the Big Easy Drivers. The test code can be found in Appendix G. Each test was successful, and the motors and motor drivers were incorporated into the final assembly.
If our original timeline (section 7.3) had remained intact, we would have completed thorough testing of each motor to confirm torque and speed capability. In order to test torque capabilities we would have commanded the motor to turn continuously and in each trial loaded the shaft of the motor with a known weight. We would have increased the weight between each trial in discrete increments until the motor no longer moved, therefore finding actual stall torque. In order to test speed capabilities, we would have attached a flag to the motor shaft, counted the number of rotations of the flag in a given period of time, and calculated the speed using that information. We would have completed this speed test at different trials using different levels of power such that we could best understand the power requirements of the motor. These tests would have been repeated for each motor.

Once the testing of each motor was completed, we would have integrated the motors and wheels into the designed drive system and completed separate testing for motion capabilities before final assembly of the entire module. We would have used the following testing procedures:

**Moving in a Straight Line**

1. Lay down tape and arrange in the shape of a compass, marking N, S, W, E, NW, SW, NE, and SE. Each spoke should be at least 3 feet from the origin.

2. Position robot at the origin, with one corner facing the “north” direction on the compass. Mark the center of the robot with tape.

3. Drive robot in one direction as straight as possible, recording the power given to each motor. Adjust power if robot does not drive straight. Return robot to origin once robot reaches the end of the tape.

4. Repeat Step 3 for all directions 10 times until motor powers for each direction are recorded.

5. For each run, a 1-inch deviation between the straight line and the center of the robot is acceptable. Inspect this difference visually as the robot is driving.

**Moving Along Curve**

1. Lay down tape and arrange to form a circle, and another to form an S-curve.

2. Position the robot on top of the tape. Mark the center of the robot with tape.

3. Drive robot along the direction of the tape as best as possible, and repeat 10 times. Record the power given to each motor. Adjust power if robot does not drive straight. Return robot to starting position once robot reaches the end of the tape.

For each run, a 1-inch deviation from the tape line and the center of the robot is acceptable. Inspect this difference visually as the robot is driving.
Had the final assembly had more reliable linear motion capabilities (see section 6.3) we would have followed these same testing procedures to ensure that the prototype was robust enough in its range of motion.

5. Housing

5.1 Roles and Responsibilities

The housing makes up the main body of the SwiftScene DMX module and was required to be large enough to accommodate all internal components and robust enough to withstand loading cycles and improper storage. Customer specifications also called for simplicity of the product, particularly in integration into an existing stage set, and strong enough to withstand modular use. The final design used a simple box housing to address all of these product goals.

5.2 Design

Initial designs began with a triangular shaped housing (see Figure 3) to match the decision to implement kiwi-drive into the module. However, it was later ruled that this design would have limited space for the module’s internal components. The next step up was a box housing (see Figure 25), which not only provided more internal space but was also comparatively simpler to analyze. Thus, the decision was made to keep the kiwi-drive, but also switch over to the box housing.

The original housing was planned to be fabricated out of 16 gauge aluminum sheet metal and folded into the final box shape. After a suggestion from SCU’s shop manager, Don MacCubbin, regarding the wide availability of pre-assembled electrical housings, the decision was made to simply purchase a housing instead of manufacturing one.

Figure 25. The electrical box housing ultimately chosen (used without permission) [22].

The housing is an 18”x18”x8”, 16-gauge steel box with knockouts, manufactured by and purchased from McMaster-Carr. The housing has a NEMA 1 environmental rating and is also UL listed, but is not IP rated for outdoor usage [22].
5.3 Theoretical Analysis

This scaled down prototype was designed to carry a maximum load of 25 pounds. In doing theoretical plate deformation calculations for the housing, two loading scenarios were considered: an evenly distributed load across the full surface of the module to simulate actual operating conditions, and a centered 25 lb point load to simulate various uneven loading scenarios, such as improper storage. We wanted to confirm the design specification of 25 lbs before purchasing the housing so that we were buying an item that would be sufficiently robust and have acceptable levels of stress and deformation, such that they are under the yield stress. Calculations for the first scenario assumed a uniform load with a simply supported edge. The housing top was initially stated to be a 12-in by 12-in square and made out of 16 gauge A36 sheet steel. Using equations provided by the RoyMech website, the maximum amount of stress for a 25 lb distributed load was 1839.08 psi, and the maximum amount of deformation experienced was 0.0225 in [23]. Based off these results, the box housing would be robust enough to handle a load of this magnitude. Scaling up the size of the top to the final dimensions did not provide any significant changes to the maximum stress and deformation values.

Calculations for the first scenario assumed a uniform load with a simply supported edge. The equation for maximum stress for a uniform load and a simply supported edge is

\[ \sigma_{max} = \frac{0.75pb^2}{t^2[1.61(\frac{b}{a})^3 + 1]} \]  

(Eq. 4)

where \( p \) is the direct stress from the applied force in psi, \( a \) and \( b \) are the side lengths in inches, and \( t \) is the thickness of the material in inches [23]. The maximum amount of stress for a 25 lb distributed load was 1839.08 psi (12680.01 kPa).

The equation for maximum deformation is

\[ y_{max} = \frac{0.142pb^4}{Ebt^3[2.21(\frac{b}{a})^3 + 1]} \]  

(Eq. 5)

where \( E \) is the elastic modulus of the material and the other variables represent the same parameters as the former equation [23]. The maximum amount of deformation experienced was 0.023 in (0.058 cm). Based off these results, the box housing would be robust enough to handle a load of this magnitude. Scaling up the size of the lid to the final dimensions did not provide any significant changes to the maximum stress and deformation values.

![Figure 26. Sketch for a uniform load on the housing (attributed to JV Ating).](image-url)
For the second scenario, the initial parameters were kept the same, using the same 12 inch by 12 inch top side and 16 gauge A36 sheet steel. The simplest scenario for a point load applied to this surface would be if the point load was applied at the exact center of the surface. The equation for the maximum stress from a centered point load is

\[ \sigma_{\text{max}} = \frac{1.5P}{\pi t^2} \left[ \left(1 + \gamma\right) \ln \left(\frac{2b}{\pi e'}\right) + K_2 \right] \]  

(Eq. 6)

where \( P \) is the applied load, \( t \) is the thickness of the plate, and \( \gamma \) is the material’s Poisson’s Ratio [23]. The variable \( e \) is the radius of applied force and \( e' \) is the effective radius, which is equivalent to \( e \) if the radius is greater than half of the material thickness. For a 1 inch radius, \( e \) can be used for \( e' \) in the above equation. \( K_2 \) is a constant value that is determined from the ratio of the plate side lengths. For a 1:1 ratio, \( K_2 \) is given to be 0.435.

Table 7. Values for \( K_1 \) and \( K_2 \) determined by the ratio of the plate side lengths [23].

<table>
<thead>
<tr>
<th>( a/b )</th>
<th>1.0</th>
<th>1.1</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
<th>3.0</th>
<th>4+</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_1 )</td>
<td>0.127</td>
<td>0.138</td>
<td>0.148</td>
<td>0.162</td>
<td>0.17</td>
<td>0.177</td>
<td>0.180</td>
<td>0.185</td>
<td>0.185</td>
</tr>
<tr>
<td>( K_2 )</td>
<td>0.435</td>
<td>0.565</td>
<td>0.650</td>
<td>0.789</td>
<td>0.875</td>
<td>0.927</td>
<td>0.958</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The equation for maximum deformation from a centered point load is given as

\[ y_{\text{max}} = K_1 \frac{Pb^2}{3Et^3} \]  

(Eq. 7)

Where \( E \) is the elastic modulus of the material and \( K_1 \) is another constant value determined from the ratio of the plate side lengths [23]. The value of \( K_1 \) is given as 0.127.

For a 25 lb concentrated load located at the center of the housing top, this resulted in a maximum stress of 9158.12 psi (63143.01 kPa) and a maximum deformation of 0.065 in (0.164 cm). These results fell within our acceptable levels of stress and deformation, even if scaled up to the final housing size. Overall, both scenarios provided enough confidence that the Swiftscene DMX module would be robust enough to withstand a general load of 25 lbs.

Figure 27. Sketch for a centered point load on the housing (attributed to JV Ating).

5.4 Finite Element Analysis

The module was also modeled and simulated in both SolidWorks and Abaqus for finite element analysis, which showed similar results to the theoretical calculations. The first model shown (Figure 28) is the centered point load of 25 lbs. The model was run with a quadratic mesh.
of 1245 elements. The seed was defined by Abaqus and was 0.59, while curvature control was on at 0.1. The model was fixed at the screw holes, just like the lid of the housing would be. A point load was centered on the lid by creating a reference point from sections of the lid. The element code for the hex-shaped elements was CD38R. We did not check for the convergence of the mesh, however, the part was processed in only one step when the job ran and typically that is a signifier (though not the sole deciding factor) of convergence.

Figure 28. Results from a centered 25 pound point load (attributed to Tiernan O’Rourke).

This model showed a maximum Von Mises stress of nearly 19 ksi, which was higher than the expected maximum Von Mises stress expected from the hand calculations. However, from figure 28, it can be seen that this maximum stress occurred at one of the screw holes, which were not accounted for in the hand calculations, and would have required a stress concentration factor be added to account for this cutout. Away from the screw holes, the maximum stress falls between 7.7 ksi and 9.2 ksi, while the hand calculation revealed an expected maximum stress of 8.2 ksi, showing that the model represented an accurate depiction of our housing. We chose the Von Mises stress because we wanted to see a summary of the maximum stress in the lid as we were more concerned with overall safety or failure of the housing that in which direction it was likely to fail. Von mises stress is useful when checking for yielding due to the max energy distortion criterion. The resulting Von Mises stresses were well below the yield stress of steel—which is at minimum 30 ksi according to W.D. Callister’s Materials Science and Engineering: An Introduction as found on AmesWeb—and so we determined that the lid would suffice [24].

The second of the models (Figure 29) was designed to examine the device if it were to see this loading in an accident or a case of improper storage. An uneven loading scenario could create problems overall for the housing. This model was run in SolidWorks and was done again with quadratic mesh. The number of elements was 29620 and the average element size was 0.66
in. The triangular elements had an a/b ratio of 1.5. The focus of this model was deflection, rather than stress because this was about the overall functionality of the product because deflection, even before plastic deformation, could cause serious functional issues for the module. We expected the maximum stresses (based on the hand calculations) to be very low and well away from yielding, and so instead focused on the deflection results.

Figure 29. Deflection results from an uneven loading situation (attributed to Hannah Sisney).

The model gave a maximum deflection of 0.0005 in which is about half of the deflection expected for the even loading calculated in the theoretical analysis. Figure 29 shows how, even with such uneven loading, that the deflection is limited. This result is consistent because the surface area of the box was cut in half and the denominator of the maximum deflection was increased overall by a factor of 2, creating half of the deflection. Furthermore, a deflection of less than 1/1000 in is not substantial enough to warrant concern. As such, no uneven loading tests were physically performed because the finite element analysis confirmed that the housing chosen was a suitable option for our purposes.

5.5 Testing and Results

A weight test was performed such that the model was loaded with weight up to 22.5 lbs, where the individual weights (each weighing 1.5 lbs) were loaded sequentially onto the device, with the deflection from the bottom of the housing to the ground being measured by a tape measure. This was the available weight for testing. Overall, the housing itself showed no visible deflection, and was clearly strong enough to hold much more weight that was applied. However, what became clear was an unexpected source of deflection. The overall height of the module was measured while weight was being loaded, and an overall deflection of 0.25 in was seen. The results of this testing are shown in Table 8 below.
Table 8. Weight Test Results

<table>
<thead>
<tr>
<th>Weight (lbs.)</th>
<th>Deflection (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>3.0</td>
<td>0</td>
</tr>
<tr>
<td>4.5</td>
<td>0</td>
</tr>
<tr>
<td>6.0</td>
<td>0.06</td>
</tr>
<tr>
<td>7.5</td>
<td>0.09</td>
</tr>
<tr>
<td>9.0</td>
<td>0.13</td>
</tr>
<tr>
<td>10.5</td>
<td>0.13</td>
</tr>
<tr>
<td>12.0</td>
<td>0.13</td>
</tr>
<tr>
<td>13.5</td>
<td>0.19</td>
</tr>
<tr>
<td>15.0</td>
<td>0.9</td>
</tr>
<tr>
<td>16.5</td>
<td>0.19</td>
</tr>
<tr>
<td>18.0</td>
<td>0.22</td>
</tr>
<tr>
<td>19.5</td>
<td>0.25</td>
</tr>
<tr>
<td>21.0</td>
<td>0.25</td>
</tr>
<tr>
<td>22.5</td>
<td>0.25</td>
</tr>
</tbody>
</table>

It is unclear whether this registered deflection was from the omni-wheel rollers, or perhaps from the motor shafts’ bending. These are the most likely sources. It is concerning that the 22.5lbs load was capable of lowering the object by a full quarter of an inch, so increasing the size of the motors during the scaling up will likely reduce or alleviate this issue.

