TrackStar: Motion Tracking Stagelight Mount

Bradley Beady, ME; Michael Bjorge, CSE; Ezra Dantowitz, EE; Jason Gurney, ME

***Abstract*—TrackStar is a stagelight mount that allows for real-time tracking using a previously non-moving stagelight. By placing an IR beacon on a performer and using a camera equipped with an IR passband filter, the system is able to detect IR patterns and track a desired performer. By using eight unique IR patterns, multiple performers can be tracked by different lights simultaneously. The light is controlled through DMX, the lighting industry standard protocol. Through DMX, the light can be set to track one of eight channels, or manually controlled to pan and tilt.**

I. Introduction

In the 2013-2014 season, 12.2 million people attended Broadway shows in New York City. This grossed $1.26 billion for the industry. "Broadway attendance for the 2013-2014 season topped those of the ten professional NY and NJ sports teams combined (Mets, Yankees, Rangers, Islanders, Knicks, Liberty, Giants, Jets, Devils, and the Nets)" [1]. In addition to Broadway productions, there are over 7,000 regional theaters in the US entertaining a total audience of 86 million people [2].

Each performance involves a dedicated stage crew to operate the lights and ensure the production goes smoothly. In current lighting configurations there are three choices for lighting fixtures: fixed stagelights, moving head lights, and follow spotlights. In current configurations, lighting crews are limited in their abilities to track a moving target. Using fixed lights, they can light the entire stage so that the performer is illuminated wherever he goes. Alternatively, using a moving head light, a performer can have a pre-planned path that is programmed into the light; as long as the performer follows the path as planned with exact timing, the light will follow him about the stage. Finally, a stagehand can operate a spotlight and manually track a performer around the stage.

There are two separate, but related problems here to be solved, and there are current solutions to solve them individually. The first problem is that most theaters have fixed stagelights that are not capable of moving. AutoYoke is a mount that takes a fixed stagelight and gives it two degrees of freedom (pan and tilt) [3]. It is controlled through DMX and can be integrated into existing stagelight setups. But AutoYoke does not address the second problem of tracking performers on stage. Wybron, a stage lighting company, used to have a product called Autopilot that supported live tracking on stage [4]. It consisted of sensors set up above the stage that tracked a beacon. Their beacon was worn as a belt on a performer, and was similar to our product in that it allowed for multiple performers to be tracked separately with different belts. Another similar product currently being sold is BlackTrax, by CAST [5]. BlackTrax is very similar to Autopilot in that it consists of multiple sensors above the stage that track a beacon on the stage. BlackTrax creates a three-dimensional map of the stage and continuously updates it.

TABLE I
SPECIFICATIONS

Specification	Initial	Actual
Range of Motion	Pan 300˚, Tilt ± 45˚	Pan 160˚, Tilt 75˚
DMX Compatible	Yes	Yes
Camera Frame Rate	80 FPS	25 FPS
Mounting	Hang from 1.5" pipe	Upright operation
Overall Size	2' x 1' x 2'	1' x 1' x 1.5'
Battery Life	8 hours	14 hours
Lights Compatible	Standard	Standard
Number of Patterns	8	8

TrackStar represents a new approach to tracking on-stage targets in real-time. The primary difference between TrackStar and existing solutions is that TrackStar allows for retrofitting individual stagelights instead of installing an entire system for the stage. TrackStar consists of a mount that a standard, fixed light is attached to; the mount is able to pan and tilt the attached light in order to follow a target anywhere on stage. An IR beacon is attached to the target to allow for tracking. The TrackStar mount has a PlayStation Eye camera with an IR passband filter, allowing the controller to locate and track the IR beacon. The IR beacon is capable of sending out eight unique signals so that multiple targets can be differentiated and tracked simultaneously. TrackStar is controlled through DMX512, the standard protocol in the lighting industry. With three DMX channels, the light can be set to track one of eight different beacon patterns, or manually controlled to pan and tilt.

TrackStar allows for unmanned light tracking in live stage performances. This will give more functionality in small scale productions that might not have the resources to operate multiple moving lights during a performance. Also, by enabling users to manually configure the light through DMX, it eliminates the need for stage crew to climb up to the lighting fixture to make adjustments. This means a safer environment and makes setting up lights accessible to more people.

