Component Analysis

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1.0 Component Analysis

The Smart Air Hockey Table (SAHT) is designed with six major components, each essential to its proper function. At its core, the microcontroller serves as the brain, interpreting and processing all data to ensure seamless gameplay. Elevating the gaming experience, a large grid of individually controlled LEDs rests beneath the playing surface, casting a vibrant under-glow and dynamic graphics, including a lit trail tracing the puck’s movement. Players can effortlessly monitor the game’s progress using score tracking displays, two dedicated OLED screens that present to each player real-time scores. To draw dynamic graphics that follow the puck, puck tracking employs hall effect sensors to pinpoint the puck’s location on the table. Validity in scoring is ensured by goal detection which utilizes photoresistors; these sensors detect a goal by identifying interruptions in a light source. Lastly, the power delivery component ensures that each component of the SAHT receives the necessary power required for operation.

1.1 Analysis of Microcontroller

While the team has some individual experience using different microcontroller brands, such as Microchip Technology and NXP Semiconductors, STMicroelectronics was the only brand that all team members had experience with. The team unanimously agreed that the team's familiarity and experience with STMicroelectronics would be greater than any potential benefit of using a different microcontroller brand, especially given the time constraints of the project. Therefore, the Smart Air Hockey Table will use an STM32.

STM32 offers a wide variety of microcontroller families broadly categorized into high performance, mainstream, ultra-low-power, and wireless, as shown in figure 1. The Smart Air Hockey Table does not require any wireless functionality, so the wireless family was excluded from the search. The project's firmware utilizes a super-loop architecture that is invoked by a one millisecond timer. Therefore, the microcontroller's processing speed is a key factor. The project will require enough RAM to store graphical data for the LEDs and a significant amount of non-volatile data for storing animation frames. The project did not require any special peripherals that would exclude any microcontroller families. Given these requirements, the team focused on the STM32F4, STM32H7, and STM32U5 families. The STM32H7 family offers the potential for the highest processing speed, but STM32U5 offers the highest possible Flash memory. The STM32F4 family is largely similar to STM32U5 with additional peripherals. The team's estimates showed that the processing speed of families would be sufficient. Thus, the STM32H7 family was removed due to its high price, given that its high processing speed was not required. Similarly, the greater number of peripherals provided by the STM32F4 family is not required and it was thus removed. Therefore, the STM32U5 family was selected. The team hopes to utilize the family's low-power capabilities to lessen the project's environmental impact.

 

*Figure 1: Microcontroller families offered by STMicroelectronics*

Once the team decided on the best potential STM32 families, the team then chose a product from each family to further investigate. The team chose to consider the STM32U585VIT6, STM32F446RET6 and STM32H743IIT6. The most pertinent characteristics of each microcontroller are listed in figure 2 below, alongside the STM32U545VET6Q. The Smart Air Hockey Table’s firmware relies on a super-loop architecture where each iteration of the super-loop occurs every millisecond. Thus, the microcontroller’s operating frequency is very important. To maximize the efficiency of the DMA used for controlling the LED matrix, it is ideal if the operating frequency is divisible by 80. STM32H743IIT6All satisfies this factor, and it has the greatest operating frequency of the examined microcontrollers. Therefore, it is the best choice in this category. All examined microcontrollers are available in a 100-pin, low-profile quad flat package. The Smart Air Hockey Table design requires 73 GPIO pins which all microcontrollers satisfy. The Smart Air Hockey Table requires two DMA controllers, one for outputting data to the LED matrix and one for loading data from the external EEPROM into flash. The STM32F446RET6 fails this criterion as it only contains one DMA controller. The Smart Air Hockey Table also requires two SPI controllers, one for communicating with the OLED displays and one for communicating with the external EEPROM. All the examined microcontrollers satisfy this criterion. Since the STM32U585VIT6 and STM32H743IIT6 have passed all criteria examined so far, the decision was reduced to determining whether the STM32H743IIT6’s greater price was worth the greater operating frequency. The team is convinced that the operating frequency of the STM32U585VIT6 is sufficient for this project. Therefore, the Smart Air Hockey Table will utilize the STM32U585VIT6. Furthermore, STMicroelectronics boasts that many microcontrollers within the same family are compatible given the same package. The team has identified that the STM32U545VET6Q is a cheaper microcontroller than the STM32U585VIT6 that only compromises on the size of its RAM and flash. Thus, if the additional RAM and flash provided by the STM32U585VIT6 are not utilized by the Smart Air Hockey Table’s final firmware revision, then the STM32U545VET6Q can alternatively be used to reduce cost.