Along with this test, two weights were loaded onto the lid at the center, as previously modeled. The available loading was 11lbs, and 20lbs, so both of those weights were used, with no visible deflection being seen. This was in line with the simulation results. However, further testing could be performed to determine where the deflection point actually occurs. But because there is only one module and it must remain functional, we chose to not push to the limit of the device and deform the box and risk damaging components.

6. Final Prototype

6.1 System Integration

Physically integrating SwiftScene as a full assembly required mounting the wheel-motor assembly to the modified lid of the electrical enclosure, mounting the electronics to the inner walls of the electrical enclosure, building the circuitry to include the receiving Show Baby, and plugging the transmitting Show Baby into a standard light board. Using the light board, four
DMX channels were patched to each DMX2STP controller (using 12 channels total out of the possible 512 of a DMX universe), to control coarse position, fine position, speed, and acceleration for each motor. The data was sent to the receiving Show Baby, which sent each command to its respective DMX2STP controller. The DMX2STP controllers were daisy chained together such that one receiver could communicate with all three controllers. Signals from the Arduino were sent to each DMX2STP controller to run the setup routine. Signals from the Arduino were also sent to each motor driver such that the enable pins were set low, and would be set high (thus stopping all motor movement) if the edge-finding light sensor sensed a distance greater than the height of the module. Each DMX2STP controller and each motor driver were powered by a 9.6 V battery. The Arduino was powered by a 9 V battery. A schematic of the final assembly and details from the final prototype can be seen in Figures 30 -32. Further details of possible assembly into a platform are provided in Appendix I.

Figure 30. Final Assembly Schematic (attributed to Tiernan O’Rourke).
6.2 Testing

Much of the initial testing was focused on the module’s drive system, mainly in outputting robot motion from an inputted command from the lightboard. The lightboard would be directly or wirelessly connected to one of the module’s DMX cards and provide commands to the three stepper motors. We successfully controlled the motors independently of one another, thus allowing a wide range of movement via the module’s kiwi-drive. In order to test the module’s range of motion and stopping capabilities, it was placed on the ground, given commands, and qualitatively observed by the team. In order to test the safety system, the module
was laid on its back, given commands, and observed by the team. If the module had behaved as expected, the testing protocols outlined in Table 9 would have been followed. However, because linear motion and battery life were unreliable, tests for speed, acceleration, and deceleration were completed while the module moved rotationally. When testing for speed and acceleration, the module was filmed such that the number of rotations could be counted against a timestamp. Two trials were completed, the results of which are detailed in section 6.3. Tests for load capacity are detailed in section 5.5.

Table 9. Experimental Protocol.

<table>
<thead>
<tr>
<th>Evaluation</th>
<th>Equipment</th>
<th>Accuracy</th>
<th>Trials</th>
<th>Expected Outcome</th>
<th>Assumptions</th>
<th>Man Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Speed</td>
<td>Stop watch, measuring tape</td>
<td>0.1 ft/s</td>
<td>5</td>
<td>1 ft/s</td>
<td>Constant speed</td>
<td>1+</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Stop watch, measuring tape</td>
<td>0.1 ft/s²</td>
<td>5</td>
<td>0.5 - 1 ft/s²</td>
<td>Constant acceleration</td>
<td>1+</td>
</tr>
<tr>
<td>Load Capacity</td>
<td>scale</td>
<td>1 lb</td>
<td>3</td>
<td>25 lbs</td>
<td>Evenly distributed load</td>
<td>0.5</td>
</tr>
<tr>
<td>Operating Time</td>
<td>none</td>
<td>15 minutes</td>
<td>N/A</td>
<td>1/10 hrs</td>
<td>Continued testing will reveal time constraints</td>
<td>5+</td>
</tr>
<tr>
<td>Braking Time</td>
<td>stopwatch</td>
<td>0.1 s</td>
<td>5</td>
<td>0.5 s</td>
<td>Surface with friction</td>
<td>1+</td>
</tr>
<tr>
<td>Directional Control</td>
<td>Tape</td>
<td>N/A</td>
<td>5</td>
<td>forward/back/rotational motion</td>
<td>One wheel is always parallel with platform</td>
<td>2+</td>
</tr>
</tbody>
</table>

6.3 Results

Each of the motors operated independently of one another, which theoretically allowed the module a near unlimited range of movement. The module was able to rotate about its center in both directions consistently when each motor was commanded to spin in the same direction as
each of the other motors. This behavior was easily repeatable, showing a high level of consistency with regards to this particular mode of motion.

The module was also able to achieve linear motion by having two motors spin in opposite directions of each other, but this linear motion was inconsistent and has yet to be fully repeatable. Closer inspection revealed that one of the wheels had simply stopped moving despite the motor still running for the given duration. This could be attributed to a number of factors such as uneven testing surface, insufficiently charged power sources, weight distribution in the module, or insufficient torque from the motors. The DMX2STP controllers and the motor drivers likely drew too much current from the batteries, which limited the amount of testing time as well as the module’s effective operating time. Upon reflection by the team, it was also determined that insufficient torque was the likely culprit of limited linear motion. When the motors were chosen (see section 4 of this report), required torque was calculated under the assumption that all motors would contribute to the movement of the module. When this was not the case and only two motors were activated, the torque of both motors was insufficient to drive the entire module.

The safety features of the module were also tested with limited success. As mentioned in the control section of this report, the emergency stop system failed to work as expected. When power was cut to the transmitting ShowBaby, the motors continued to operate on their original command. Three trials proved that cutting power to the ShowBaby (therefore cutting data transmission) failed as an emergency stop system. The edgefinding system, however, did work as expected. When the distance sensor was covered by a hand in any range between the distance sensor itself and lid of the enclosure, the motors operated as commanded. When the hand was removed, the motors immediately ceased all motion.

Expected speed and acceleration values were achieved in our tests. By observing the number of rotations at top speed in a given amount of time, the ‘linear’ speed was calculated as 1.2 ft/s in both trials. This result matches our desired speed of at least 1 ft/s. By observing the time it took to achieve top speed from rest and rest from top speed, the acceleration and deceleration were calculated as 0.4 ft/s². This results matches our desired acceleration range. Each of these speeds and accelerations could be easily changed by reprogramming the DMX2STP cards. The results of all tests are summarized in Table 10. In the future, problems encountered with testing of the full system will be addressed in multiple ways. Use of a different type of DMX2STP card, one that is designed specifically for multidirectional motion, will achieve more accurate control of the module and cut down set up time. Centralizing and simplifying the power source will allow the module to run for longer periods of time without having to worry about insufficient power. This will also allow for a robust emergency stopping system. The housing will be designed such that the wheels account for a larger footprint of the module and that weight is distributed more evenly, ensuring more physical stability.
Table 10. Testing Results for Control Parameters, Part 2.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Units</th>
<th>Parameters</th>
<th>Target Range</th>
<th>Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Speed</td>
<td>ft/s</td>
<td>1</td>
<td>Y, 1</td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>ft/s²</td>
<td>0.5 - 1</td>
<td>Y, N/A</td>
<td></td>
</tr>
<tr>
<td>Braking Time</td>
<td>seconds</td>
<td>0.5 - 1</td>
<td>Y, 0.05</td>
<td></td>
</tr>
<tr>
<td>Directional Control</td>
<td>N/A</td>
<td>forward/back/rotate</td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>
7. Team and Project Management

7.1 Introduction

This project was completed by a team of three mechanical engineers. When the idea for SwiftScene was first conceived, the project was thought ideal for an interdisciplinary team of mechanical, electrical, and possibly computer engineering students. Department and time constraints necessitated that the project be purely mechanical. Nonetheless, future interdisciplinary senior design teams are encouraged to adopt SwiftScene for further iterations of the project.

7.2 Team Member Roles

With such a small team, clearly defined member roles were not always necessary. Tiernan O’Rourke was elected team leader for his extensive background knowledge of DMX technology and automated scenery prior to the project’s beginnings and his connections to the entertainment industry. This role morphed into a point of contact role with project sponsors, as well as the team member with the most oversight over the control aspect of the design. Hannah Sisney fell into the role of project manager and administrator, keeping the team up to date and on track in regards to assignments and deadlines. JV Ating brought a prior set of knowledge from the realm of robotics to the team. Each team member shared design and testing duties equally throughout the project.

7.3 Project Challenges

Challenges along the way significantly impacted SwiftScene. The first challenge of any project is maintaining the proper budget. In order to develop an appropriate prototype but remain within the university provided budget, it was imperative that the team accept equipment loans. Once loans were secured (overcoming the challenge of budget), the new and most significant challenge of the project was dependency on external companies. Waiting for equipment to be delivered set back our initial timeline by approximately two months. Miscommunication between the team and our sponsors led to misunderstanding of desired equipment capabilities and the receiving of equipment not fully up to the initial standards of the team. These challenges caused us to have to abandon expected testing protocols for our subsystems, and to update our design specifications of the prototype.

7.4 Timeline

Three timelines are shown in Figures 33 - 35. The first is the initial timeline set in Fall, the second is the timeline set at the beginning of Winter, and the third is the timeline set at the beginning of Spring. A waiting period of almost two months for equipment significantly diminished the time we had for assembly testing. Specific testing of subsystems had to be abandoned, and testing of the prototype assembly had to be extended further into the Spring than was initially planned.
Figure 33. Fall Timeline.
Figure 34. Winter Timeline.
Figure 35. Spring Timeline.
7.5 Budget

Initial budget proposals greatly overestimated the required funds for SwiftScene as they were in anticipation of a much more robust project. Ultimately, our team was rewarded $1,500 from the university. Thanks to the generosity of our sponsors, we were able to remain within budget for the entirety of the project. We have estimated that without loaned equipment, the final prototype would have cost $3,833.51. The actual cost of our prototype was $846. Adding the purchase of extra tools and backup equipment, our team spent approximately $1,000 of our $1,500. The remaining $500 will go to shipping costs of returning loaned equipment, and paying for any damages sustained during use. An abbreviated budget is shown in table 11, while a detailed budget can be found in Appendix H.

Table 11. Abbreviated Budget.

<table>
<thead>
<tr>
<th>Category</th>
<th>Sought</th>
<th>Committed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grant</td>
<td>$2,850</td>
<td>$2,850</td>
</tr>
<tr>
<td>Category</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drive</td>
<td>$525</td>
<td>$596</td>
</tr>
<tr>
<td>Control/Safety</td>
<td>$119</td>
<td>$137</td>
</tr>
<tr>
<td>Housing</td>
<td>$156</td>
<td>$211</td>
</tr>
<tr>
<td>Platform</td>
<td>$59</td>
<td>$59</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>$110</td>
<td>$108</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>$1,111</td>
</tr>
</tbody>
</table>

8. Engineering Standards and Realistic Constraints
8.1 Political Impact of SwiftScene

In the spring of 2018 President Donald Trump threatened to eliminate the National Endowment for the Arts for the U.S. budget for 2018-2019. Congress rebuffed his actions, however, even the threat of losing the NEA was a devastating reminder to the arts world that arts education is still undervalued and still in need of creative ways to navigate the cost of performances [25]. SwiftScene aims to lower the costs of production for educational theater, the type of theater most in need of funding. This product will have political impact by allowing theaters to do their work producing plays and fulfilling such a necessary and important role in society. However, the arts have never been apolitical and educational theater in particular has a reputation for challenging all political structures. By creating a piece of theatrical equipment we understand that there are potentially artists who will use SwiftScene for political commentary,
and we would be honored to be included in any piece of art created for political commentary. Toni Morrison is believed to be the one who said, “the best art is political and you ought to be able to make it unquestionably political and irrevocably beautiful at the same time” [26]. If nothing else, we chose a project like SwiftScene because we wanted to be participants in the artistic world, not to judge or condemn other artists and how they might use our product.

8.2 Economic Impact of SwiftScene

For good reason, the cost of creating moving scenery for theatrical productions is high. Safety is of utmost importance in live performance and moving scenery poses a great safety risk. That being said, because of technological advances the integrability of computer-aided user interfaces movement technology is the new gold-standard for innovation in theater. This technology is on the way to being affordable for every theater, but it is not there yet. Therefore the economic impact of a low-cost scenic motion device cannot be overstated. If the cost of SwiftScene remains low and it is easy to use, other companies will have to follow suit or be outperformed. This race towards affordable scenic motion will create positive impacts for the larger theater community and the net economic impact will be larger audiences and even more productions. We believe that we have demonstrated an initial viability for the use of DMX as a control protocol, and therefore as a pathway towards lowering the cost of automation. DMX infrastructure exists in theaters, and because SwiftScene was designed to be a plug-and-play module, the integration cost is virtually nothing, and the end user will only be paying for the manufacturing and sale of the device, nothing more. This is the first step to challenging the current cost of automation.