B. Beady from Weymouth, MA (email: bbeady@ umass.edu)
M. Bjorge from Swansea, MA (email: mbjorge@umass.edu)
E. Dantowitz from Millburn, NJ (email: edantowi@umass.edu)
J. Gurney from Weymouth, MA (email: jgurney@umass.edu)

II. Design

A. Overview

The TrackStar mount consists of three components. The first is the tilt shaft, which connects directly to the stagelight and allows the light to be tilted up or down 45 degrees. The tilt shaft is supported by the pan arms, which allow the stagelight to be panned 300 degrees from left to right. The combination of the tilt and pan motions enables the system to follow a performer anywhere on stage.

The pan arms are connected to the base, which serves two purposes. The base has four legs to allow it to stand upright; the base could also be modified to have C-clamps in order to hang from standard lighting scaffolding. In addition, the base contains all of the electronics used for controlling of the mount.

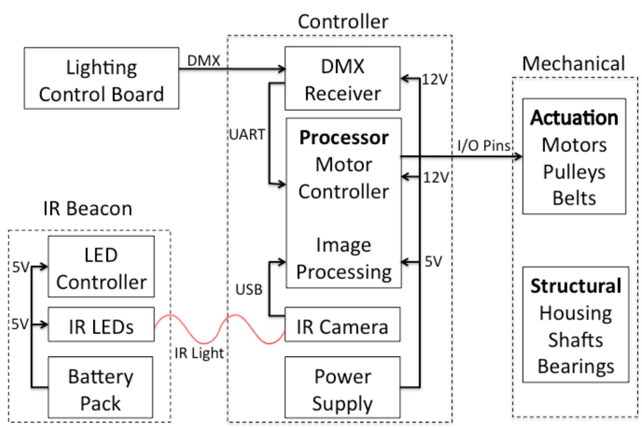

Fig. 1. TrackStar block diagram

An IR camera is placed on the light itself, and a performer wears an IR beacon. The camera then sends data to an image processing algorithm, the output of which is fed into a motor controller, which then actuates the motors to track the performer.

B. IR Beacon

The IR beacon allows the controller to track a performer on stage. The beacon consists of high-power, 880nm IR LEDs, a microcontroller, an input switch, and a battery pack. The microcontroller blinks the IR LEDs in a unique pattern, depending on the user input, allowing multiple beacons to be tracked simultaneously.

The IR LEDs were selected based on two criteria. First, they needed to be bright enough to be easily detected from a distance of at least 50 feet. Ideally, they would be significantly brighter than any reflected light coming from the stage so that the IR beacon would be easily identifiable. The particular LEDs selected have a radiant intensity of 31 mW/sr at 100mA [6]. Tests done in the theater at Amherst Regional High School demonstrated visibility at distances of 200 feet. The second important criterion is the spectrum of light the LED emits. The LED cannot emit in the visible spectrum, as this would be distracting to the audience. The LED should also stay out of the thermal IR range, since interference with human bodies could become an issue. The selected 880nm wavelength is between visible red light and thermal radiation. To ensure the IR emission is not dangerous to humans, it must meet the IEC 60825-1 standard [7]. As we are using them, the LEDs are not a danger to anyone more than 2 meters away. Thus the audience is safe. As long as performers are not within 2 meters of each other, and looking at the LEDs for more than 10 seconds, this should not be an issue. To ensure safety requirements are met, we may have to turn down the power the LEDs are drawing.

An ATTiny45 was selected to control the IR beacon. The microcontroller is responsible for reading in the user selected channel from the hex switch and blinking the LEDs in the corresponding pattern. A user can select from eight patterns. At any given time, generally at most three performers are in different spotlights at once; if there were anymore, the stage would be lit more fully and spotlights would no longer be needed. By having eight selectable patterns, there are enough combinations to accommodate tracking many different groups throughout a performance.

Each pattern is seven bits long, where each bit corresponds to the LED either being on or off for 135ms. The length of each bit was chosen to correspond to approximately 3 frames from the camera, as this was found experimentally to result in good recognition of both on and off bits. Patterns were chosen such that the LED was always on for at least half of the pattern, to maximize tracking capabilities; the tracking system is only able to acquire a definite position of the beacon when

