TrackStar: Motion Tracking Stagelight Mount

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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 set to a desired pan and tilt angle.**

I. Introduction

In the 2013-2014 season, 12.21 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 group to operate the lights and ensure the production goes smoothly. In current lighting configurations there are three choices: 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. Or 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. The first is that most theaters have fixed stagelights not capable of moving. AutoYoke is a mount that takes a fixed stagelight and gives it two degrees of freedom, to pan and tilt [3]. It is controlled through DMX and can be integrated into existing stagelight setups. But AutoYoke does not address the issue 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.

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TABLE I
Specifications

Specification	Value
Range of Motion	Pan 300˚, Tilt ± 45˚
Speed	180 deg/sec
Camera Frame Rate	120 Hz
Mounting	Hang from 1.5" pipe
Overall Size	2' x 1' x 2'
Battery Life	>5 hours
Operation Noise	≤50 dB

TrackStar represents a new approach to track on-stage targets in real-time. The biggest difference between TrackStar and existing solutions is that TrackStar allows for retrofitting of 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 set to specified pan and tilt angles.

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 set the angle of 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.

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 C-clamps in order to attach to standard lighting scaffolding. In addition, the base contains all of the electronics used for processing and control of the mount.

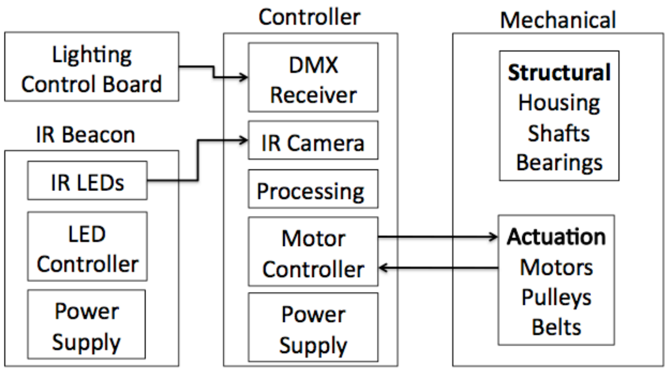

Fig. 1. TrackStar block diagram

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. For actors on stage coming in close contact, we need to do some further testing to measure the LED intensity and determine what is acceptable. However, if 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 selected channel from the user 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 50ms. Patterns were chosen such that the LED was always on at least half of the time, to maximize tracking capabilities. 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 350ms, since each bit is 50ms 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.

0111111	0101111
0011111	0110111
0001111	0110011
0100111	0101011

Table 2. Our eight IR Beacon LED blinking patterns

C. IR Camera

The IR camera is responsible for receiving the IR signal from the beacon. The camera is mounted on the stagelight 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 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 that does image processing to locate and discriminate between beacons. The received image is thresholded, to remove noise. The image is then put through a contour

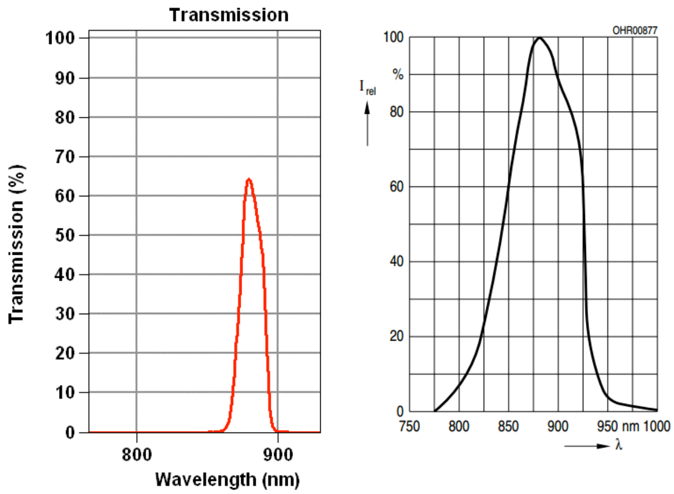

Fig. 2. IR filter bandwidth (left) and IR LED emission bandwidth (right).

Fig. 3. Visual output of IR tracking. The beacon can be seen in the middle of the screen. The pattern detected is in the upper left corner. The upper right corner displays the frame rate of the camera. The bars at the bottom and left represent the amount the motors need to move the system.

detector. The contours are then classified based on size, shape, and brightness. Small, circular, bright contours are assumed to iterating over the most recent 350ms 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. The pan motion is controlled by a stepper motor. The stepper motor has a resolution 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 6400 steps per revolution (0.56 degrees per step). The stepper motor has a 11.25 in-lb holding torque.