8.3 Manufacturability

All of the components of SwiftScene exist as pieces that can be purchased today. Stepper motors, DMX2STP, motor drivers, batteries, show babies, etc. can be (and in our case were) all ordered online. The challenge of manufacturing this device was not in obtaining or creating parts from scratch. It was interfacing each of the components correctly. Having already done this, however, the manufacturing of this device is simple. We understand how each of the components work together, and we have expectations for how to simplify the connection of the device. The device would be made in bulk meaning costs for each component will go down, and the labor will be the most expensive part of creating SwiftScene modules. In theory, custom sizing and manufacturing could be done down the line as a way of engaging a broader customer base, however, this type of manufacturing would begin well after the initial SwiftScene device is deployed. On the whole, this device would be easy to make in the quantities necessary for the entertainment industry.

8.4 Ethical Impact of SwiftScene

There are several ways to look at the ethics involved in designed SwiftScene. First and foremost our responsibility is the safety of all users and operators of the SwiftScene product. Not
only are we legally liable for the safety of our customers, but we are ethically bound to ensure that we design, test, and manufacture SwiftScene to rigorous safety standards. Moving large pieces of scenic equipment inevitably creates danger. Ethically, we must not and cannot lose sight of this danger when discussing SwiftScene. We are not yet ready to manufacture or sell this product because of safety concerns more than any other.

We are also attempting to create this device at a low cost to others. There is however, an ethical obligation to not choose low quality parts or accept less-than professional standards while aiming for the lowest possible price point. There is a distinct difference between cutting cost and cutting corners. We chose the appropriate price point to maintain our safety standards and maintain ethical manufacturing procedures. This included sourcing materials and parts that hold up to U.S. standards environmentally and in accordance with labor laws.

Finally, the ethical creation of SwiftScene, as with all new products, is important to maintain. Many of the parts that comprise SwiftScene are already functional products sold and operable independently. Developing partnerships with the makers of these products and working with them as we develop the SwiftScene technology will be a crucial step to ensuring that we are ethically using and distributing these other parts. Executing our vision for SwiftScene will require acting with these ethics guidelines in mind.

8.5 Social Impact of SwiftScene

Perhaps the simplest way to assess the social implications of SwiftScene is to assess how SwiftScene might affect the theatrical workplace. SwiftScene can create job opportunities in theater—that is to say trained operators will be necessary—it will open avenues for various production companies to further their performances and it could be a vital element of future social engagements like theater or immersive art and technology. SwiftScene is new technology and there are few better places than the theatrical environment for new technology to have an immediate impact.

9. Conclusion

9.1 Summary

SwiftScene DMX Control was started as a project to bring engineering and the arts together in a way never before seen by Santa Clara University. Although this project encountered obstacles, it produced a prototype to prove the viability of using DMX as valid protocol for scenic automation technology, illustrated the importance of safety in any design project, and ultimately began a line of inquiry into new possibilities for scenic automation at SCU and other educational theatres. We proved that consistent rotational motion and mostly consistent linear motion of a robot can be achieved with DMX control. We learned that in order for the module to have a true emergency stop system, power must be consolidated into one source with an on/off switch. We did, however, also prove that an edge finder can be successfully incorporated as a secondary means of safety. We believe that this project has started the conversation that will lead
to more robust experiments in DMX technology, and further interest in small scale scenic automation.

9.2 Future Work

We hope that this project inspires future work in the realm of small scale automation and DMX technology. We completed this project with future iterations in mind, so that future senior design teams can build upon our work and improve SwiftScene overall. Future teams will have the opportunity to address the centralization of power for the physical module, work towards streamlined multidirectional drive through different types of DMX2STP cards, expand the housing design to achieve stability, ensure robust safety systems, and scale up the project in terms of power and motor strength. We intend to pursue a patent if it is deemed possible, and would hope that with our work or even other senior design teams we could make this a viable product for the future of all theaters.
References


Appendix

Appendix A. Customer Needs Raw Data

David Sword’s Answers:

● Do you feel our product would benefit your productions?
  ○ yes

● How often would you use a product like this?
  ○ Once or twice a season

● What type of technology are you already using in your department?
  ○ A lot of lighting equipment uses the same dmx control
  ○ Projector dowsers
  ○ Intelligent lighting fixtures
  ○ Color changers

Technology specifications?

● What type of technology do you see your department using in the future?
  ○ More automated scenery or more automated control (expensive)

● How well versed are your students in current entertainment technology?
  ○ Fairly well versed in the user level, but not the set up level

● What technologies does your department prioritize?
  ○ Doing more in terms of automation in sound and lighting (rather than scenery)

● What aspects of technology does your department prioritize (safety, ease of use, cost, etc.)?
  ○ Cost is priority #1, then usability, safety

● How much weight does our product need to support?
  ○ Move around a maximum of 200 lbs, overcoming friction and inertia of casters, need to find out the torque necessary to get 200 lbs rolling

● How fast does it need to go?
  ○ Spinning something around would be a useful move, and then laterally
  ○ Two axes of movement would be ideal (at least really cool), maybe a track ball?
  ○ Anything less than 5 feet is not meaningful, 1 ft/s would be reasonable

● How often does it need to be used?
  ○ It’s not being used constantly
  ○ It would never need to move more than 40 ft at a time
  ○ 4 to 6 (10 ft) moves per show
  ○ Need to think about overworking motors or how long the batteries last

● How fast does it need to stop?
  ○ 1 second range of stopping
Kim Mohne-Hill’s Answers

● Do you feel our product would benefit your productions?
  ○ Depends on the size of theater-- mayer is a yes, fess no b/c no moveable deck
  ○ Entirely dependent on size of space

● How often would you use a product like this?
  ○ Once or twice a season in a big space

● What type of technology are you already using in your department?
  ○ Only ever used a pulley track system. Straight on straight off track
  ○ Only used manual large platform pushes and flying

● Why would you use a product like this as a director?
  ○ Free up bodies on space
  ○ Make transitions predictable and controllable (take out human error)

● What are your concerns as a director
  ○ Any kind of technological failure
  ○ Relying on tech, is there a manual override?

● What specifications do you think you would need from the product?
  ○ Training on the system
  ○ User-friendly interface
  ○ Not learn to code to use it
  ○ Flexibility of movement that is greater than what a human can do

● General Notes
  ○ Beyond college and touring company markets?
  ○ Does it have an operating system? Can we stretch to not just DMX?

Tanya Gillette’s Answers

● Would you use this product (trackless) vs traditional automation (tracked)?
  ○ Broadway would never do it because the consistency of the floor
  ○ Setup must be maintained town to town
  ○ Smaller shows more feasible

● How often would you use this?
  ○ Perfect for park bench, couch, can you move THAT?
  ○ Then it becomes more likely
  ○ Simple things that aren’t meant to be danced on
  ○ Cheaper than labor

● What specs and safety specs do you want?
  ○ Autostop or Estop
  ○ Tilt stop
  ○ Aesthetically what does the base look like and is it too heavy?
  ○ Stabilization?
    ■ Can people walk on it?
    ■ Any brake system?
○ Order of movement
○ Someone on deck with a camera and would need a secondary operator

Erin Crocker’s Answers:
● Do you feel our product would benefit your productions?
  ○ I feel at the very least the low cost of this product would benefit our productions. We are an educational theater so there is a positive and potentially negative side to the product for us. On the positive side, we could develop more complex productions with such technology, stimulating our department and quality of education. The negative side is that automating our scene changes, while emulating professional-level theater, may detract from the experience of students who work in our running crew and need to learn the basics of scene changing and backstage organization. On a larger scale, this may impact the number of people needed in professional productions but will also take jobs out of the theater that some people rely on. Overall I feel it would be a product that would benefit our theater.
● How often would you use a product like this?
  ○ We would likely use this product at least once a year for the larger Spring musical produced on our mainstage.
● What type of technology are you already using in your department?
  ○ We are utilizing technology that has been developed in the last 20 years. However, our department does not have access to technology that has been developed in the last 5-10 years, nor do we have professors with the technical experience to teach those technologies.
● What type of technology do you see your department using in the future?
  ○ In the future, I see our department pursuing more recent lighting technology as our current scene shop setup does not support the implementation of new processes. Lighting is an area of ours that tends to stay on top of current technology than others.
● How well versed are your students in current entertainment technology?
  ○ Our students are utilized in general theater technology, but not with new/current technology.
● What aspects of technology does your department prioritize (safety, ease of use, cost, etc.)?
  ○ Our department prioritizes the safety of use and cost when it comes to new technology.
● How much weight does our product need to support?
  ○ Specific to our department the product would need to hold as much as multiple levels of metal scaffolding. I say this because this would be likely the heaviest set we would utilize.
• How often does it need to be used (i.e. in any given show or day)?
  ○ This product would need to be used about 5-7 times a day. This would be for rehearsal days when changes are done repeatedly, as well as performance days with proper safety checks and two full runs of the production. My qualification for one time of use would be using the product to set and strike a scenic piece fully.

• How fast does it need to stop?
  ○ It is important this product is able to stop IMMEDIATELY. This is imperative for safety reasons.
Appendix B. Original Metrics and PDS

Table B 1. Metrics Chart.

<table>
<thead>
<tr>
<th>Metric No.</th>
<th>Needs No.</th>
<th>Metric</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2, 11</td>
<td>Size of physical module</td>
<td>inches</td>
</tr>
<tr>
<td>2</td>
<td>1, 4, 13, 16</td>
<td>Wheel type</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>2, 13</td>
<td>Wheel size</td>
<td>inches</td>
</tr>
<tr>
<td>4</td>
<td>4, 15, 16</td>
<td>Motor strength</td>
<td>hp</td>
</tr>
<tr>
<td>5</td>
<td>4, 9, 10</td>
<td>Battery type</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>5, 6, 7, 8, 12, 13</td>
<td>Type of controls</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>Integrity of physical module</td>
<td>psi</td>
</tr>
<tr>
<td>8</td>
<td>8, 16</td>
<td>Maximum travel distance</td>
<td>ft</td>
</tr>
</tbody>
</table>

Table B 2. Initial Benchmark Chart from Fall 2018.

<table>
<thead>
<tr>
<th>Metric No.</th>
<th>Need No.</th>
<th>Metric</th>
<th>Imp.</th>
<th>Units</th>
<th>Scenery Rotator</th>
<th>Track Runner</th>
<th>RC Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,11</td>
<td>Not larger than 48x48”</td>
<td>3</td>
<td>inch</td>
<td>7x9”</td>
<td>11x8”</td>
<td>27x27”</td>
</tr>
<tr>
<td>2</td>
<td>1, 4, 13, 16</td>
<td>Omni Wheel</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Regular wheels</td>
</tr>
<tr>
<td>3</td>
<td>2, 13</td>
<td>Wheel diameter less than 5”</td>
<td>3</td>
<td>inch</td>
<td>N/A</td>
<td>N/A</td>
<td>4” - 8”</td>
</tr>
<tr>
<td>4</td>
<td>4, 15, 16</td>
<td>Approximately 1/6th hp</td>
<td>1</td>
<td>hp</td>
<td>7.4 ft-lb of torque</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>5</td>
<td>4, 9, 10</td>
<td>Standard 12 V battery</td>
<td>3</td>
<td>V</td>
<td>120 V AC input</td>
<td>120 V AC input</td>
<td>Two 12 V batteries</td>
</tr>
<tr>
<td>6</td>
<td>5, 6, 7, 8, 12, 13</td>
<td>ETC Mosaic or a reprogrammed light board</td>
<td>1</td>
<td>N/A</td>
<td>unknown</td>
<td>unknown</td>
<td>Multi direction remote control</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>Able to withstand a 200 lb vertical load</td>
<td>1</td>
<td>psi</td>
<td>110 lb load limit</td>
<td>220 lb load limit</td>
<td>400 lb load limit</td>
</tr>
<tr>
<td>8</td>
<td>8,16</td>
<td>40 ft</td>
<td>1</td>
<td>ft</td>
<td>N/A</td>
<td>165 ft</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Appendix C. Patent Research

Selections from the patents for Motorization System for Scenic Environment, Automation and Motion Control System, and Battery Powered Wireless DMX LED Lighting System are found in this Appendix.
DEMANDE DE BREVET D'INVENTION

Date de dépôt : 09.07.15.
Priorité :

Date de mise à la disposition du public de la demande : 13.01.17 Bulletin 17/02.