0111111	0101111
0011111	0110111
0001111	0110011
0100111	0101011

Table 2. The eight IR Beacon LED blinking patterns

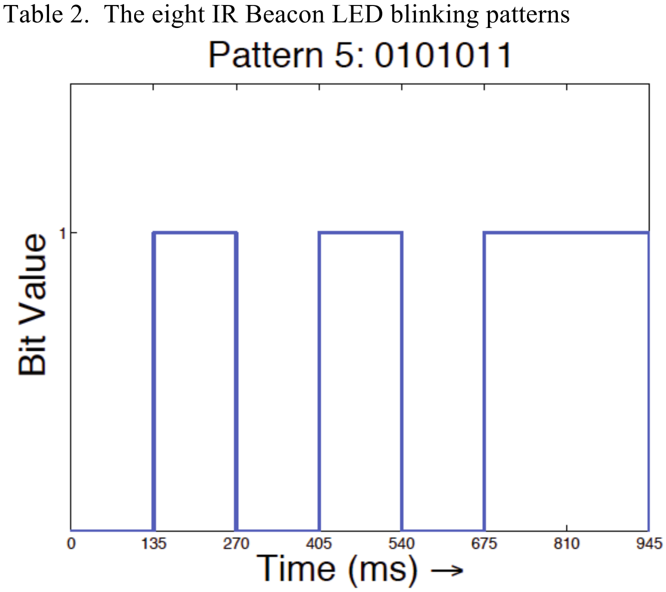

Fig. 2. Waveform representation of pattern 5

the LEDs are on. The patterns were also designed such that, when looking at any seven bit window, a pattern could be uniquely identified. By limiting the number of available patterns, the total length required to have unique patterns is also shortened. This allows the initial pattern detection to take less time. With seven bit patterns, detecting a pattern takes at least 945ms, since each bit is 135ms wide.

The final component of the IR beacon is the battery pack, which supplies power to the system. The battery pack holds four AAA batteries, providing a total of 3.4 to 4.8 Ah [8]. The microcontroller and LEDs draw 280mA when held on, however due to the patterns used the actually duty cycle varies between 58% and 86%. This gives an expected lifetime of the IR beacon of at least 14 hours, which is long enough to last several performances.

C. IR Camera

The IR camera is responsible for receiving the IR signal from the beacon. The camera is mounted on the stagelight via an adjustable strap and is aimed such that the center of the camera image matches the center of the light on stage. The key characteristics for the IR camera are its frame rate, resolution, and spectrum bandwidth. The PS3Eye camera was selected, as it is capable of 75 frames per second at VGA (640x480) resolution or 125 frames per second at QVGA (320x240) resolution [9]. In practice, the camera was only able to produce 25 FPS. In addition, an IR 880nm passband filter was added to the camera, so that only the output spectrum from the IR LEDs would be detected.

At 75 frames per second, a person moving at Olympic sprinting speeds can be tracked at a distance of 50 feet. VGA resolution provides an accuracy of 1 in / pixel at a distance of 50 feet, since the camera has a 56 degree field of view.

The camera feeds its output via USB to an embedded system, a BeagleBone Black that does image processing to locate and discriminate between beacons. The received image is thresholded in order to remove noise. The image is then put through a contour detector. The contours are then classified

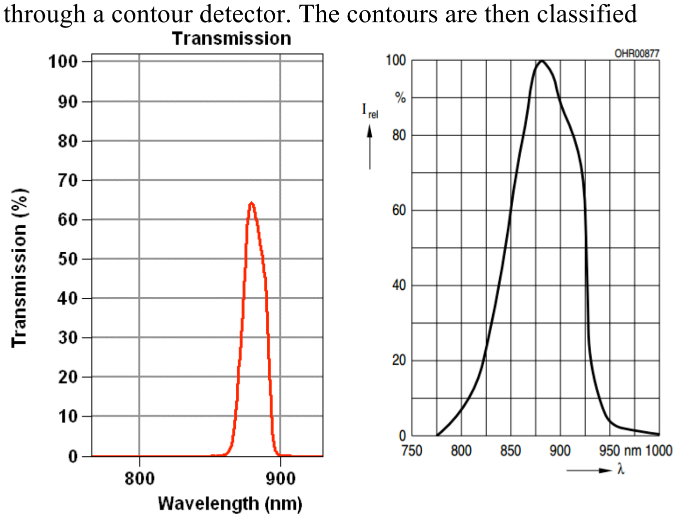

Fig. 3. IR filter bandwidth (left) and IR LED emission bandwidth (right).