The tilt shaft is driven by a brushed DC motor. The motor unit has a 30:1 gearbox, which results in the motor having a

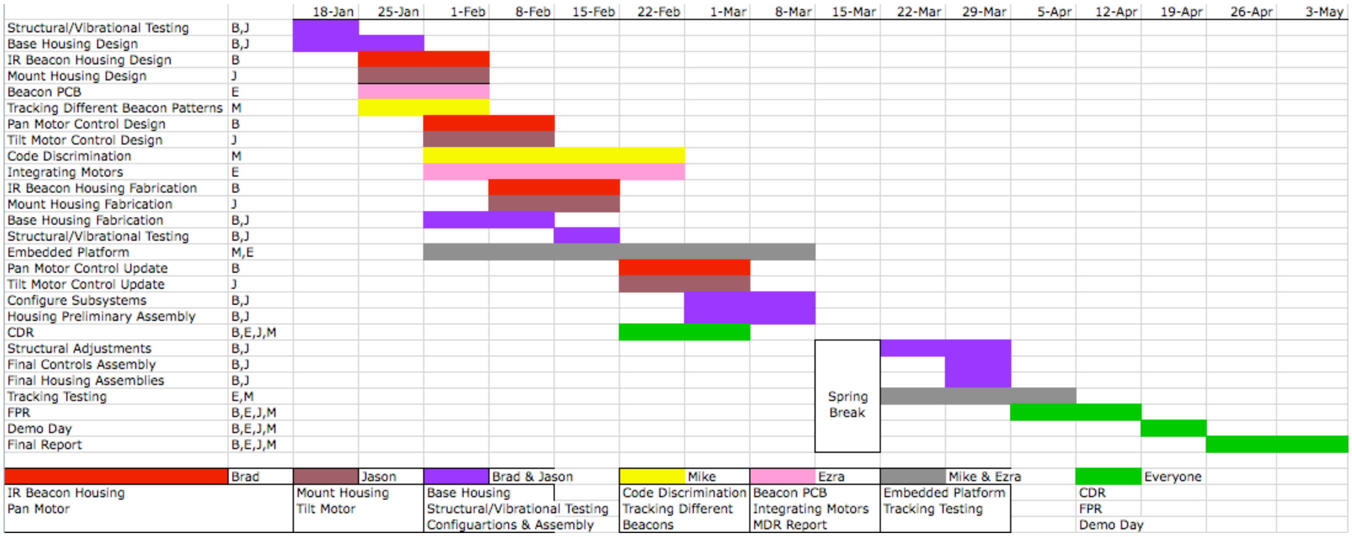

Fig. 4. Gantt chart for spring semester

6.875 in-lb stall torque. In addition, the motor has a 64 count per revolution (CPR) encoder, which provides velocity feedback to the motor controller.

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. 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 main housing is made from aluminum 6063 U-channels, which balances strength and weight. 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 motors. Roller bearings are used with the tilt shaft. Thrust bearings are used with the pan shaft, since it must provide support for the frame and stagelight weight.

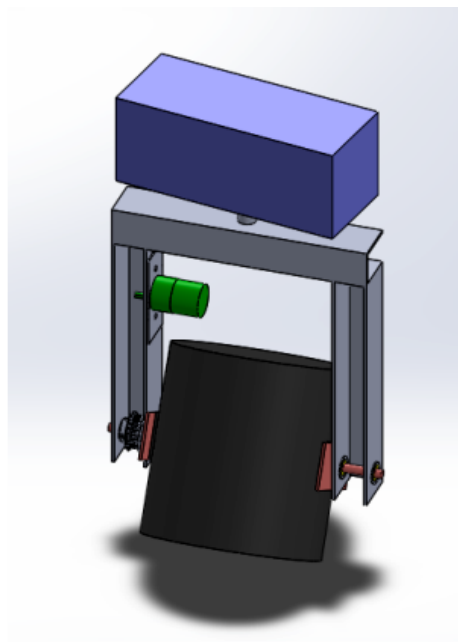

Fig. 5. CAD drawing of TrackStar with stagelight.