Liste des documents cités dans le rapport de recherche préliminaire : Se reporter à la fin du présent fascicule.

Références à d'autres documents nationaux apparentés :

Demande(s) d'extension :

Demandeur(s) : EXMACHINA Société par actions simplifiée — FR.

Inventeur(s) : GUICHON MATTHIEU, NICOLAS et RAPIDEL BENOIT, JEAN-FRANCOIS.

Titulaire(s) : EXMACHINA Société par actions simplifiée.

Mandataire(s) : CABINET DIDIER MARTIN.

SYSTÈME DE MOTORISATION POUR ENVIRONNEMENT SCÉNIQUE, PROCEDE DE RÉALISATION ASSOCIÉ.

Système de motorisation pour environnement scénique, procédé de réalisation associé.

Système de motorisation caractérisé en ce qu'il forme un système module comprenant une partie un module de motorisation (1) incluant un moteur et d'autre part une plurality de modules élémentaires de transmission indépendants pourvus chacun d'un accessoire d'entraînement mobile, ledit module de motorisation (1) et chacun desdits modules élémentaires de transmission indépendants étant pourvu de moyens d'accouplement complémentaires (14) conçus pour accoupler ledit module de motorisation (1) à l'un quelconque desdits modules élémentaires de transmission indépendants de façon que ledit accessoire d'entraînement mobile dont est pourvu le module élémentaire de transmission ainsi accouplé puisse être mis en mouvement par ledit moteur.

Systèmes de motorisations pour environnements scéniques.
**ABSTRACT**

An automation and motion control system for theatrical objects, such as theatrical props, cameras, stunt persons, lighting, scenery, drapery or other similar types of devices or items, is provided to coordinate the movement of the objects on a large scale and/or to control the operation of the objects.

6 Claims, 19 Drawing Sheets
BATTERY POWERED WIRELESS DMX LED LIGHTING SYSTEM

Inventor: Jhansen Reinoso, Miami, FL (US)
Assignee: Leilani Reinoso, Miami Gardens, FL (US)

Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

Filed: Apr. 20, 2012
Int. Cl. G05F 1/00 (2006.01)
USPC 315/291; 315/307; 315/247; 315/185 S; 315/312

Field of Classification Search
USPC 315/291, 294, 312, 316, 324
See application file for complete search history.

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* cited by examiner

Primary Examiner — Tuyet Thi Vo
Attorney, Agent, or Firm — Christopher J. Vandam, PA; Chris Vandam

ABSTRACT

A DMX based wireless, light emitting device and system including wireless modules that are battery powered and wirelessly receive and transmit DMX to other modules or a controller device. The modules can optionally be hard wired to both a DMX signal and external power supply. An integrated processor can independently control a pre-selected lighting effects, channels, addresses, programs and other light effect features.

14 Claims, 5 Drawing Sheets
Appendix D. Concept Selection and Scoring Matrices

Figure D 1. Overall System Concept A

Figure D 2. Overall System Concept B.
Figure D 3. Overall System Concept C

Figure D 4. Drive Subsystem Concept A.
Figure D 5. Drive Subsystem Concept B.
Figure D 6. Drive Subsystem Concept C.
Figure D 7. Controller Subsystem Concept A.

Figure D 8. Controller Subsystem Concept B.
Figure D 9. Controller Subsystem Concept C.

Figure D 10. Controller Subsystem Concept D
**Concept Selection:**

Table D 1. Concept Selection Matrix for Overall System

<table>
<thead>
<tr>
<th>Overall System</th>
<th>Concepts</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection Criteria</td>
<td>Concept A</td>
<td>Concept B</td>
<td>Concept C</td>
</tr>
<tr>
<td>Can move in multiple directions</td>
<td>minus</td>
<td>plus</td>
<td>plus</td>
</tr>
<tr>
<td>Reliable braking/parking</td>
<td>plus</td>
<td>plus</td>
<td>plus</td>
</tr>
<tr>
<td>Visually disappears into platform</td>
<td>zero</td>
<td>zero</td>
<td>zero</td>
</tr>
<tr>
<td>User friendly</td>
<td>zero</td>
<td>zero</td>
<td>zero</td>
</tr>
<tr>
<td>User friendly for all experience levels</td>
<td>zero</td>
<td>zero</td>
<td>zero</td>
</tr>
<tr>
<td>Can be stopped or moved quickly and easily</td>
<td>minus</td>
<td>zero</td>
<td>plus</td>
</tr>
<tr>
<td>Accurate position/speed</td>
<td>zero</td>
<td>zero</td>
<td>zero</td>
</tr>
<tr>
<td>Holds charge</td>
<td>zero</td>
<td>zero</td>
<td>zero</td>
</tr>
<tr>
<td>Easy to install</td>
<td>minus</td>
<td>plus</td>
<td>minus</td>
</tr>
<tr>
<td>Affordable</td>
<td>minus</td>
<td>plus</td>
<td>plus</td>
</tr>
<tr>
<td>Ease of manufacture</td>
<td>minus</td>
<td>plus</td>
<td>minus</td>
</tr>
<tr>
<td>Sum +</td>
<td>1</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Sum 0</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Sum -</td>
<td>5</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Net Score</td>
<td>-4</td>
<td>5</td>
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</tr>
<tr>
<td>Rank</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Continue with concept?</td>
<td>No</td>
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<td>No</td>
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Table D 2. Concept Selection Matrix for Drive Subsystem

<table>
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<th>Drive subsystem</th>
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<tr>
<td>Selection Criteria</td>
<td>Concept A</td>
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<td>Concept C</td>
</tr>
<tr>
<td>Can move in multiple directions</td>
<td>plus</td>
<td>zero</td>
<td>minus</td>
</tr>
<tr>
<td>Reliable braking/parking</td>
<td>minus</td>
<td>plus</td>
<td>zero</td>
</tr>
<tr>
<td>User friendly</td>
<td>zero</td>
<td>plus</td>
<td>minus</td>
</tr>
<tr>
<td>Can be stopped or moved quickly and easily</td>
<td>plus</td>
<td>plus</td>
<td>zero</td>
</tr>
<tr>
<td>Accurate position/speed</td>
<td>minus</td>
<td>plus</td>
<td>plus</td>
</tr>
<tr>
<td>Easy to install</td>
<td>minus</td>
<td>plus</td>
<td>minus</td>
</tr>
<tr>
<td>Selection Criteria</td>
<td>Concept A</td>
<td>Concept B</td>
<td>Concept C</td>
</tr>
<tr>
<td>--------------------------------------------------------</td>
<td>-----------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>Can control movement for multiple directions</td>
<td>minus</td>
<td>plus</td>
<td>plus</td>
</tr>
<tr>
<td>Reliable stop and go controls</td>
<td>plus</td>
<td>zero</td>
<td>plus</td>
</tr>
<tr>
<td>Visually appealing</td>
<td>zero</td>
<td>plus</td>
<td>minus</td>
</tr>
<tr>
<td>User friendly</td>
<td>plus</td>
<td>plus</td>
<td>zero</td>
</tr>
<tr>
<td>User friendly for all experience levels</td>
<td>plus</td>
<td>zero</td>
<td>zero</td>
</tr>
<tr>
<td>Exists such that the system can stop or move quickly</td>
<td>plus</td>
<td>zero</td>
<td>plus</td>
</tr>
<tr>
<td>Can control movement for multiple speeds</td>
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<td>plus</td>
<td>zero</td>
</tr>
<tr>
<td>Ease of installation</td>
<td>zero</td>
<td>zero</td>
<td>minus</td>
</tr>
<tr>
<td>Emergency stop incorporated</td>
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<td>plus</td>
</tr>
<tr>
<td>Affordable</td>
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<td>zero</td>
<td>zero</td>
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**Table D 3.** Concept Selection Matrix for Control Subsystem

---

**Concept Scoring**

| Overall System | | | | | |

**Table D 4.** Concept Scoring Matrix for Overall System
<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Weight</th>
<th>Concept A</th>
<th></th>
<th>Concept B</th>
<th></th>
<th>Concept C</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rating</td>
<td>Score</td>
<td>Rating</td>
<td>Score</td>
<td>Rating</td>
<td>Score</td>
</tr>
<tr>
<td>Can move in multiple directions</td>
<td>10%</td>
<td>3</td>
<td>0.3</td>
<td>5</td>
<td>0.5</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>Reliable braking/parking</td>
<td>10%</td>
<td>3</td>
<td>0.3</td>
<td>3</td>
<td>0.3</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>Size constraints</td>
<td>5%</td>
<td>4</td>
<td>0.2</td>
<td>4</td>
<td>0.2</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>User friendly</td>
<td>9%</td>
<td>4</td>
<td>0.36</td>
<td>4</td>
<td>0.36</td>
<td>4</td>
<td>0.36</td>
</tr>
<tr>
<td>User friendly for all experience levels</td>
<td>7%</td>
<td>4</td>
<td>0.28</td>
<td>3</td>
<td>0.21</td>
<td>3</td>
<td>0.21</td>
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<tr>
<td>Can be stopped or moved quickly and easily</td>
<td>12%</td>
<td>2</td>
<td>0.24</td>
<td>3</td>
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<td>3</td>
<td>0.36</td>
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<tr>
<td>Accurate position/speed</td>
<td>9%</td>
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<td>0.18</td>
<td>4</td>
<td>0.36</td>
<td>4</td>
<td>0.36</td>
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<tr>
<td>Holds charge</td>
<td>7%</td>
<td>1</td>
<td>0.07</td>
<td>2</td>
<td>0.14</td>
<td>2</td>
<td>0.14</td>
</tr>
<tr>
<td>Easy to install</td>
<td>10%</td>
<td>3</td>
<td>0.3</td>
<td>3</td>
<td>0.3</td>
<td>3</td>
<td>0.3</td>
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<tr>
<td>Affordable</td>
<td>11%</td>
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<td>0.22</td>
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<tr>
<td>Ease of manufacture</td>
<td>10%</td>
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<td>0.3</td>
<td>1</td>
<td>0.1</td>
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<td>2</td>
<td></td>
</tr>
<tr>
<td>Continue with concept?</td>
<td></td>
<td>No</td>
<td></td>
<td>Yes</td>
<td></td>
<td>No</td>
<td></td>
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Table D 5. Concept Scoring Matrix for Drive Subsystem
<table>
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<tr>
<th>Selection Criteria</th>
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<th>Concept A</th>
<th>Concept B</th>
<th>Concept C</th>
<th>Concept D</th>
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<tbody>
<tr>
<td>Can control movement for multiple directions</td>
<td>11%</td>
<td>3 0.33</td>
<td>4 0.44</td>
<td>4 0.44</td>
<td>2 0.22</td>
</tr>
<tr>
<td>Reliable stop and go controls</td>
<td>10%</td>
<td>4 0.4</td>
<td>3 0.3</td>
<td>3 0.3</td>
<td>4 0.4</td>
</tr>
<tr>
<td>Visually appealing</td>
<td>7%</td>
<td>3 0.21</td>
<td>4 0.28</td>
<td>1 0.07</td>
<td>4 0.28</td>
</tr>
<tr>
<td>User friendly</td>
<td>11%</td>
<td>4 0.44</td>
<td>4 0.44</td>
<td>2 0.22</td>
<td>3 0.33</td>
</tr>
<tr>
<td>User friendly for all experience levels</td>
<td>9%</td>
<td>4 0.36</td>
<td>3 0.27</td>
<td>2 0.18</td>
<td>2 0.18</td>
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<tr>
<td>Exists such that the system can stop or move quickly and easily</td>
<td>12%</td>
<td>4 0.48</td>
<td>2 0.24</td>
<td>3 0.36</td>
<td>2 0.24</td>
</tr>
<tr>
<td>Can control movement for multiple speeds</td>
<td>7%</td>
<td>1 0.07</td>
<td>4 0.28</td>
<td>3 0.21</td>
<td>4 0.28</td>
</tr>
<tr>
<td>Ease of installation</td>
<td>10%</td>
<td>3 0.3</td>
<td>3 0.3</td>
<td>1 0.1</td>
<td>5 0.5</td>
</tr>
<tr>
<td>Emergency stop incorporated</td>
<td>12%</td>
<td>1 0.12</td>
<td>1 0.12</td>
<td>4 0.48</td>
<td>1 0.12</td>
</tr>
<tr>
<td>Affordable</td>
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<td>4 0.44</td>
<td>4 0.44</td>
<td>2 0.22</td>
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<td>Total Score</td>
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<td>Rank</td>
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<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Continue with concept?</td>
<td></td>
<td>Yes</td>
<td>Maybe</td>
<td>No</td>
<td>Maybe</td>
</tr>
</tbody>
</table>
Appendix E. Functional Analysis Details

