Shot Consultation Refinement Applied Through Computer Hardware

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***Abstract* — The Shot Consultation Refinement Applied Through Computer Hardware (SCRATCH) System is a billiards training tool which can improve the performance of both visually impaired users as well as non-visually impaired users. This system will consist of four subsystems that will communicate data that can be used to provide shot feedback as well as being able to help the visually impaired user with navigation and shot taking via live aim assistance. These subsystems are organized as follows, the HUD refers to the user worn apparatus which is worn similarly to glasses, and conveys information auditorily and visually, while also obtaining data via a camera. The glove refers to the mouse shaped system used for accurate aiming of the cue stick for the visually impaired user. The Cue Stick refers to the system that accurately records information of the user's cue stick movements and orientation. The final subsystem is the Central Control Unit (CCU), which as the name implies acts as the major workhorse of the system, performing all computations and directing all subsystem intercommunication. Each of these subsystems will perform specific tasks that will help the user while at the same time not negatively impact performance.**

***Index Terms* — Bluetooth Low Energy, DAC, I2C, SPI, Inertial Measurement Unit, Computer Vision, Sensors**

I. Introduction

The game of billiards, commonly known as pool, is enjoyed by hundreds of thousands of players yearly. In many situations, billiards can serve as an icebreaker and a facilitator of social interactions between different people. In other situations, the game is played competitively by professional athletes. Nevertheless, there are many people who cannot reap the social benefits of the game due to a lack of proficiency, and even more so by those with visual impairments. SCRATCH was conceived and developed as a means of solving these two majors problems: (1) the proficiency wall that beginners face and find difficult to overcome when playing with or against those more familiar to the game then them, and (2) visually impaired individuals are entirely excluded from the game, regardless of talent, ability, or desire. As engineers, it is our job to implement modern technology and innovative design to solve these problems.

While SCRATCH works to optimize the user's cue stick control parameters such as orientation, cue ball impact point, force, and bridge hand placement, there is an entire other side of billiards which is equally important for both visually impaired and non-visually impaired users which occurs before the person ever gets in position to take a shot. This is shot selection and body location. For this, the SCRATCH team will be working with another group developing a system called Visually Impaired Spatially Interaction Orientation Network (VISION). VISION will tackle the challenging task of table analysis to determine the best shot for the user to take, which then correlates directly to localizing and directing the visually impaired user to the table in the correct spot and orientation. Then SCRATCH's subsystems are responsible for hand placement and cue aim.

This document lays out the key technologies, designs, implementation, integration, fabrication, and testing procedures used to develop and refine the SCRATCH system.

II. In Depth Overview of the Subsystems

The overall functionality of the project is to solve the two problems mentioned above in the introduction. In short, it is to provide a lightweight, low-power, and convenient training system that aids in improving users proficiency in the game of billiards by providing pre-shot guidance and post-shot feedback in a simple-to-understand manner. The secondary goal is to make those shot refinements and instruction so clear that the game of billiards becomes more accessible to a visually impaired user. To do this, SCRATCH will focus on technologies and developments that enable precise data collection, processing, and presentation via wearable and mountable equipment that is custom-made for this project. This is accomplished via the four subsystems discussed in the abstract which are the HUD, the Glove, the Cue Stick, and the Central Control Unit. Each of these plays a vital role in achieving the project's total goal and will be discussed in much greater detail below.

A. HUD

The subsystem of the HUD consists of three different subsystems in and of itself. These are an audio system, a camera system, and a display system. The speaker and display serve to provide impaired and unimpaired users with the necessary pre and post-shot information that is both required for user improvement and even more critically for the visually impaired users positioning and movement.

The visual information will be directed to the non-impaired user via a Heads-Up Display system similar in concept to the ones found in road vehicles and even fighter jets, but much simpler in design and implementation. A simple 128x64 LCD display will act as a light source and have its image reflected off a mirror and onto a clear pane of glass, both of which have been treated to maximize image quality. This allows the user to receive the information at any time, regardless of position or shot taking stage, as the necessary information is projected right in front of their eye.

The audio system is necessary for giving necessary movement information to the impaired user. To do this, a DAC and speaker will be used to play pre-recorded audio files that are stored on an SD card located in the HUD's enclosure. These audio commands will orient the user via phrases like "Move stick left." or "Move Hand Forward". The position of the cue stick and glove will be fine tuned via these commands until the user is in position and will receive the final pre-shot command. "Shoot!".