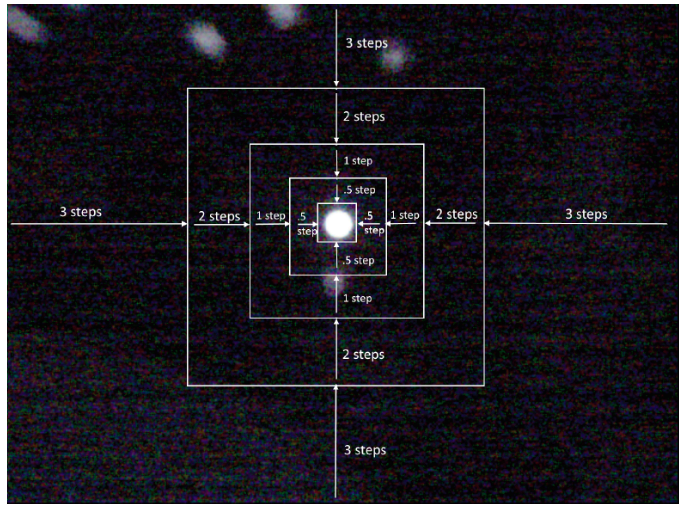

Fig. 4. The proportional motor controller actuates the pan and tilt motors based on how far the beacon is from the center of the image. The IR camera creates a closed loop system for the controller.

based on size and shape. Small, circular contours are assumed to correspond to beacon LEDs. A history of the locations of the detected contours is maintained. Iterating over the most recent 945ms of history, a pattern can be detected. If the detected pattern matches one of the predefined patterns, then the signal is likely to be an IR beacon. If the pattern does not match (e.g. if it is always on), then the contour is likely to be a reflection or some other anomaly and will not be tracked.

D. DMX Controller

In the theatrical lighting industry, the standard protocol for communication is DMX512. In this protocol, every lighting device is part of a DMX universe. A universe consists of 512 channels, each of which contains one byte of data. A DMX master device controls all of the devices in its universe by repeatedly outputting messages containing the settings for each of the channels. DMX slave devices are configured to listen to a specific channel (or range of channels). If there are multiple slave devices in the same universe, they can be daisy-chained together to pass the message from the master to each of the slaves [10].

The DMX controller consists of an Arduino Uno and a DMX Shield. The DMX shield has a female XLR port for input and a male XLR port for daisy-chaining with other slave devices. The controller needs three DMX channels for full functionality. The first channel serves two functions. When set to a value of 0-7, IR tracking is disabled and manual configuration mode is enabled. The remaining 8-255 values are split into eight groups of 31 (i.e. 8-38, 39-69, 70-100, etc.), which tell the controller which IR beacon pattern to track. When the controller is in manual configuration mode, the remaining two channels allow the user to set the pan and tilt angles. These channels are ignored when in IR tracking mode.

E. Motor Controller

The motor controller takes input from the DMX controller and the IR camera. When the DMX controller indicates manual configuration mode, all input from the IR camera is ignored. The motor controller takes the value from the pan and tilt channels and converts it

into an angle. This angle is then input to the motors.

The pan motor is a stepper motor, so the angle is input by stepping the motor the appropriate number of steps. In order to control the stepper motor, the motor controller uses five control inputs: one for direction, three for step size, and one to step the motor. By varying the step size inputs, the stepper motor can vary a step size from a full, 1.8 degree step to a step that is 1/32 that size. Inputting a rising edge causes the motor to advance by a step.

The tilt motor is a dc motor with an encoder, so the controller uses the feedback from the encoder to move to the correct tilt angle. The feedback from the controller provides velocity information for the motor, so the controller needs to integrate these velocities over time to get an accurate position.

When the DMX controller indicates tracking mode, the motor controller ignores the pan and tilt DMX channels and uses the data from the IR camera. The motor controller takes the position of the beacon that matches the pattern specified by the DMX value and finds the errors in both the vertical and horizontal position from the center of the camera. These errors are then used as inputs to a PID controller that drives the errors towards zero. Errors in the horizontal direction are mapped to steps in the pan motor, and errors in the vertical direction are mapped to torques in the tilt motor. By constantly driving the errors towards zero, the detected IR beacon signal will be centered in the camera, which means that the performer is centered in the light. When tracking, the motor controller uses feedback from the camera instead of from the motors to make continual adjustments to both the pan and tilt positions.

F. Actuation

A system of motors, pulleys, and timing belts is used to pan and tilt and the stagelight. Both degrees of freedom are controlled by Pololu stepper motors. Both motors have resolutions of 200 steps per revolution, providing 1.8 degrees per step. Using a stepper motor controller allows the stepper motor to move in fractional steps, effectively allowing for 400 steps per revolution (0.9 degrees per step). The tilt motor draws 2.8 A at 2.5 V per coil allowing for a holding torque of 180 oz-in. The pan motor draws 1 A at 8.6 V per phase allowing for a holding torque of 190 oz-in.