|  | Microcontroller |
| --- | --- |
| Property | STM32U545VET6Q | STM32U585VIT6 | STM32F446RET6 | STM32H743IIT6 |
| Single Unit Cost\* | $8.12 | $10.74 | $11.47 | $19.08 |
| Current Stock\* | 150 | 289 | 11850 | 228 |
| Operating Frequency (MHz) | 160 | 160 | 180 | 480 |
| Flash Size (kB) | 512 | 2048 | 512 | 2048\*\* |
| RAM Size (kB) | 274 | 786 | 128 | 1024 |
| Total I/Os | 83 | 83 | 114 | 114 |
| DMA Controller Count | 2 | 2 | 1 | 4 |
| SPI Count | 3 | 3 | 3 | 6 |
| Supply Voltage Min - Max (V) | 1.71 - 3.6 | 1.71 - 3.6 | 1.8 - 3.6 | 1.62 - 3.6 |

*\* Cost and stock count from DigiKey as of 9-16-2023 [9][10][11][12]*

*\*\* Dual-bank Flash
Figure 2: Comparison of STM32 microcontrollers investigated by the team [1][2][3][4]*

1.2 Analysis of Matrix of Individually Controlled LEDs

As the most visually significant portion of the SAHT, the LED matrix requires us to carefully consider all available options with any potential tradeoffs in mind. In brief, the LED matrix must be able to achieve the following:

1. Individual control of every LED by the primary microcontroller
2. Update RGB color with low latency (50 ms maximum) to maintain synchronization with ongoing gameplay
3. Able to be placed in groups of four across a grid of interconnected PCBs (daughterboards)

During our initial evaluation of possible options that meet these requirements, we considered two major alternatives. The first option was to mount individual RGB LEDs on each daughterboard and multiplex the output of the primary microcontroller to drive each one separately. The concern with this intent is lacking enough IO pins on the microcontroller to drive 512 LEDs simultaneously. Additionally, multiplexing from one source to 512 individual components would become a major technical hurdle as those components could be more than a meter away from each other. To remedy this, we had planned on placing lower-powered microcontrollers (so-called row masters) at the head of each row of PCBs, so that each one would have enough IO to control their respective row of LEDs. The primary microcontroller would then communicate to each of these row masters the current state of their respective LEDs.

Although the first option would be technically possible, it still represents a major design challenge and would be relatively inefficient in terms of power and materials cost. Fortunately, individually addressable LED lighting exists as a self-contained solution already on the market. WS2812 [5] (and other closely related specifications) are a specification for individually controlling an arbitrary number of RGB LEDs through a singular serial data line. Each LED has an embedded microcontroller that repeats the received signal to the next, while subtracting the part of the data associated with itself. Utilizing this technology reduces the number of microcontroller IO pins required to drive the matrix down to just one. As a result of this approach, the previously mentioned row master microcontrollers are no longer necessary.

The table shown below presents a list of factors that differentiate these two designs.

| **Trait** | **Row Master & Multiplex** | **WS2812** |
| --- | --- | --- |
| IO Pins Required | 8 to 16 on primary controller | 1 on primary controller |
| Materials Required | Row master microcontrollers + 512 standalone LED modules | 512 WS2812 (or similar) LED modules |
| Comparative Materials Cost | Greater | Lower |
| Comparative Design Complexity | Greater, synchronizing communication between several microcontrollers and multiplexing their individual LED rows | Minimal, all LEDs are continuous strand with 3 conductors between them |

*Figure 3: Comparison between approaches for constructing and driving LED matrix*

Due to the overwhelming number of factors favoring WS2812 LED integration, we have chosen to proceed with this approach in our design.