The final subsystem found within the HUD is the camera. The camera is used to take pictures of the shot in real time, as the shot is taken and the cue stick is moving towards the ball. The picture will then be sent via Bluetooth Low Energy (BLE) for processing at the central control unit via computer vision. A laser assists the computer vision system in determining the cue ball impact point, converts this point to coordinates, and relays this information back to the HUD for post-shot feedback.

All of these are controlled and managed via an ESP32 dev board which uses BLE to communicate with the central control unit.

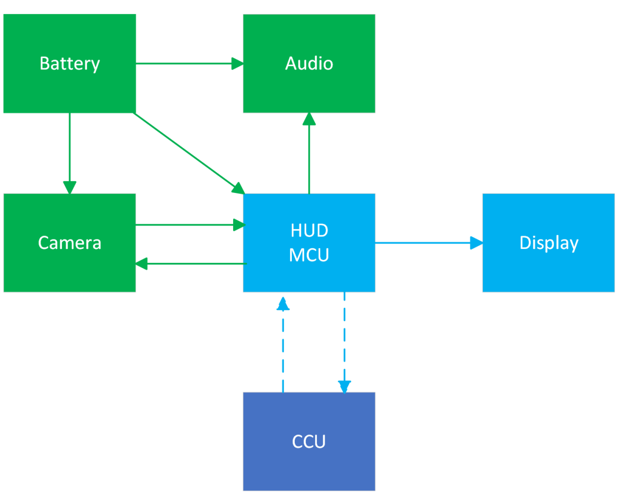

Fig.1. HUD Block Diagram

B. Cue Stick

The primary function of the cue stick subsystem is to accurately determine the orientation and speed of the user's cue stick. This gives the rest of the system the data necessary to provide meaningful and constructive feedback to both impaired and non-impaired users. The secondary function of the cue stick is to give the user control of the system to enter the different available modes.

To accomplish these tasks, the cue stick will be mounted with several peripherals including a custom designed PCB. These are the laser, the buttons, an IMU, and a battery which are all joined together and controlled via a custom mounted ESP32.

As this system will be mounted to a cue stick, it is critical that this system be as lightweight as possible to minimize changes to the user's shot. As this system will not have a physical connection to any other subsystem, it must be able to wirelessly communicate with the other subsystems. For that same reason, the stick's system must be a low-power solution as it will be battery-powered.

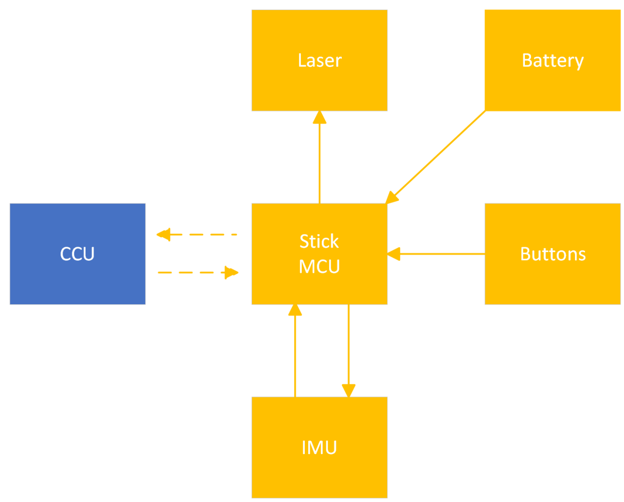

Fig. 2. Cue Stick Block Diagram

A. Glove

The primary function of the glove is to assist the vision-impaired user with pre-shot feedback in order to be facing the cue ball at the correct angle as well as at the correct distance from the ball, this angle will be provided by the VISION team. This system will have to be very compact in order to not impact the user's shot.

The design of the mouse shaped enclosure will feature a channel for controlling the cue stick. That way, once the system has localized the bridge hand into the correct spot, all the visually impaired user has to do to make correct contact with the ball is push straight forward.

Within the enclosure there will be a button, an IMU, an ultrasonic sensor, and a battery which are controlled via an ESP32 dev board that utilizes BLE to communicate with the central control unit.