Operation of SwiftScene:

1. Set step limit and speed on DMX-to-Stepper-Motor conversion cards
2. Set desired distance for emergency stop edge finder (in microcontroller code)
3. Power on motors/motor drivers
4. Power on DMX-to-Stepper-Motor conversion cards
5. Power on microcontroller (run setup routine)
6. Each motor has a corresponding slider on the lightboard, move the respective slider to full in order to run the desired motor
   a. Use the power matrix described in section X to determine what level to set each motor for a desired motion
7. If the distance sensors senses the threshold distance, the motor drivers will be disabled
Appendix F. Control

Arduino Code

```c
#include <Adafruit_VL6180X.h>
#include <Wire.h>
#define limit 4
#define enable 2

Adafruit_VL6180X vl = Adafruit_VL6180X();

void setup() {
  // put your setup code here, to run once
  Serial.begin(115200);
  pinMode(enable, OUTPUT);
  pinMode(limit, OUTPUT);
  digitalWrite(limit, HIGH);
  delay(2000);
  digitalWrite(limit, LOW);
  delay(2000);
  digitalWrite(limit, HIGH);
  digitalWrite(enable, LOW);

  // wait for serial port to open on native usb devices
  while (!Serial) {
    delay(1);
  }

  Serial.println("Adafruit VL6180x test!");
  if (!vl.begin()) {
    Serial.println("Failed to find sensor");
    while (1);
  }
  Serial.println("Sensor found!");
}

void loop() {
  // put your main code here, to run repeatedly:
  digitalWrite(limit, HIGH);
  digitalWrite(enable, LOW);
  uint8_t range = vl.readRange();
  uint8_t status = vl.readRangeStatus();
  if (status == VL6180X_ERROR_NONE) {
    Serial.print("Range: "); Serial.println(range);
    while(range >= 150) {
      digitalWrite(enable, HIGH);
      range = vl.readRange();
      Serial.println("IM HIGH AND STOPPED");
    }
  }
}
```
}  
digitalWrite(enable, LOW);
Appendix G. Motor Testing

Test Code [19]:

******************************************************************************
**
SparkFun Big Easy Driver Basic Demo
Toni Klopfenstein @ SparkFun Electronics
February 2015
https://github.com/sparkfun/Big_Easy_Driver

Simple demo sketch to demonstrate how 5 digital pins can drive a bipolar
stepper motor,
using the Big Easy Driver (https://www.sparkfun.com/products/12859). Also
shows the ability to change
microstep size, and direction of motor movement.

Development environment specifics:
Written in Arduino 1.6.0

This code is beerware; if you see me (or any other SparkFun employee) at the
local, and you've found our code helpful, please buy us a round!
Distributed as-is; no warranty is given.

Example based off of demos by Brian Schmalz (designer of the Big Easy
Driver).
http://www.schmalzhaus.com/EasyDriver/Examples/EasyDriverExamples.html
******************************************************************************
*/

//Declare pin functions on Arduino
#define stp 2
#define dir 3
#define MS1 4
#define MS2 5
#define MS3 6
#define EN 7

//Declare variables for functions
char user_input;
int x;
int y;
int state;

void setup() {
    pinMode(stp, OUTPUT);
    pinMode(dir, OUTPUT);
    pinMode(MS1, OUTPUT);
    pinMode(MS2, OUTPUT);
    pinMode(MS3, OUTPUT);
    pinMode(EN, OUTPUT);
resetBEDPins(); //Set step, direction, microstep and enable pins to default states
Serial.begin(9600); //Open Serial connection for debugging
Serial.println("Begin motor control");
Serial.println();
//Print function list for user selection
Serial.println("Enter number for control option:");
Serial.println("1. Turn at default microstep mode.");
Serial.println("2. Reverse direction at default microstep mode.");
Serial.println("3. Turn at 1/16th microstep mode.");
Serial.println("4. Step forward and reverse directions.");
Serial.println();
}

//Main loop
void loop() {
  while(Serial.available()){
    user_input = Serial.read(); //Read user input and trigger appropriate function
digitalWrite(EN, LOW); //Pull enable pin low to set FETs active and allow motor control
    if (user_input == '1')
    {
      StepForwardDefault();
    }
    else if(user_input == '2')
    {
      ReverseStepDefault();
    }
    else if(user_input == '3')
    {
      SmallStepMode();
    }
    else if(user_input == '4')
    {
      ForwardBackwardStep();
    }
    else
    {
      Serial.println("Invalid option entered.");
    }
  }
  resetBEDPins();
}

//Reset Big Easy Driver pins to default states
void resetBEDPins()
{
  digitalWrite(stp, LOW);
}
digitalWrite(dir, LOW);
digitalWrite(MS1, LOW);
digitalWrite(MS2, LOW);
digitalWrite(MS3, LOW);
digitalWrite(EN, HIGH);
}

//Default microstep mode function
void StepForwardDefault()
{
    Serial.println("Moving forward at default step mode.");
    digitalWrite(dir, LOW); //Pull direction pin low to move "forward"
    for(x = 1; x<1000; x++)  //Loop the forward stepping enough times for motion
to be visible
    {
        digitalWrite(stp,HIGH); //Trigger one step forward
        delay(1);
        digitalWrite(stp,LOW); //Pull step pin low so it can be triggered again
        delay(1);
    }
    Serial.println("Enter new option");
    Serial.println();
}

//Reverse default microstep mode function
void ReverseStepDefault()
{
    Serial.println("Moving in reverse at default step mode.");
    digitalWrite(dir, HIGH); //Pull direction pin high to move in "reverse"
    for(x = 1; x<1000; x++)  //Loop the stepping enough times for motion to be visible
    {
        digitalWrite(stp,HIGH); //Trigger one step
        delay(1);
        digitalWrite(stp,LOW); //Pull step pin low so it can be triggered again
        delay(1);
    }
    Serial.println("Enter new option");
    Serial.println();
}

// 1/16th microstep foward mode function
void SmallStepMode()
{
    Serial.println("Stepping at 1/16th microstep mode.");
    digitalWrite(dir, LOW); //Pull direction pin low to move "forward"
digitalWrite(MS1, HIGH); //Pull MS1,MS2, and MS3 high to set logic to
1/16th microstep resolution
digitalWrite(MS2, HIGH);
digitalWrite(MS3, HIGH);
for(x= 1; x<1000; x++)  //Loop the forward stepping enough times for motion to be visible
{
    digitalWrite(stp, HIGH);  //Trigger one step forward
    delay(1);
    digitalWrite(stp, LOW);  //Pull step pin low so it can be triggered again
    delay(1);
}
Serial.println("Enter new option");
Serial.println();

//Forward/reverse stepping function
void ForwardBackwardStep()
{
    Serial.println("Alternate between stepping forward and reverse.");
    for(x= 1; x<5; x++)  //Loop the forward stepping enough times for motion to be visible
    {
        //Read direction pin state and change it
        state=digitalRead(dir);
        if(state == HIGH)
        {
            digitalWrite(dir, LOW);
        }
        else if(state == LOW)
        {
            digitalWrite(dir, HIGH);
        }

        for(y=1; y<1000; y++)
        {
            digitalWrite(stp, HIGH);  //Trigger one step
            delay(1);
            digitalWrite(stp, LOW);  //Pull step pin low so it can be triggered again
            delay(1);
        }
    }
    Serial.println("Enter new option");
    Serial.println();
}
## Appendix H. Budget

### Table H 1. Budget

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<tr>
<th>Category</th>
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<th>Committed</th>
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<tr>
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<td>Photo Sensor</td>
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<td><strong>TOTAL</strong></td>
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<td>Breadboard/jumpers</td>
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<td>Breadboard/jumpers</td>
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<td>Screw pins</td>
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<td>Control Connectors</td>
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Table H 2. Estimated cost into final prototype
Figure I 1. Short plank
Figure I 2. Long plank
Figure 13. Platform lid.
Figure 14. Platform assembly.
Figure I 5. Modifications to electrical enclosure lid
Appendix J. Data Sheets
The SHoW DMX SHoW Baby® 6 represents a breakthrough in plug-and-play wireless DMX and RDM transmission, and can be used either as a wireless DMX transmitter or receiver.

Using up to six Show Baby 6 transmitters on the different available SHoW IDs you can set up a multi-universe system or use multiple separate SHoW Baby systems in the same area.

The SHoW DMX SHoW Baby 6 features include:

- SHoW DMX Neo® 2.4GHz Frequency Hopping Spread Spectrum (FHSS) Radio
- Wirelessly broadcast and receive a full Universe (512 slots) of DMX
- Robust wireless DMX512 and RDM data transmission
- Six Possible SHoW IDs:
  - Green, SHoW ID 201, Neo Adaptive Frequency Hopping Spread Spectrum (AFHSS), the original SHoW Baby SHoW ID
  - Cyan, SHoW ID 102, Neo Frequency Hopping Spread Spectrum (FHSS) Full Bandwidth
  - Magenta, SHoW ID 117, Neo FHSS Low Limited Bandwidth
  - White, SHoW ID 133, Neo FHSS Mid Limited Bandwidth
  - Red, SHoW ID 149, Neo FHSS High Limited Bandwidth
  - Yellow, SHoW ID 165, Neo FHSS High Limited Bandwidth (Neo Max)
- Full compatibility with previous SHoW Babys
- Extremely low 7mS latency
- RDM proxy and responder functions
- Instant plug-and-play configuration: For a Transmitter, connect DMX IN, for a Receiver, don’t!
- 72mW ETSI broadcast power
- Mounting Bracket for installation with C-Clamps or similar hanging hardware
- Included CL2 12VDC Power Supply with international plug set
- Included 2dBi Omni-directional Antenna
- Neutrik® 5P XLR Connectors for DMX IN and DMX OUT (3 Pin in 5702M-3)

**Mechanical**

- NEMA 1 Steel and ABS enclosure
- Mounting Bracket for ½” Hardware for C-Clamp or other hanging hardware

**Electronic/ Functional Features**

- DMX IN and OUT via Neutrik 5P XLRs (3 Pin in 5702M-3)
- LED indicators:
  - Tx (set as transmitter)
  - Rx (set as receiver)
  - ID/Data (data present): color indicates SHoW ID
    - Green – SHoW ID 201

Rev C
• Cyan – SHoW ID 102
• Magenta – SHoW ID 117
• White – SHoW ID 133
• Red – SHoW ID 149
• Yellow - SHoW ID 165
  o RF Signal Strength (4 LEDs) Low to High

**Compliance:**
• CE, FCC & RoHS Compliant
• CE Certified
• FCC Certified

**CTI Part #:** 5702M (5 pin version), 5702M-3 (3 pin version)
**Power:** 7.5-30VDC, 2.4w max draw (100-240VAC 50/60 Hz to 12VDC Adapter provided)
**Weight:** 0.4 lbs
**Dimensions:** 3.625"W x 1.8"H x 3"D
Features and Benefits

- Low $R_{DS(ON)}$ outputs
- Automatic current decay mode detection/selection
- Mixed and Slow current decay modes
- Synchronous rectification for low power dissipation
- Internal UVLO
- Crossover-current protection
- 3.3 and 5 V compatible logic supply
- Thermal shutdown circuitry
- Short-to-ground protection
- Shorted load protection
- Five selectable step modes: full, 1/2, 1/4, 1/8, and 1/16

Description

The A4988 is a complete microstepping motor driver with built-in translator for easy operation. It is designed to operate bipolar stepper motors in full-, half-, quarter-, eighth-, and sixteenth-step modes, with an output drive capacity of up to 35 V and ±2 A. The A4988 includes a fixed off-time current regulator which has the ability to operate in Slow or Mixed decay modes.

The translator is the key to the easy implementation of the A4988. Simply inputting one pulse on the STEP input drives the motor one microstep. There are no phase sequence tables, high frequency control lines, or complex interfaces to program.

The A4988 interface is an ideal fit for applications where a complex microprocessor is unavailable or is overburdened.

During stepping operation, the chopping control in the A4988 automatically selects the current decay mode, Slow or Mixed. In Mixed decay mode, the device is set initially to a fast decay for a proportion of the fixed off-time, then to a slow decay for the remainder of the off-time. Mixed decay current control results in reduced audible motor noise, increased step accuracy, and reduced power dissipation.