1.3 Analysis of Score Tracking Displays

As gameplay proceeds and goals are scored by each player, an important aspect of player experience will be keeping track of the game’s score. To facilitate this, we will embed two small displays within each player’s vicinity to provide a readout of the current score. Although the opportunity exists to rely on the LED matrix to display score to the players, this method would reduce the usable display area of the matrix, and not maintain the level of clarity we are targeting. The display options we considered are compared in the following table.

| **Trait** | **Adafruit OLED [6]** | **SSD1309 OLED [7]** | **Lab Kit OLED [8]** |
| --- | --- | --- | --- |
| Display Type | Full Pixel | Full Pixel | Character |
| Panel Technology | Monochrome OLED | Monochrome OLED | Monochrome OLED |
| Display Size | 2.20" x 1.14" | 2.8” x 1.71” | 2.24" x 0.47" |
| Pixel Resolution | 128 x 64 | 128 x 64 | 80 x 16 |
| Communication Protocol | SPI, I2C | SPI, I2C | SPI |
| Operating Voltage | 3.3 V | 3.3-5 V | 5 V |
| Familiarity | None | None | Intermediate |
| Cost | $80 total | $30 total | Free |

*Figure 4: Comparison between options for a score-keeping display*

After considering the alternatives showcased above, we made the choice to utilize the SSD1309 OLED for our score tracking displays. There are some immediate positives to making this choice, such as flexible supply voltage, full pixel manipulation, and low cost. Additionally, the display size is adequate for the purpose of score tracking. The Lab Kit OLED suffers from drawbacks such as low resolution, character display only, and operating voltage differing from that of our microcontroller. The score keeping display needs to clearly show large figures to accomplish its required function, and the increased contrast from employing an OLED display will increase visual clarity during gameplay.

1.4 Analysis of Puck Tracking Sensors

To facilitate dynamic graphics that adapt in real-time based on the puck’s position, the SAHT requires a system that can pinpoint the puck’s location on the playing surface both precisely and swiftly. The team explored three primary approaches for this task:

1. Embedding an inertial measuring unit (IMU) within the puck.
2. Employing a high-speed camera to monitor the puck.
3. Integrating a matrix of Hall effect sensors beneath the playing surface.

Figure 5, presented below, offers a comparative analysis of these strategies.

| Method | Advantages | Disadvantages |
| --- | --- | --- |
| IMU embedded inside puck | Direct tracking from the puck | Complexity, IMU errors, requires embedding a computer in the puck that can send position information to an external computer |
| Using a camera | Can potentially track multiple objects, common method for object tracking, simple to install | Requires more powerful external computing in order for it to be performant, weird edge cases |
| Grid of Hall effect sensors | Could integrate with the daughter boards that will hold the RGB LEDs, could use a basic algorithm that is performant | Requires meticulous placement of all sensors, potential interference from other components |

*Figure 5: Comparison of approaches to tracking a puck on the playing surface.*

Upon assessing the above, it becomes clear that the grid of Hall effect sensors positioned under the playing surface stands out as the most viable option, given the project’s timeline and current specifications and objectives.

**1.4.1 Hall Effect Sensors**

The choice of the precise Hall effect sensor type to incorporate within the grid required careful deliberation. Initial consideration leaned towards analog sensors. However, the complexities associated with translating the analog output to a digital format – specifically, the necessity for two comparator circuits for each sensor – steered the decision towards digital Hall effect sensors. In this realm, two variants emerged as frontrunners:

1. *Hall effect latch*: Capable of detecting both the north and south magnetic poles, it offers an interrupted detection spectrum.
2. *Omnipolar Hall effect switch*: The switch is triggered by the presence of either magnetic pole.

The decision was to go with an omnipolar hall effect switch since it will simplify the design as it does not require a specific magnet pole orientation. Given the dynamics of air hockey, where the puck can flip and spin in unpredictable ways, using an omnipolar sensor ensures consistent and reliable tracking irrespective of the magnet’s orientation within the puck. Another determination had to be made as well regarding the output configuration:

* *Push-pull*: This configuration can drive the output both high and low. It offers faster response times and can be directly interfaced with microcontrollers without needing an external pull-up resistor.
* *Open-drain*: This variant solely drives the output to a low state and relies on an external pull-up resistor to realize a high state.