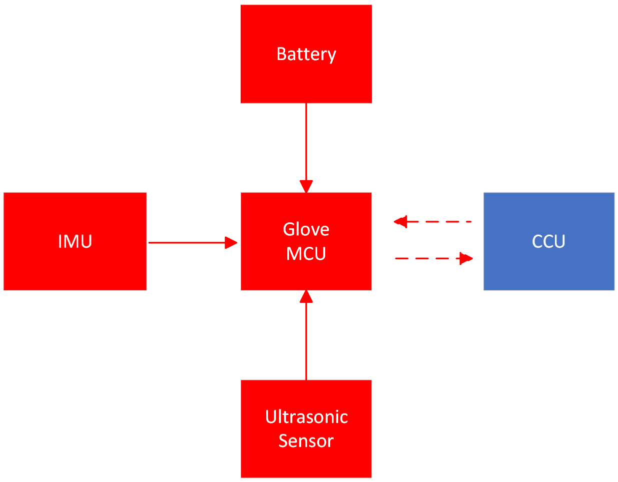

Fig.3. Glove Block Diagram

D. Central Control Unit

As the name implies, the central control unit will be the subsystem responsible for sending and receiving data to and from the other subsystems. This will also be the portion of our project that will communicate with the VISION team's system.

When communicating with the HUD, the CCU has two major responsibilities. The first is rendering and sending the images that will be displayed on the HUD's display when in normal use. When the system is being used by the visually impaired, the CCU will be responsible for telling the HUD's audio system which audio clip to play. The second responsibility is to interface with the HUD's camera system. The CCU will be responsible for controlling when the camera begins recording. The CCU will then receive the images from the HUD; with this data, the CCU will render a low-resolution image of the location of cue impact on the ball that will be sent back to the HUD to provide feedback to the user.

When communicating with the cue stick, the CCU's primary responsibility is to receive the motion from the cue stick and use it to provide meaningful feedback to the user. The secondary responsibility is to receive the button input data from the stick and change the state of the CCU's program accordingly. Related to both of these responsibilities is the fact that the CCU will occasionally have to send switching information to the cue stick depending on the button inputs.

When communicating with the glove, the CCU will receive sensor data from the glove. With this data, the CCU will determine whether the user should position their hand closer or farther from the cue ball.

When communicating with the VISION team, the CCU will be responsible for receiving the angle and speed data for the desired shot. The CCU will also be responsible for notifying the other system when SCRATCH is ready for the next shot.

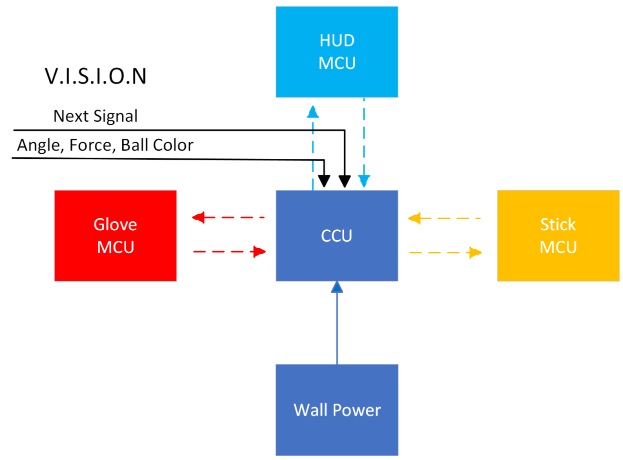

Fig.4. Central Control Unit Block Diagram

III. Components

A. Central Control Unit Processor

The responsibilities of the CCU are that it must have the ability to communicate with the other team's system. It must be able to wirelessly communicate with the cue stick, glove, and the HUD. It must be able to process shot data and correlate that data to post-shot information for user feedback. It has to render and process the image taken on the HUD, for display onto the HUD. Finally, it must be able to be plugged into an AC power outlet.

With the high computational power required for computer vision data processing and managing the communication of the three other subsystems, a very powerful controller is required. The chosen microprocessor was the Raspberry Pi 4 Model B. This processor gave 8 GB of LPDDR4 RAM, and 1.5 GHz Quad-Core Broadcom processor, built in USB, SPI, I2C, I2S, UART and Ethernet communication ports for wired connectivity and Bluetooth 5.0/BLE for wireless connectivity allowing for nearly unlimited compatibility for communication between peripherals and the VISION teams system.