The motors are connected to their respective shafts via 2:1 flanged pulleys with belts. Using 2:1 pulleys allows the motors to be smaller, as they only need to produce half the necessary torque. The belts are tensioned by hand and secured by a sliding motor and bolting mechanism. Using pulleys and belts also eliminates backlash, which would be a problem in a gear-based solution [11]. Pulleys and belts are also quieter than gears, which is important since the audience should not be distracted by the noise of the system. Pulleys also allow the motors to be kept relatively close to the control box, which minimizes wiring.

G. Structural

The structural design consists of tilt arms, shafts, bearings and a three layer base. The tilt arms are made from aluminum 6063 U-channels, which balances strength and weight. These are welded together in a U shaped fashion, where the light is centralized between the ends of each tilt arm. The tilt shafts are solid aluminum, which provides the strength needed to hold the weight of the stagelight. The pan shaft is hollow to allow wires to be routed from the control box to the tilt motor. Roller bearings are used to provide radial support for the pan shaft, as well as thrust bearings to provide axial support. These bearings are mounted in the center of the top two layers of the structural base. These layers are constructed from 1 foot squares of sheet metal and are mounted to aluminum angle with screws and nuts. The layers are not welded together permanently to allow for easier accessibility to inner components. The bottom most layer supports the pan motor, power supply and processing units.

III. Project Management

Our interdisciplinary team is diverse in interests and expertise, making for a strong group. Bradley is well versed in motors and mechanical analysis. Jason has experience in CAD modeling and structural design. Michael has a strong background in software engineering and embedded systems. Ezra is skilled in electronics design. We meet regularly as a team and additionally with our advisor, Professor Wolf, to discuss progress and setbacks. Our team has great rapport and gets along well.

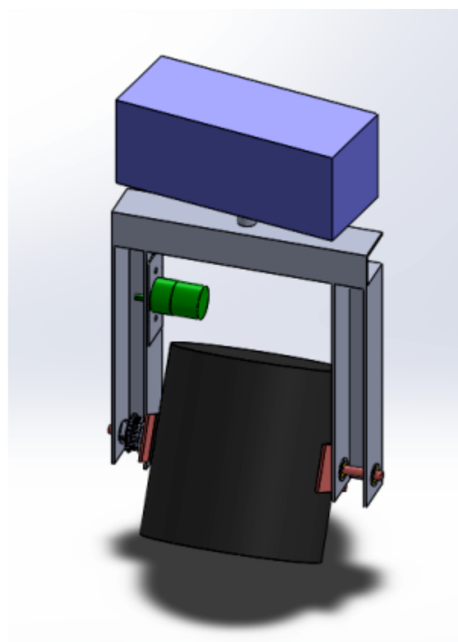

Fig. 5. CAD drawing of TrackStar with stagelight.

Our team maintains a Google Drive to keep track of all our documents. As we are also responsible for MIE 415 requirements, organization is key to success. Our team works together on some tasks, but also delegates certain tasks to individuals. We look over each other's designs to catch errors and also split workloads when necessary.

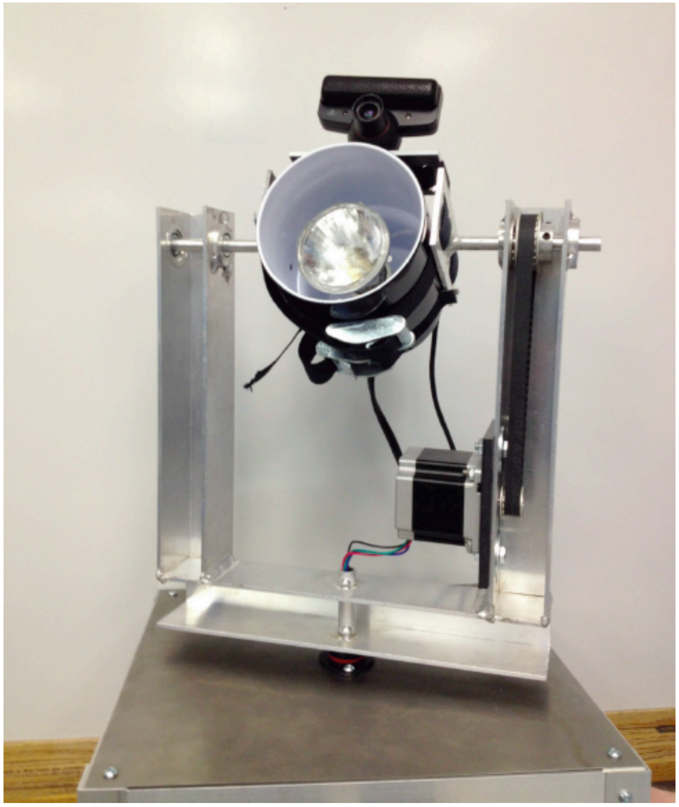

Fig. 6. TrackStar

IV. Conclusion

We were able to construct a functioning prototype with all subsystems properly integrated.