III. Project Management

We have our subsystems in mostly functional states. The biggest task for next semester will be integrating them. The biggest integration task will be incorporating the motors with our controller. Our PID controller is dependent on feedback to drive the error to zero and in turn get our target in the center of the light. For the pan motor, we can rotate the light an exact number of steps to move the light as desired. For the tilt motor, we need to use the feedback from the encoder to determine how much the light has tilted.

For tracking we need to discriminate between different IR beacon patterns. This step is crucial to being able to track multiple actors with different lights. Currently, we can successfully identify which pattern a beacon is on, but we need to be able to tell the difference between different patterns when more than one beacon is present.

The mechanical engineers will be responsible for designing and building housings for both the IR beacon and also the controller. The IR beacon needs to be compact so that a performer can clip it onto his belt, much like a wireless microphone.

The housing for the controller needs hold the controller in place and be mounted to the structure holding the light. It also needs to allow for power to come into the system.

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.

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.

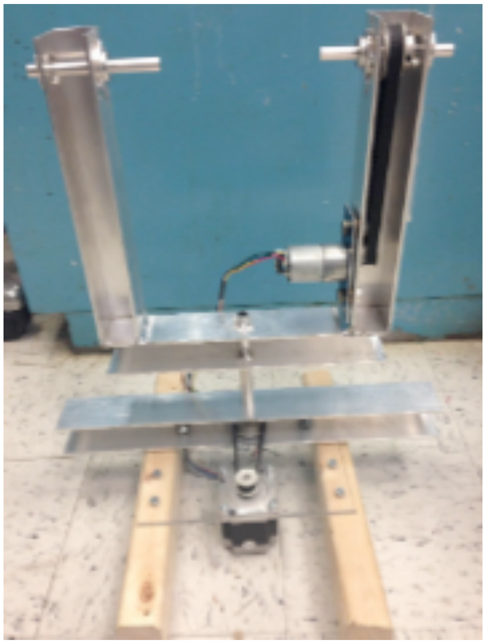

Fig. 6. Mount that attaches to stagelight

IV. Conclusion

The individual components are independently functional. A prototype of the IR beacon has been assembled and programmed with the blinking patterns, and user is able to both turn the beacon on and off and select which pattern to emit.

The camera has been retrofitted with the IR filter and is able to communicate over USB to a laptop computer. The computer then handles the image processing. In the final design, the laptop will be replaced by a smaller embedded system, such as a RaspberryPi or a BeagleBone. The image processing algorithm is able to identify a single beacon, detect which pattern the beacon is blinking, and measure the offset from the center of the image. The pan and tilt information derived from the image processing is then sent over a serial connection to an Arduino Uno.

The Arduino serves as both the motor controller and the DMX interface. A DMX shield is attached to the Arduino and is capable of receiving DMX signals from a Chauvet Obey 3, which is a three-channel DMX console. In the current prototype setup, the Arduino controls two servo motors, which are attached to the camera to allow for pan and tilt motions. The servo motors can be controlled via either the IR tracking system or manually from the DMX console.

An initial prototype of the pan arms has been constructed. The pan shaft, tilt shaft, pulleys, belts, and bearings have all been assembled in the pan arms. The tilt motor has been attached to the pan arms with a mounting plate, while the pan motor is only mounted to a temporary base.

Using the motor drivers, the Arduino was able to successfully drive the tilt motor forwards and backwards. There was no attempt to interface with the encoder. The stepper motor driver for the pan motor was non-functional, so the stepper motor has not yet been actuated.

There are five primary components that need to be worked on currently. First, the PCB design for the IR beacon board needs to be completed. The design is currently lacking connections for batteries and may need to be condensed, as form factor is a major concern for the beacon.

Second, the IR tracking algorithm needs to be improved so that multiple beacons can be detected and tracked at once. This is needed so that different beacon patterns can be tracked at different times and so multiple beacons can be onstage simultaneously.

Third, a mounting plate that allows a light to be attached to the tilt shaft needs to be designed and fabricated.

Fourth, the base of the mount needs to be constructed. It must have clamps that allow it to connect to standard scaffolding. It needs to be strong enough to support the rest of the mount and the light. It also needs to be large enough to house the controllers while being small enough to be unobtrusive. The base also needs a socket that will allow the stagelight to get power.

Finally, the motors need to be installed, powered, and controlled. This requires interfacing with the motor driver boards, getting feedback from the encoders, and converting the current motor driver algorithm to work with a stepper motor and a DC motor instead of two servo motors.

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