Fig. 5. Raspberry Pi 4 Model B

B. Peripheral's Central Processor

In the interest of minimizing integration complications, it was decided to choose one common controller that fits the bill for the variety of requirements and challenges posed by each subsystem. For all of the peripherals, the controller needed to be small, lightweight, have BLE or Wifi capabilities built in for wireless communications, have I2C, SPI, and I2S wired communication protocols built in for sensor control and data collection.

With these common requirements in mind, the NodeMCU ESP-32S was selected as the best option. The onboard Dual-Core 240 MHz processor, 520 KB of SRAM, maximum flash size of 4 MB, and maximum power consumption of 1.65 W will be more than enough to drive the sensors and the ESP-32S utilizes all the require wire and wireless communication protocols for system integration and functionality.

With regard to the PCB found on the cue stick, the ESP32 MCU Module will be utilized while on the rest of the system where custom PCB design is not required the NodeMCU ESP-32S was determined to be the best development board option available.

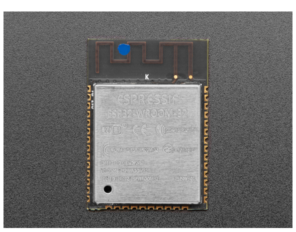

Fig. 6. ESP32 MCU Module

C. Ultrasonic Sensor

Ultrasonic sensors work by sending out a sound wave at a frequency above the range of human hearing. The transducer of the sensor acts as a microphone to receive and send the ultrasonic sound. The sensor determines the distance to a target by measuring time lapses between the sending and receiving of the ultrasonic pulse. For this case we could use the ultrasonic sensor because the ball has a hard surface it would be easily detectable by the ultrasonic sensor giving us a reading of distance. With our power requirements in mind we needed a sensor that could be powered with 3.3V and is compatible with our ESP32. Therefore the RCWL-1601 was selected, this device works perfectly because of its accuracy of 2cm - 450cm and its small size.

Fig. 7. RCWL-1601

D. Display

The start of, and arguably the most important part of the optical path that the heads-up display will take begins at the display. The chosen display needs to be capable of clearly and concisely displaying the pre and post shot information. After mocking up potential display information layouts as shown in Figure 8, it was determined that the optimal size that offered the best middle ground between small size to fit in the HUD and large enough to display the information was 128x64 pixels large.

Fig. 8. HUD Information Layout

Next, for compatibility with the ESP32 and to avoid conflict with other sensors and peripherals within the HUD subsystem, I2C was chosen as the preferred communication protocol. SPI was already being utilized by other peripherals and the benefits of higher data rates were not necessary for this application.

After considering all the options available on the market, the selected option was the HiLetGo 128x64 LCD OLED Display for its small overall size, crisp display output, 3.0-5.0V input and I2C communication protocol.

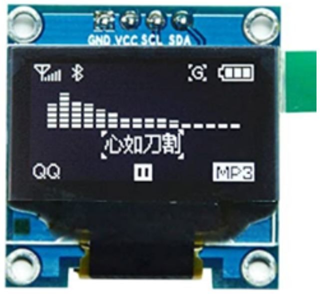

Fig. 9. HiLetGo 128x64 LCD OLED Display

E. Camera

Placing the camera on the HUD results in multiple challenges. First, the camera has to be small and lightweight in order to maintain the desired size and weight of the HUD. If breached, these can then cause practical issues and make the HUD inconvenient for the user. Second, the camera has to be low power, as the HUD Power System must be limited. This is to reduce heat generation and increase both the safety and convenience of the HUD. While the quality of the camera is relatively important, this will not be an issue due to two reasons: first, modern cameras are very powerful and provide more than enough resolution. Secondly, the laser reflection should facilitate the location of the point of impact.

With this in mind, the chosen MCU oriented camera module is the ArduCAM 2MP. This was chosen over the competition due to its ease of programming, low power consumption of .35 W and relatively small size.

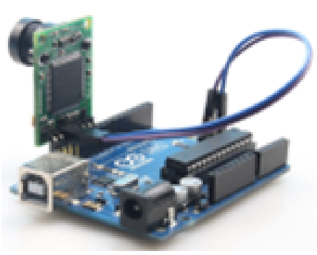

Fig. 10. ArduCAM module

F. IMU

The IMU is required for this project to track the cue stick's orientation and speed when striking the cue ball. The data from these sensors is sent to the central computer where the path and speed of the pool cue are then compared to the ideal "shot" provided by the table team's AI algorithm. The system then provides the user with feedback as to how accurate their attempt was to the ideal shot. After multiple shots and sessions, it is expected that the user's billiard stroke would become more consistent and accurate, specifically their path of motion and speed control. This IMU will also be placed in the glove subsystem in order to determine a precise angle of the glove in order direct the visually impaired user into the correct position to take a shot.