Typical Application Diagram
DMOS Microstepping Driver with Translator And Overcurrent Protection

A4988

Description (continued)

Internal synchronous rectification control circuitry is provided to improve power dissipation during PWM operation. Internal circuit protection includes: thermal shutdown with hysteresis, undervoltage lockout (UVLO), and crossover-current protection. Special power-on sequencing is not required.

The A4988 is supplied in a surface mount QFN package (ES), 5 mm × 5 mm, with a nominal overall package height of 0.90 mm and an exposed pad for enhanced thermal dissipation. It is lead (Pb) free (suffix –T), with 100% matte tin plated leadframes.

Selection Guide

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<thead>
<tr>
<th>Part Number</th>
<th>Package</th>
<th>Packing</th>
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<tr>
<td>A4988SETTR-T</td>
<td>28-contact QFN with exposed thermal pad</td>
<td>1500 pieces per 7-in. reel</td>
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Absolute Maximum Ratings

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<th>Notes</th>
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<td>35</td>
<td>V</td>
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<tr>
<td>Output Current I_{OUT}</td>
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<td>±2</td>
<td>A</td>
<td></td>
</tr>
<tr>
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<td>V</td>
<td></td>
</tr>
<tr>
<td>Logic Supply Voltage V_{DD}</td>
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<td>−0.3 to 5.5</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td>Motor Outputs Voltage V_{SENSE}</td>
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<td>−2.0 to 37</td>
<td>V</td>
<td></td>
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<td></td>
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<tr>
<td>Reference Voltage V_{REF}</td>
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<td>V</td>
<td></td>
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<td>Operating Ambient Temperature T_{A}</td>
<td>Range S</td>
<td>−20 to 85</td>
<td>°C</td>
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</tr>
<tr>
<td>Maximum Junction T_{j}(max)</td>
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<td>150</td>
<td>°C</td>
<td></td>
</tr>
<tr>
<td>Storage Temperature T_{stg}</td>
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<td>−55 to 150</td>
<td>°C</td>
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</table>
DMOS Microstepping Driver with Translator
And Overcurrent Protection

Functional Block Diagram
### ELECTRICAL CHARACTERISTICS

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<th>Characteristics</th>
<th>Symbol</th>
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<th>Min.</th>
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<td>$V_{BB}$</td>
<td>Operating</td>
<td>8</td>
<td>–</td>
<td>35</td>
<td>V</td>
</tr>
<tr>
<td>Logic Supply Voltage Range</td>
<td>$V_{DD}$</td>
<td>Operating</td>
<td>3.0</td>
<td>–</td>
<td>5.5</td>
<td>V</td>
</tr>
<tr>
<td>Output On Resistance</td>
<td>$R_{DSON}$</td>
<td>Source Driver, $I_{OUT} = -1.5$ A</td>
<td>–</td>
<td>320</td>
<td>430</td>
<td>mΩ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sink Driver, $I_{OUT} = 1.5$ A</td>
<td>–</td>
<td>320</td>
<td>430</td>
<td>mΩ</td>
</tr>
<tr>
<td>Body Diode Forward Voltage</td>
<td>$V_F$</td>
<td>Source Diode, $I_{F} = -1.5$ A</td>
<td>–</td>
<td>–</td>
<td>1.2</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sink Diode, $I_{F} = 1.5$ A</td>
<td>–</td>
<td>–</td>
<td>1.2</td>
<td>V</td>
</tr>
<tr>
<td>Motor Supply Current</td>
<td>$I_{BB}$</td>
<td>$f_{PWM} &lt; 50$ kHz</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operating, outputs disabled</td>
<td>–</td>
<td>–</td>
<td>2</td>
<td>mA</td>
</tr>
<tr>
<td>Logic Supply Current</td>
<td>$I_{DD}$</td>
<td>$f_{PWM} &lt; 50$ kHz</td>
<td>–</td>
<td>–</td>
<td>8</td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outputs off</td>
<td>–</td>
<td>–</td>
<td>5</td>
<td>mA</td>
</tr>
<tr>
<td><strong>Control Logic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logic Input Voltage</td>
<td>$V_{IN(1)}$</td>
<td>$V_{DD} \times 0.7$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>$V_{IN(0)}$</td>
<td></td>
<td>–</td>
<td>–</td>
<td>$V_{DD} \times 0.3$</td>
<td>V</td>
</tr>
<tr>
<td>Logic Input Current</td>
<td>$I_{IN(1)}$</td>
<td>$V_{IN} = V_{DD} \times 0.7$</td>
<td>–20</td>
<td>&lt;1.0</td>
<td>20</td>
<td>μA</td>
</tr>
<tr>
<td></td>
<td>$I_{IN(0)}$</td>
<td>$V_{IN} = V_{DD} \times 0.3$</td>
<td>–20</td>
<td>&lt;1.0</td>
<td>20</td>
<td>μA</td>
</tr>
<tr>
<td>Microstep Select</td>
<td>$R_{MS1}$</td>
<td>MS1 pin</td>
<td>–</td>
<td>100</td>
<td>–</td>
<td>kΩ</td>
</tr>
<tr>
<td></td>
<td>$R_{MS2}$</td>
<td>MS2 pin</td>
<td>–</td>
<td>50</td>
<td>–</td>
<td>kΩ</td>
</tr>
<tr>
<td></td>
<td>$R_{MS3}$</td>
<td>MS3 pin</td>
<td>–</td>
<td>100</td>
<td>–</td>
<td>kΩ</td>
</tr>
<tr>
<td>Logic Input Hysteresis</td>
<td>$V_{HYS(IN)}$</td>
<td>As a % of $V_{DD}$</td>
<td>5</td>
<td>11</td>
<td>19</td>
<td>%</td>
</tr>
<tr>
<td>Blank Time</td>
<td>$t_{BLANK}$</td>
<td></td>
<td>0.7</td>
<td>1</td>
<td>1.3</td>
<td>μs</td>
</tr>
<tr>
<td>Fixed Off-Time</td>
<td>$t_{OFF}$</td>
<td>OSC = VDD or GND</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>μs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$R_{OSC} = 25$ kΩ</td>
<td>23</td>
<td>30</td>
<td>37</td>
<td>μs</td>
</tr>
<tr>
<td>Reference Input Voltage Range</td>
<td>$V_{REF}$</td>
<td></td>
<td>0</td>
<td>–</td>
<td>4</td>
<td>V</td>
</tr>
<tr>
<td>Reference Input Current</td>
<td>$I_{REF}$</td>
<td></td>
<td>–3</td>
<td>0</td>
<td>3</td>
<td>μA</td>
</tr>
<tr>
<td>Current Trip-Level Error</td>
<td>$err_1$</td>
<td>$V_{REF} = 2$ V, $%I_{TRIP_MAX} = 38.27%$</td>
<td>–</td>
<td>–</td>
<td>±15</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{REF} = 2$ V, $%I_{TRIP_MAX} = 70.71%$</td>
<td>–</td>
<td>–</td>
<td>±5</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{REF} = 2$ V, $%I_{TRIP_MAX} = 100.00%$</td>
<td>–</td>
<td>–</td>
<td>±5</td>
<td>%</td>
</tr>
<tr>
<td>Crossover Dead Time</td>
<td>$t_{DT}$</td>
<td></td>
<td>100</td>
<td>475</td>
<td>800</td>
<td>ns</td>
</tr>
<tr>
<td><strong>Protection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overcurrent Protection Threshold</td>
<td>$I_{OCPST}$</td>
<td></td>
<td>2.1</td>
<td>–</td>
<td>–</td>
<td>A</td>
</tr>
<tr>
<td>Thermal Shutdown Temperature</td>
<td>$T_{TSD}$</td>
<td></td>
<td>–</td>
<td>165</td>
<td>–</td>
<td>°C</td>
</tr>
<tr>
<td>Thermal Shutdown Hysteresis</td>
<td>$T_{TSDHY5}$</td>
<td></td>
<td>–</td>
<td>15</td>
<td>–</td>
<td>°C</td>
</tr>
<tr>
<td>VDD Undervoltage Lockout</td>
<td>$V_{DDUVLO}$</td>
<td>$V_{DD}$ rising</td>
<td>2.7</td>
<td>2.8</td>
<td>2.9</td>
<td>V</td>
</tr>
<tr>
<td>VDD Undervoltage Hysteresis</td>
<td>$V_{DDUVLOHY5}$</td>
<td></td>
<td>–</td>
<td>90</td>
<td>–</td>
<td>mV</td>
</tr>
</tbody>
</table>

1For input and output current specifications, negative current is defined as coming out of (sourcing) the specified device pin.
2Typical data are for initial design estimations only, and assume optimum manufacturing and application conditions. Performance may vary for individual units, within the specified maximum and minimum limits.
3$V_{ERR} = \frac{(V_{REF}/8) - V_{SENSE}}{(V_{REF}/8)}$.
4Overcurrent protection (OCP) is tested at $T_A = 25°C$ in a restricted range and guaranteed by characterization.
## THERMAL CHARACTERISTICS

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package Thermal Resistance</td>
<td>$R_{\text{JA}}$</td>
<td>Four-layer PCB, based on JEDEC standard</td>
<td>32</td>
<td>°C/W</td>
</tr>
</tbody>
</table>

*Additional thermal information available on Allegro Web site.*

![Power Dissipation versus Ambient Temperature](chart.png)
**DMOS Microstepping Driver with Translator And Overcurrent Protection**

**Figure 1. Logic Interface Timing Diagram**

<table>
<thead>
<tr>
<th>Time Duration</th>
<th>Symbol</th>
<th>Typ.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEP minimum, HIGH pulse width</td>
<td>$t_A$</td>
<td>1</td>
<td>μs</td>
</tr>
<tr>
<td>STEP minimum, LOW pulse width</td>
<td>$t_B$</td>
<td>1</td>
<td>μs</td>
</tr>
<tr>
<td>Setup time, input change to STEP</td>
<td>$t_C$</td>
<td>200</td>
<td>ns</td>
</tr>
<tr>
<td>Hold time, input change to STEP</td>
<td>$t_D$</td>
<td>200</td>
<td>ns</td>
</tr>
</tbody>
</table>

*Figure 1. Logic Interface Timing Diagram*

**Table 1. Microstepping Resolution Truth Table**

<table>
<thead>
<tr>
<th>MS1</th>
<th>MS2</th>
<th>MS3</th>
<th>Microstep Resolution</th>
<th>Excitation Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>L</td>
<td>L</td>
<td>Full Step</td>
<td>2 Phase</td>
</tr>
<tr>
<td>H</td>
<td>L</td>
<td>L</td>
<td>Half Step</td>
<td>1-2 Phase</td>
</tr>
<tr>
<td>L</td>
<td>H</td>
<td>L</td>
<td>Quarter Step</td>
<td>W1-2 Phase</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>L</td>
<td>Eighth Step</td>
<td>2W1-2 Phase</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>H</td>
<td>Sixteenth Step</td>
<td>4W1-2 Phase</td>
</tr>
</tbody>
</table>
**Device Operation.** The A4988 is a complete microstepping motor driver with a built-in translator for easy operation with minimal control lines. It is designed to operate bipolar stepper motors in full-, half-, quarter-, eighth, and sixteenth-step modes. The currents in each of the two output full-bridges and all of the N-channel DMOS FETs are regulated with fixed off-time PWM (pulse width modulated) control circuitry. At each step, the current for each full-bridge is set by the value of its external current-sense resistor ($R_{S1}$ and $R_{S2}$), a reference voltage ($V_{REF}$), and the output voltage of its DAC (which in turn is controlled by the output of the translator).

At power-on or reset, the translator sets the DACs and the phase current polarity to the initial Home state (shown in figures 8 through 12), and the current regulator to Mixed Decay Mode for both phases. When a step command signal occurs on the STEP input, the translator automatically sequences the DACs to the next level and current polarity. (See table 2 for the current-level sequence.) The microstep resolution is set by the combined effect of the MSx inputs, as shown in table 1.

When stepping, if the new output levels of the DACs are lower than their previous output levels, then the decay mode for the active full-bridge is set to Mixed. If the new output levels of the DACs are higher than or equal to their previous levels, then the decay mode for the active full-bridge is set to Slow. This automatic current decay selection improves microstepping performance by reducing the distortion of the current waveform that results from the back EMF of the motor.

**Microstep Select (MSx).** The microstep resolution is set by the voltage on logic inputs MSx, as shown in table 1. The MS1 and MS3 pins have a 100 kΩ pull-down resistance, and the MS2 pin has a 50 kΩ pull-down resistance. When changing the step mode the change does not take effect until the next STEP rising edge.

If the step mode is changed without a translator reset, and absolute position must be maintained, it is important to change the step mode at a step position that is common to both step modes in order to avoid missing steps. When the device is powered down, or reset due to TSD or an over current event the translator is set to the home position which is by default common to all step modes.