The camera is retrofitted with an IR filter and communicates with a BeagleBone Black over USB. The BeagleBone Black finds where the appropriate beacon is and determines an error in the horizontal and vertical directions to input to the motor controller. The motor controller then steps the pan and tilt motors proportionally to the error in the horizontal and vertical direction respectively.

A user controls the system with a DMX console, similar to what would be used in a theater. An Arduino reads in the DMX values through a DMX shield and then passes the three values over a serial connection to the BeagleBone Black. The system is fully operational with DMX and is ready to be integrated into a theater.

We have printed circuit boards for our IR beacons and a 3D printed enclosure to encapsulate both the PCB and the battery pack. The IR LEDs are wired from the PCB and can be clipped onto the performer while the enclosure sits in the performer's pocket. This implementation is similar to how a stage performer would wear a wireless microphone.

The system works at a distance of 50 feet and can successfully track a performer as he moves across the stage. The biggest limiting factor of the system is the processor. While the camera is capable of achieving 75 frames per second, while running image processing on the BeagleBone Black, our system only reached 25 frames per second. This limits how quickly the system can both find and follow a performer around the stage. A successor to TrackStar would have more processing power to enable better tracking.

Acknowledgment

We would like to thank John Bechtold and the Amherst Regional High School for letting us test on their stage. We would also like to thank Brenda Cortina and the UMass Theater Department for lending us a stagelight to use. We would like to thank Neil Jeronimo and the Swansea Grange for lending us a stagelight, as well. Finally, we would like to thank Mr. Gerard Mills for his advice.

References

[1] The Broadway League, "Research and Information" [Online]. Available: http://www.broadwayleague.com/ [Accessed Web. 3 Dec. 2014.]

[2] American Association of Community Theater, "About AACT" [Online]. Available: http://www.aact.org/ [Accessed Web. 3 Dec. 2014.]

[3] City Theatrical, "AutoYoke," [Online] Available: http://www.citytheatrical.com/Products/2012/02/10/autoyoke- [Accessed Web 14 Oct. 2014.]

[4] Wybron, "Autopilot II Quick Setup" [Online] Available: http://www.wybron.com/stage-lighting-service-and-repair/documentation/user-manuals/Autopilot_II_quick_start.pdf

[5] CAST, "BlackTrax" [Online] Available: http://www.cast-soft.com/blacktrax/ [Accessed 14 Oct. 2014.]

[6] OSRO, "GaAIAs Infrared Emitter (880 nm)," *SFH 487 Datasheet*. [Online]. Available: http://www.osram-os.com/Graphics/XPic1/00084298_0.pdf. [Accessed Web. 27 Oct. 2014.]

[7] International Electrotechnical Commission "IEC 60825-1" International Standard, [Online] Available: http://www.microasu.com/download/jqlaser/certificate/IEC_60825_1.pdf [Accessed Web. 12 Dec. 2014.]

[8] Energizer, "Product Datasheet Energizer E92," *E92 AAA Datasheet*. [Online]. Available: http://data.energizer.com/PDFs/E92.pdf. [Accessed Web. 3 Dec. 2014.]

[9] PlayStation, "PlayStationEye Datasheet" [Online] Available: http://nz.playstation.com/media/247868/7010571%20PS3%20Eye%20Web_GB.pdf [Accessed Web. 10 Dec. 2014.]

[10] *Asynchronous Serial Digital Data Transmission Standard for Controlling Lighting Equipment and Accessories*, ANSI E1.11 - USITT DMX512-A, 2004

[11] R. G. Budynas and J. K. Nisbett, "Gears - General," in *Shigley's Mechanical Engineering Design*, 9th ed. New York, McGraw-Hill, 2011, ch. 7, pp. 676-698.

[12] OpenCV "Open Source Computer Vision Library" [Online] Available: http://opencv.org/ [Accessed Web 25 Oct. 2014.]

[13] Code Laboratories, "Eye Driver Platform" [Online] Available: https://codelaboratories.com/products/eye/driver [Accessed Web 25 Oct. 2014.]