The team preferred the push-pull configuration for its direct interfacing capabilities and rapid response times, key for real-time puck tracking in a fast-paced game like air hockey. The current choice of Hall effect switch is the DRV5033 by Texas Instruments [13]. A comparison of hall effect sensors using different output configurations can be seen in Figure 6.

| **Trait** | **DRV5033 [13]** | **DRV5053 [14]** | **TMAG5231 [15]** |
| --- | --- | --- | --- |
| Input voltage | 2.5-38 V | 2.5-38 V | 1.65-5.5 V |
| Output configuration | Open-drain | Analog | Push-pull |
| Update frequency | 30 KHz | 20 KHz | 20-216 Hz |
| Cost | $0.44 | $0.46 | $0.21 |

Figure 6: Power supply comparison

1.5 Analysis of Goal Detection Sensors

The project's goal detection requires that each goal contains a switch that is activated when the puck passes through. The team identified three potential sensors to create this switch. First, the team considered a mechanical switch using a pushbutton as a sensor. The mechanical switch would be activated when the puck passes over a hinged ramp that presses the pushbutton. If the pushbutton's sensitivity is well calibrated, this method is extremely accurate. However, this method is contingent on the mechanical design of the goal, which the team felt unconfident they would be able to optimize. Thus, the team instead considered creating a switch activated by a photoresistor or an infrared receiver. The photoresistor and infrared receiver based switches work similarly. After passing through the goal, a chute slightly larger than the dimensions of the puck will funnel the puck into a single location. The chute will contain the appropriate light emitter pointing at the sensor. The puck blocking the sensor from the light source as it passes through the chute activates the switch. The infrared receiver's main benefit over the photoresistor is that it eliminates the potential for ambient light to affect the accuracy of the goal detection. However, the design of the chute implicitly blocks ambient light from affecting the sensor. Photoresistors tend to be cheaper than infrared receivers and, since the light source can be seen, easier to design. Thus, the team decided to use a photoresistor as the goal detection sensor.

1.6 Analysis of Power Delivery

The project’s power delivery will come from multiple components for the various peripherals and devices integrated within it. The primary power source will be from a standard 120 VAC wall outlet. This will be used to power the air hockey fan blower through a microcontroller-controlled relay. However, for all other components, DC supplies are necessary.

For the LEDs, hall effect sensors, and digital logic gates, a 5 VDC supply is needed. Instead of engineering a rectifier circuit, the team decided to buy a pre-built power supply to avoid electrical hazards. They compared a few options, including exposed-PCB converters, enclosed units, and solderable modules with everything enclosed. A comparison of some of the options considered is seen in Figure 7.

| **Trait** | **Aclorol PSU [16]** | **IRM-60-5 [17]** | **Phone Charger** |
| --- | --- | --- | --- |
| Input voltage | 110/220VAC | 85-264VAC | 110VAC |
| Output voltage | 5V | 5V | 5V |
| Output current (max) | 70A | 10A | 3A |
| Connection type | Screw terminal | THT | Soldered USB cable |
| Enclosed unit? | Yes | Yes | Yes |
| Cost | ~$35 | ~$20 | Free |

Figure 7: Power supply comparison

After evaluating these options, the team decided to buy the Aclorol PSU. Although not from a well-known manufacturer, it is the only option that satisfies the power requirements in a safe enclosure. Additionally, numerous reviews and safety features such as a grounded chassis and integrated cooling fan ensure safe operation.

In addition to the 5V supply, our microcontroller also needs a 3.3V supply. To achieve this, the team will integrate a buck converter IC onto their primary PCB, stepping a 5V input to the desired 3.3V output. Again, the team considered multiple buck converter ICs based on their needs. This part evaluation can be seen in Figure 8.

| **Trait** | **TLV62568 [18]** | **TPS562201 [19]** | **TPS563208 [20]** |
| --- | --- | --- | --- |
| Input voltage | 2.5-5.5V | 4.5-17V | 4.5-17V |
| Output voltage | 0.6V-Vin | 0.76-7V | 0.76-7V |
| Output current (max) | 1A | 2A | 3A |
| Package | SOT-23 | SOT-23 | SOT-23 |
| Cost | $0.38 | $0.39 | $0.41 |

Figure 8: Buck converter IC comparison

After considering these ICs, the team decided on the TLV62568, since they did not need the higher current capabilities. Additionally, this IC requires fewer external passive components to work effectively, according to its datasheet [21]. The 3.3V output from this buck converter will only be used to power the microcontroller.

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