**Mixed Decay Operation.** The bridge operates in Mixed decay mode, at power-on and reset, and during normal running according to the ROSC configuration and the step sequence, as shown in figures 8 through 12. During Mixed decay, when the trip point is reached, the A4988 initially goes into a fast decay mode for 31.25% of the off-time, $t_{OFF}$. After that, it switches to Slow decay mode for the remainder of $t_{OFF}$. A timing diagram for this feature appears on the next page.

Typically, mixed decay is only necessary when the current in the winding is going from a higher value to a lower value as determined by the state of the translator. For most loads automatically-selected mixed decay is convenient because it minimizes ripple when the current is rising and prevents missed steps when the current is falling. For some applications where microstepping at very low speeds is necessary, the lack of back EMF in the winding causes the current to increase in the load quickly, resulting in missed steps. This is shown in figure 2. By pulling the ROSC pin to ground, mixed decay is set to be active 100% of the time, for both rising and falling currents, and prevents missed steps as shown in figure 3. If this is not an issue, it is recommended that automatically-selected mixed decay be used, because it will produce reduced ripple currents. Refer to the Fixed Off-Time section for details.

**Low Current Microstepping.** Intended for applications where the minimum on-time prevents the output current from regulating to the programmed current level at low current steps. To prevent this, the device can be set to operate in Mixed decay mode on both rising and falling portions of the current waveform. This feature is implemented by shorting the ROSC pin to ground. In this state, the off-time is internally set to 30 μs.

**Reset Input (RESET).** The RESET input sets the translator to a predefined Home state (shown in figures 8 through 12), and turns off all of the FET outputs. All STEP inputs are ignored until the RESET input is set to high.

**Step Input (STEP).** A low-to-high transition on the STEP input sequences the translator and advances the motor one increment. The translator controls the input to the DACs and the direc-
Figure 2. Missed steps in low-speed microstepping

Figure 3. Continuous stepping using automatically-selected mixed stepping (ROSC pin grounded)
tion of current flow in each winding. The size of the increment is determined by the combined state of the MSx inputs.

**Direction Input (DIR).** This determines the direction of rotation of the motor. Changes to this input do not take effect until the next STEP rising edge.

**Internal PWM Current Control.** Each full-bridge is controlled by a fixed off-time PWM current control circuit that limits the load current to a desired value, I_{TRIP}. Initially, a diagonal pair of source and sink FET outputs are enabled and current flows through the motor winding and the current sense resistor, R_{Sx}. When the voltage across R_{Sx} equals the DAC output voltage, the current sense comparator resets the PWM latch. The latch then turns off the appropriate source driver and initiates a fixed off-time decay mode.

The maximum value of current limiting is set by the selection of R_{Sx} and the voltage at the VREF pin. The transconductance function is approximated by the maximum value of current limiting, I_{TripMAX} (A), which is set by

\[ I_{TripMAX} = \frac{V_{REF}}{8\times R_S} \]

where R_S is the resistance of the sense resistor (Ω) and V_{REF} is the input voltage on the REF pin (V).

The DAC output reduces the V_{REF} output to the current sense comparator in precise steps, such that

\[ I_{trip} = \left(\frac{\%I_{TripMAX}}{100}\right) \times I_{TripMAX} \]

(See table 2 for \%I_{TripMAX} at each step.)

It is critical that the maximum rating (0.5 V) on the SENSE1 and SENSE2 pins is not exceeded.

**Fixed Off-Time.** The internal PWM current control circuitry uses a one-shot circuit to control the duration of time that the DMOS FETs remain off. The off-time, t_{OFF}, is determined by the ROSC terminal. The ROSC terminal has three settings:

- **ROSC tied to VDD — off-time internally set to 30 μs, decay mode is automatic Mixed decay except when in full step where decay mode is set to Slow decay**
- **ROSC tied directly to ground — off-time internally set to 30 μs, current decay is set to Mixed decay for both increasing and decreasing currents for all step modes**
- **ROSC through a resistor to ground — off-time is determined by the following formula, the decay mode is automatic Mixed decay for all step modes.**

\[ t_{OFF} \approx \frac{R_{OSC}}{825} \]

Where t_{OFF} is in μs.

**Blanking.** This function blanks the output of the current sense comparators when the outputs are switched by the internal current control circuitry. The comparator outputs are blanked to prevent false overcurrent detection due to reverse recovery currents of the clamp diodes, and switching transients related to the capacitance of the load. The blank time, t_{BLANK} (μs), is approximately

\[ t_{BLANK} \approx 1 \mu s \]

**Shorted-Load and Short-to-Ground Protection.** If the motor leads are shorted together, or if one of the leads is shorted to ground, the driver will protect itself by sensing the overcurrent event and disabling the driver that is shorted, protecting the device from damage. In the case of a short-to-ground, the device will remain disabled (latched) until the SLEEP power is removed. A short-to-ground overcurrent event is shown in figure 4.

When the two outputs are shorted together, the current path is through the sense resistor. After the blanking time (≈1 μs) expires, the sense resistor voltage is exceeding its trip value, due to the overcurrent condition that exists. This causes the driver to go into a fixed off-time cycle. After the fixed off-time expires the driver turns on again and the process repeats. In this condition the driver is completely protected against overcurrent events, but the short is repetitive with a period equal to the fixed off-time of the driver. This condition is shown in figure 5.

During a shorted load event it is normal to observe both a positive and negative current spike as shown in figure 3, due to the direction change implemented by the Mixed decay feature. This is shown in figure 6. In both instances the overcurrent circuitry is protecting the driver and prevents damage to the device.

**Charge Pump (CP1 and CP2).** The charge pump is used to generate a gate supply greater than that of VBB for driving the source-side FET gates. A 0.1 μF ceramic capacitor, should be connected between CP1 and CP2. In addition, a 0.1 μF ceramic capacitor is required between VCP and VBB, to act as a reservoir for operating the high-side FET gates.

Capacitor values should be Class 2 dielectric ±15% maximum, or tolerance R, according to EIA (Electronic Industries Alliance) specifications.
**V_{\text{REG}} (VREG).** This internally-generated voltage is used to operate the sink-side FET outputs. The nominal output voltage of the VREG terminal is 7 V. The VREG pin must be decoupled with a 0.22 \( \mu \)F ceramic capacitor to ground. \( V_{\text{REG}} \) is internally monitored. In the case of a fault condition, the FET outputs of the A4988 are disabled.

Capacitor values should be Class 2 dielectric \( \pm 15\% \) maximum, or tolerance R, according to EIA (Electronic Industries Alliance) specifications.

**Enable Input (ENABLE).** This input turns on or off all of the FET outputs. When set to a logic high, the outputs are disabled. When set to a logic low, the internal control enables the outputs as required. The translator inputs STEP, DIR, and MSx, as well as the internal sequencing logic, all remain active, independent of the ENABLE input state.

**Shutdown.** In the event of a fault, overtemperature (excess \( T_J \)) or an undervoltage (on VCP), the FET outputs of the A4988 are disabled until the fault condition is removed. At power-on, the UVLO (undervoltage lockout) circuit disables the FET outputs and resets the translator to the Home state.

**Sleep Mode (SLEEP).** To minimize power consumption when the motor is not in use, this input disables much of the internal circuitry including the output FETs, current regulator, and charge pump. A logic low on the SLEEP pin puts the A4988 into Sleep mode. A logic high allows normal operation, as well as start-up (at which time the A4988 drives the motor to the Home microstep position). When emerging from Sleep mode, in order to allow the charge pump to stabilize, provide a delay of 1 ms before issuing a Step command.

**Mixed Decay Operation.** The bridge operates in Mixed Decay mode, depending on the step sequence, as shown in figures 8 through 12. As the trip point is reached, the A4988 initially goes into a fast decay mode for 31.25% of the off-time, \( t_{OFF} \). After that, it switches to Slow Decay mode for the remainder of \( t_{OFF} \). A timing diagram for this feature appears in figure 7.

**Synchronous Rectification.** When a PWM-off cycle is triggered by an internal fixed-off time cycle, load current recirculates according to the decay mode selected by the control logic. This synchronous rectification feature turns on the appropriate FETs during current decay, and effectively shorts out the body diodes with the low FET \( R_{\text{DS(ON)}} \). This reduces power dissipation significantly, and can eliminate the need for external Schottky diodes in many applications. Synchronous rectification turns off when the load current approaches zero (0 A), preventing reversal of the load current.
Figure 7. Current Decay Modes Timing Chart

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{off}}$</td>
<td>Device fixed off-time</td>
</tr>
<tr>
<td>$I_{\text{PEAK}}$</td>
<td>Maximum output current</td>
</tr>
<tr>
<td>$t_{SD}$</td>
<td>Slow decay interval</td>
</tr>
<tr>
<td>$t_{FD}$</td>
<td>Fast decay interval</td>
</tr>
<tr>
<td>$I_{OUT}$</td>
<td>Device output current</td>
</tr>
</tbody>
</table>
**Application Layout**

**Layout.** The printed circuit board should use a heavy ground-plane. For optimum electrical and thermal performance, the A4988 must be soldered directly onto the board. Pins 3 and 18 are internally fused, which provides a path for enhanced thermal dissipation. These pins should be soldered directly to an exposed surface on the PCB that connects to thermal vias used to transfer heat to other layers of the PCB.

In order to minimize the effects of ground bounce and offset issues, it is important to have a low impedance single-point ground, known as a *star ground*, located very close to the device. By making the connection between the pad and the ground plane directly under the A4988, that area becomes an ideal location for a star ground point. A low impedance ground will prevent ground bounce during high current operation and ensure that the supply voltage remains stable at the input terminal.

The two input capacitors should be placed in parallel, and as close to the device supply pins as possible. The ceramic capacitor (CIN1) should be closer to the pins than the bulk capacitor (CIN2). This is necessary because the ceramic capacitor will be responsible for delivering the high frequency current components. The sense resistors, RSx, should have a very low impedance path to ground, because they must carry a large current while supporting very accurate voltage measurements by the current sense comparators. Long ground traces will cause additional voltage drops, adversely affecting the ability of the comparators to accurately measure the current in the windings. The SENSEx pins have very short traces to the RSx resistors and very thick, low impedance traces directly to the star ground underneath the device. If possible, there should be no other components on the sense circuits.
Pin Circuit Diagrams

[Diagrams showing pin connections and circuitry for the DMOS Microstepping Driver with Translator and Overcurrent Protection]
**DMOS Microstepping Driver with Translator and Overcurrent Protection**

**Figure 8. Decay Mode for Full-Step Increments**

**Figure 9. Decay Modes for Half-Step Increments**

**Figure 10. Decay Modes for Quarter-Step Increments**
Figure 11. Decay Modes for Eighth-Step Increments

*With ROSC pin tied to GND

DIR= H
Figure 12. Decay Modes for Sixteenth-Step Increments
### Table 2. Step Sequencing Settings

<table>
<thead>
<tr>
<th>Full Step #</th>
<th>Half Step #</th>
<th>1/4 Step #</th>
<th>1/8 Step #</th>
<th>1/16 Step #</th>
<th>Phase 1 Current [% ItripMax] (%)</th>
<th>Phase 2 Current [% ItripMax] (%)</th>
<th>Step Angle (º)</th>
<th>Full Step #</th>
<th>Half Step #</th>
<th>1/4 Step #</th>
<th>1/8 Step #</th>
<th>1/16 Step #</th>
<th>Phase 1 Current [% ItripMax] (%)</th>
<th>Phase 2 Current [% ItripMax] (%)</th>
<th>Step Angle (º)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>100.00</td>
<td>0.00</td>
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<td>9</td>
<td>17</td>
<td>33</td>
<td>–100.00</td>
<td>0.00</td>
<td>180.0</td>
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</tr>
<tr>
<td>2</td>
<td>99.52</td>
<td>9.80</td>
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<td>34</td>
<td>–99.52</td>
<td>–9.80</td>
<td>185.6</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>98.08</td>
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Pin-out Diagram

Terminal List Table

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<td>No connection</td>
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<td>PAD</td>
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<td>Exposed pad for enhanced thermal dissipation*</td>
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*The GND pins must be tied together externally by connecting to the PAD ground plane under the device.
DMOS Microstepping Driver with Translator
And Overcurrent Protection

ET Package, 28-Pin QFN with Exposed Thermal Pad

For Reference Only; not for tooling use
(reference JEDEC MO-220VHHD-1)
Dimensions in millimeters
Exact case and lead configuration at supplier discretion within limits shown

Terminal #1 mark area
Exposed thermal pad (reference only, terminal #1 identifier appearance at supplier discretion)
Reference land pattern layout (reference IPC7351 QFN50P50X50X100-29V1M);
All pads a minimum of 0.20 mm from all adjacent pads; adjust as necessary to meet application process requirements and PCB layout tolerances; when mounting on a multilayer PCB, thermal vias at the exposed thermal pad land can improve thermal dissipation (reference EIA/JEDEC Standard JESD51-5)
Coplanarity includes exposed thermal pad and terminals
Revision History

<table>
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<th>Revision Date</th>
<th>Description of Revision</th>
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<tr>
<td>Rev. 4</td>
<td>January 27, 2012</td>
<td>Update $I_{OCPST}$</td>
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The DIN Rail mounted interface provides Step-And-Direction control of stepper motor drivers based on DMX512 input data.