The BNO055 is an IMU made by Adafruit that uses sensors from Bosch. It contains a MEMS accelerometer, magnetometer, and gyroscope, as well as an ARM Cortex-M0-based processor. This 9-DOF sensor is special as it uses "sensor fusion algorithms" to blend the sensor data into a stable three-axis orientation output. The accelerometer has four sensitivity ranges (2g, ±4g, ±8g, or ±16g) and the gyroscope has five sensitivity ranges (±125, ±250, ±500, ±1000, and ±2000°/sec). The dimensions of the IMU are 20.0mm x 27.0mm x 4.0mm. The supply voltage ranges from 2.4 to 3.6V; the total supply current is 12.3mA. This results in a typical power draw of 36.9mW.

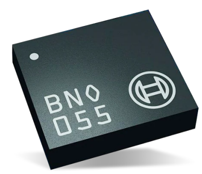

Fig. 11. BNO055 Absolute Orientation Sensor

G. Battery

Based on the engineering and marketing requirements, the HUD will require a power supply that keeps the HUD operational at an absolute minimum of at least 30 minutes before needing to be charged. This requirement and the voltage requirements of each individual component are the driving factors that determine what size and array of batteries need to be utilized in this design. Table 1 shown below lists the voltage and power draw requirements for each component. The power draw requirements will have a range from maximum to minimum draw and be listed in mA.

After voltage, the next most important parameter for the battery supply selection is size. This size is given most commonly in mAh. Milliamp-hours (Or mAh) is the measure of how many hours a battery can sustain a constant draw of current. For instance, if a device requires 100 mA of current, a battery with a 1000 mAh capacity could supply those 100 mAs of current for 10 hours.

The equation that describes this relationship is shown below.

$$\frac{Battery\ Capacity}{Average\ Current\ Consumption} = Maximum\ Lifetime \quad (1)$$

TABLE I. Peripheral Battery Voltage Requirements

Battery Requirements			
Component	**Voltage Req**	**Power Draw (Peak)**	**Power Draw (Typical)**
ESP32	3.3 or 5	240	80
Display	3.3	0.78	0.43
Camera	5	70	20
DAC/Speaker	3 to 6	40	16
Total		351	117
Total (With 1.25 Tolerance)		439	146

After considering the options, the determination was made to use the standard 9V battery due to its high output which can be downconverted to meet each component's demands, its 600 mAH capacity, reasonably small size, and wide availability for replacements.

G. Audio System

For the impaired user, an audio system is required for conveying the necessary information auditorily rather than visually. To complete this system, three components are required, an SD card and reader to store the pre recorded audio files, a DAC, and finally the speaker itself.

For the DAC, the MAX98357A was chosen. It takes I2S signals as an input and outputs the analogue signal to directly drive any standard non-active speaker. The final output is a 300KHz PWM signal and the operating voltage for this board is between 3 and 6 volts. The output power is 3.2W for 4 ohm impedance, and 1.8W for 8 ohm impedance. Efficiency is 92% if load resistance is 8 ohms and output power is 1W. Maximum quiescent current is 2.9mA.

The chosen speaker is the simple to use, Adafruit 3" passive speaker.

G. Buck Converter

While on the custom design PCB there will be a down conversion system, for the peripherals, an external solution is necessary. For this application, a simple buck converter is the perfect option. The only requirements are that the converter can receive an input power with 9V in the range, and is adjustable to output both 3.3V and 5.0V.

The chosen option was the eBoot Mini DC-DC Buck Converter. This module was chosen for its small size, low output noise, and both input and output ranges meeting the requirements.

IV. Software Detail

Each subsystem has their own software flow that is run through the individual microcontrollers but this section will focus on the main software flow that connects all the individual subsystems together through the central control unit (CCU) as well as the Cue stick finite state machine.. Each of these subsystems has different BLE characteristics that it will update and send to the CCU; these are then used to control the general flow of the full system. The CCU will have two separate software diagrams depending on what mode it is in, that being normal or impaired user mode.