User provided parameters are: DMX512 starting address, Total number of steps, Maximum velocity, Maximum acceleration, Jerk, Number of steps between the limit switch and position zero, Homing velocity, and Creep velocity.

Power input: 9 to 15 VDC on 2 position screw terminal block.

DMX512 input: Common, Data-, and Data+ on 3 position screw terminal block.

DMX512 pass-through: 3 position screw terminal block in parallel with DMX512 input. DMX512 through is supplied with a 120 Ohm termination resistor. If the through terminal block is used to connect DMX512 to the next device, the termination resistor must be removed.

DMX512 isolation: DMX512 connections are isolated from power and outputs to 1500V. DMX512 Common is isolated from DC Power Supply Common. DMX512 input is protected against 60 VDC continuous and 15KV transients.

Outputs: DC Common, Step, Direction, CW, and CCW are provided on a 5 position screw terminal block. Maximum output current is 20mA. Output voltage is nominal 5V. Outputs are protected against transients to 15KV.

Output isolation: Outputs are isolated from DMX512 in and through. Output Common is tied to the power supply negative terminal.

Enable input: Common, and Enable appear on a 2 position screw terminal block. To enable motion, the enable input must be held low (connected to DC Common). If the enable input is allowed to go high, motion is disabled and, if moving, motion is brought to a halt using maximum Jerk and Acceleration.

Home input: Common and Home appear on a 2 position screw terminal block. To home on power-up, the home input should be tied low (connected to DC Common). To home on command, the home input should be left open, and pulled low to begin homing. A re-home command may be issued by allowing the home input to go high followed by again pulling the input low.

Limit input: A normally open limit switch is required across the 2 position LIMIT screw terminal block. The homing routine will rotate the motor in reverse until the limit switch is closed (limit input goes low). The motor will then run forward until the limit switch opens, and run an additional (user provided) number of steps before halting at zero position.

All switch inputs are pulled high (to nominal 5V) by passive pull up resistors. Switch inputs are protected against transients to 15KV.

E-Stop: A normally closed e-stop switch, if required, is placed in series with the positive power supply connection. An e-stop is issued by removing power from the board.
DMX512 channel assignments:

Starting Address is user selectable. Default address is 001.

Channel 1 (Starting Address) is coarse position.
Channel 2 (Starting Address + 1) is fine position.
Channel 3 (Starting Address + 2) is speed.
Channel 4 (Starting Address + 3) is acceleration.

The user provides the total number of steps the motor is to turn. The target position is calculated from the values of channels 1 and 2 as follows:

\[ \text{TargetPosition} = \text{TotalSteps} \times \left( \text{Chn}_1\_\text{Level} \times 256 + \text{Chan}_2\_\text{level} \right) / 65535. \]

Channel levels are in decimal (0 to 255) not percentage (not 0 - 100%).

The user provides the maximum step frequency, up to 32,000 steps per second. The target velocity is calculated from the value of channel 3 as follows:

\[ \text{TargetVelocity} = \text{MaximumVelocity} \times \text{Chn}_3\_\text{Level} / 255. \]

Channel levels are in decimal (0 to 255) not percentage (not 0 - 100%).

The user provides the maximum acceleration in steps per second squared. The target acceleration is calculated from the value of channel 4 as follows:

\[ \text{TargetAcceleration} = \text{MaximumAcceleration} \times \text{Chn}_4\_\text{Level} / 255. \]

Channel levels are in decimal (0 to 255) not percentage (not 0 - 100%).

**Operation**

Once the system has homed, each movement consists of nine states:
1) Ramp acceleration up to the target acceleration (using provided jerk).
2) Accelerate toward the target velocity (at target acceleration).
3) Ramp acceleration down to zero (using provided jerk).
4) Run at constant velocity (at target velocity).
5) Ramp deceleration up to the target acceleration value (using jerk).
6) Decelerate towards zero velocity (at target acceleration).
7) Ramp deceleration to zero (using provided jerk).
8) Creep to final target position (using provided creep velocity).
9) Stop

Changing target acceleration during a move may not take effect until motion has stopped.

Changing target velocity during a move may not take effect until motion has stopped.

**Set up**

Upon power up, the DMX512 address is displayed. Pressing the up/down buttons cycle through the parameters in the following order:

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<th>Parameter</th>
<th>Range</th>
<th>Factory Value</th>
<th>Units</th>
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<tr>
<td>DMX512 ADDRESS</td>
<td>0 to 512</td>
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<tr>
<td>TOTAL STEPS</td>
<td>1 to 9,999,999</td>
<td>1,000,000</td>
<td>steps</td>
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<td>STEPS OFF LIMIT</td>
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<td>steps</td>
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<td>MAXIMUM SPEED</td>
<td>1 to 32,000</td>
<td>1,000</td>
<td>steps/sec</td>
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<td>CREEP SPEED</td>
<td>1 to 32,000</td>
<td>10</td>
<td>steps/sec</td>
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</table>
HOMING SPEED 1 to 32,000 10 steps/sec
ACCELERATION 1 to 99,999 1,000 steps/sec^2
JERK 1 to 3,000 200 ms

To edit a parameter, press either the left or right button. A cursor will appear which can be moved left and right. With the cursor under a digit, the up and down buttons change the value of the digit. Press the center key to exit editing mode. The new value is not saved to EEPROM until the center key is pressed.

DMX ADDRESS is the starting address of the four levels used for control.
TOTAL STEPS is the number of steps from 'zero' to 'end'.
STEPS OFF LIMIT is the number of steps from the limit switch to 'zero'.
MAXIMUM SPEED is the speed the motor will go (with channel 3 at full).
CREEP SPEED is the speed the motor will go in the final second of movement.
HOMING SPEED is the speed the motor will go (in reverse) until limit is hit.
ACCELERATION is the rate at which speed is increased (with chn. 4 at full).
JERK (in ms) is the time it takes to go from stopped to maximum acceleration.
6-ga Steel (0.0598")

Approximate Internal Dimensions: Ht. 17 7/8", Wd. 17 7/8", Dp. 7 7/8"
Specifications

1. Phase Number
2. Step Angle
3. Rated Voltage
4. Rated Current
5. Holding Torque
6. Phase Resistance
7. Phase Inductance
8. Rotor Inertia
9. Motor Weight
10. Insulation Class

Unit: mm

Hybrid Stepping Motor

Moons' Stepping Motor

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MOONS' Electric Co., Ltd.

Shanghai
SwiftScene

DMX Controlled Scenic Automation

Hannah Sisney, Tiernan O’Rourke, JV Ating

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2. Beginning of SwiftScene
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5. Obstacles
6. Testing
7. Impact of SwiftScene
8. Future of the Project
9. Conclusion
10. Questions

Introduction

Who Are We, and Why Did We Choose This Project?

Project Mission

Develop a scenic automation tool for an underserved market that is safe, reliable, and affordable.

Introduction

- All mechanical engineers
- Robotics backgrounds, theater backgrounds
- SwiftScene began as something that someone said “what if…”
Introduction

What is the product?

SwiftScene is a low-cost, wireless modular device controlled by DMX.

Beginnings of SwiftScene

A Lunch Conversation Turned Senior Design Project

What if we could bring that experience to our theater?

How would we go about it?

Use DMX
- DMX: Digital Multiplex
- Industry Standard
- Easily Integrable

Photos courtesy Hudson Scenic Studios

Courtesy SCU Presents and Sokol Photography

Courtesy Phantom Dynamics
Design of SwiftScene

Concept to Construction

Research

Courtesy Innovative Entertainment

Customer Needs and Product Design Specifications

Ideal Product
- Moves in any direction
- Travels up to 40 ft
- Long lasting charge
- Moves 200 lb of scenery
- Controlled via ETC Mosaic or lightboard
- Travels at 1 ft/s velocity
- Stops in 1 second

Scaled Prototype
- Rotates, moves back and forth
- Travels up to 40 ft
- 1 hour operation time
- Moves 25 lb of scenery
- Controlled via ETC Mosaic or lightboard
- Travels at 1 ft/s velocity
- Stops in 1 second

Design Ideation

Courtesy McMaster-Carr

Smallest Area - Triangle
- Minimize Space
- Beneficial to have everything in one space, less dangerous to components
- Wheels Outside Housing
- Realization that space is key
- Create more space by moving wheels

Final Design - Square
- Housing
- Smaller footprint
- Easier to maneuver
- More efficient use of space

01 02 03

Design Ideation

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01 02 03
Design of SwiftScene

Design Ideation

Analysis of SwiftScene

Translating a Design to Viable Product

Budget

- Major materials lent
- Other materials purchased

Total Cost: $3,833.51
Net Cost: $821.51
Estimated Manufacturing Cost: $1,277.84

Housing Analysis

- Goal: 25 lb load
- Electrical housing
  - 16 gauge sheet metal
  - 33.7 lb load max
Analysis of SwiftScene

Motor Needs

\[ T_{\text{total}} = (F_{\text{weight}} + F_{\text{friction}})r + T_o \]

\[ T_e = \sum I \dot{\theta} \]

\[ T_{\text{max}} = (F_{\text{weight}})r + T_o \]

\[ T_{\text{max}} = 142 \text{ oz-in} \]

Images Courtesy McMaster-Carr, City Theatrical, SparkFun Electronics, Amazon.com, RobotShop, and Pathway Connectivity

Obstacles

What Went Wrong
Testing of SwiftScene

Measuring the Success of Our Product

Current Test Results

- Control motors independently
- Rotate 360 degrees reliably
- Cannot reliably move linearly
- Batteries drain quickly

Future Testing Plans

<table>
<thead>
<tr>
<th>Elements</th>
<th>Units</th>
<th>Target Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Speed</td>
<td>ft/s</td>
<td>1</td>
</tr>
<tr>
<td>Acceleration</td>
<td>ft/s²</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>Load Capacity</td>
<td>pounds</td>
<td>25</td>
</tr>
<tr>
<td>Operating Time</td>
<td>hours</td>
<td>1/10</td>
</tr>
<tr>
<td>Braking Time</td>
<td>seconds</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>Directional Control</td>
<td>N/A</td>
<td>forward/back/rotate</td>
</tr>
</tbody>
</table>

Impact of SwiftScene

Social Impact

- 62% Agree audience experience would be enhanced
- 80% Agree cast & crew would benefit from SwiftScene
- 69% Believe overall production value would increase with SwiftScene

Economic

Creating a new market type for low cost automation

Political

Theater and politics are continuously linked

Ethical

Our duty is to customer safety
Future of SwiftScene

Seeking Further Progress

What we would do differently

- Better communication
- More powerful motors
- Longer lasting single source battery

It is our hope that this project will continue as a personal project as well as perhaps passing it on to a new senior design team

Conclusion

What have we learned?

- Proof of Concept
  - DMX can control and position a device
- SwiftScene will have positive impact in target market
- Many goals achieved with still more testing to come

Thank you to our advisors and sponsors

- Timothy Hight, Mechanical Engineering
- Michael Taylor, Mechanical Engineering
- David Sword, Theatre and Dance
- Doug Fleenor Design
- ETC
- Parlights, Inc.

Thank you!

Questions?
Finite Element Analysis

- Attempted to model impact with accelerated point load
  - FOS: ~5, Reliability questionable
- Would like to pursue a dynamic model in future
- Also modeled uneven loading scenario

Housing Modification

- Made in machine shop
- Would be custom in future
- Hands on for students

Future Iterations Continued

- Single Source Battery
- Work with Doug Fleenor to design a new card
- Power switch on the device
- Circuitry to cut power with signal loss
- Edgefinding system all the way around

Defining Omnidirectional Motion

\[ a = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ b = \begin{pmatrix} 1.0, -1.0, 1.0, -1.0 \end{pmatrix} \]
\[ c = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ d = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ e = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ \alpha = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ \beta = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ \gamma = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ \delta = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ \theta = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ \phi = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ \psi = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]
\[ \omega = \begin{pmatrix} 1.0, 0.0, 1.0, 0.0 \end{pmatrix} \]