A. Non-Impaired Mode

This starts with the IMU being zeroed out on the cue stick and then the user will press a button to signal to the CCU that the user is about to take a shot. Once the CCU determines that a shot attempt is occuring, it sends a signal to the HUD to initiate its camera to take a burst of pictures. The pictures are sent back to the CCU where image processing will be used to determine the point of contact between the cue ball and the cue stick. Then a comparison with an ideal shot vs shot taken is done on the CCU and displayed on the HUD.

B. Impaired Mode

The impaired mode unlike the non-impaired mode will utilize both the glove and the speaker systems to guide the user to take the correct shot the first step is to have the user zero out the glove so that an accurate angle can be achieved then a sweep will be performed where the CCU will determine if the users hand is in the correct position and then based off position will send a message to the speaker system to direct the user to move the glove until they reach the correct position. Then the CCU will check if the user is the correct distance to the ball using the ultrasonic sensor on the glove. Once they are the correct distance and the cue stick and glove are aligned then the CCU will send a message to tell the user to take a shot.

C. Cue Stick Finite State Machine

The cue stick state machine is used to help with determining where the user is in the process of taking a shot. This is necessary due to the camera needing a signal to determine when to take a picture to get an accurate placement of where on the ball the user is aiming. So in this state machine there are five different states, state 0: NOT_READY, this is where the stick is stationary and the user is not ready, State 1: READY, this is where stick is stationary but the user is not ready to take a shot, State 2: WAITING, this is where stick is stationary and user is ready to take a shot, State 3: TAKING_SHOT, stick is not stationary and user is taking shot, State 4: SHOT_TAKEN, stick is stationary and user is done taking shot.

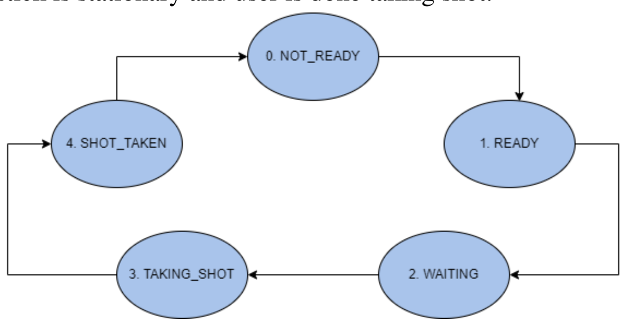

Fig. 12. Cue Stick Finite State Machine

Using this state machine we are able to perform certain tasks at specific times in the user shot process, this helps with knowing when to pull specific information from the sensors or send crucial data to the CCU.

IV. Testing

Each subsystem had to undergo some form of testing in order to achieve desired functionality. Some of the key tests will be discussed below.

A. Ball Speed Correlation

To achieve an accurate relationship with the acceleration of the cue stick to the speed of the ball we took a large sample of test shots where we measured the deceleration cue stick IMU and then measured the speed of the ball directly after being hit. We then take this data and plot the cue stick deceleration vs the ball speed and take a line of best fit.

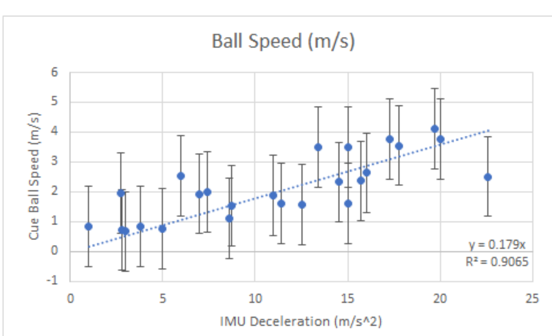

Fig. 13. IMU Data Accuracy Plot

This data will then be correlated to five different levels of speed that will be displayed on the HUD to tell the user.

To collect this data we took the peak deceleration values to know how fast the cue stick is moving. This is shown in the plot below but when collecting acceleration data we had the ESP32 print the peak acceleration values on the screen so we could correlate these values to the speed of the ball after contact.

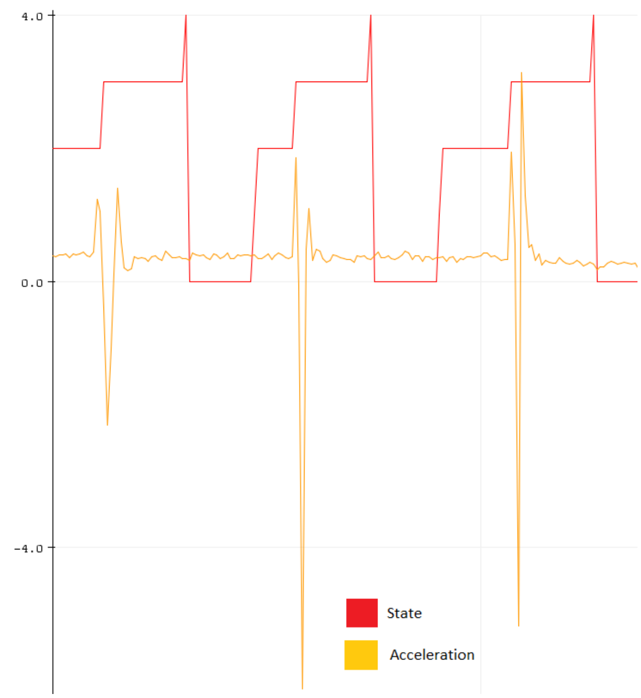

Fig. 14. Acceleration Plot

B. IMU Angle Testing

Since both the glove and cue stick subsystems utilize the BNO055 inertial measurement unit we had to perform some tests to show that the desired angle can be matched within our specifications of an error of less than 3 degrees. On the sensor we use a I2C burst of six registers to obtain our raw data that we can then use to calculate the desired values. When performing this testing we would simply pick an angle on a protractor and move the IMU to match that position, then we were able to see the difference between the angles. For a majority of tests this error value was below 2 degrees.

C. Feedback Speed Test

One of our key specifications is being able to provide feedback to the non impaired player within 8 seconds after the shot has been completed. There are two types of feedback that we supply to the user, point of contact and the power of the shot. To provide point of contact we use the camera on the HUD to take a picture and send the data via BLE to the CCU to then be processed and find the location of the shot. The power is determined by the IMU on the stick and the line of best fit discussed above. We tested this originally by just testing the point of contact timing due to this process taking significantly longer than the power due to the size of the files that had to be sent via BLE. Originally this took longer than the specified time but this process was able to be sped up by sending larger packets at a time and changing the connection parameters. Now this feedback is received in about 6 seconds in total from contact.

D. Audio Feedback Test

The last key specification is to provide audio feedback based on position in less than two seconds. This specification involves guiding the user to the correct angle via the speakers located on the HUD, this was tested by simply sampling the angle on the glove and choosing the correct audio to supply based on that angle. This audio is able to be supplied in the time specified above.

VII. Conclusion

All of the subsystems, programming, and integration testing shown above comes together to create the entire Shot Consultation Refinement Through Accurate Computer Hardware system. With this system, both impaired and unimpaired individuals can come together and enjoy the great game of billiards at a higher level through both the refinement of their play, to an introduction to a sport never before imagined as an activity to enjoy.

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Biography

Mark Nelson is a senior electrical engineering student on the RF and Microwaves track. While in college, he has held multiple industry internships ranging from a mechanical engineer at a local cable assembly manufacturer, a systems engineer at Peraton, and a systems engineer at Lockheed Martin. After graduation, Mark will return to Peraton to work as a Systems Engineer on satellite ground terminals.

Goran Lalich is a senior graduating with his bachelor's degree in Electrical Engineering. During his UCF career he has had Internships with both Lockheed Martin and Texas Instruments and upon graduation Goran has accepted a full-time offer to join L3Harris's digital CCA design team for the space and airborne system division.

Luke Ambray is a senior graduating with his bachelor's degree in Computer Engineering. He is currently a CWEP at Lockheed Martin MFC as an HWIL Engineer. Luke has accepted an offer to return to Lockheed Martin as a full-time GNC Associate Engineer and plans to pursue a master's degree in Computer Engineering at UCF.

Mena Mishriky is a senior graduating with a BS in Electrical Engineering and a minor in Computer Science. Throughout his time at UCF, he has interned at Apple, AMD and Texas Instruments. He has also had multiple TA and lab assistant positions with the Department of ECE, and was nominated for the Order of Pegasus Award. After Graduation, Mena hopes to continue his Masters degree here at UCF, and then launch his career in the chip design and verification industry.