Component Analysis

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1.0 Component Analysis:

The main components of the Air-Hockey Robot project include the microcontroller, the camera, the 7-segment display, and the motors and motor drivers. The microcontroller’s role in this project is to (1) control the output of the 7-segment display and (2) interpret data from the camera and leverage that data to control the motor drivers and motors. The camera is to be used in capturing images of an air hockey puck in motion. The 7-segment display is to be used in logging the score of the game to the end user. Finally, the motors and motor drivers are to be used in moving the robot’s paddle in a defensive position to block and return the moving puck.

1.1 Analysis of Component 1: Microcontroller

When identifying a microcontroller suitable for the Air Hockey Robot project, the team considered three options: the STM32F091RCT6 [1], the Teensy 3.0 [2], and the ESP32-S3-Wroom [3]. These microcontrollers were chosen as potential candidates given their specifications and reputations as high-performance microcontrollers commonly used in industry. To decide between these microcontrollers, several specifications were considered. These features can be seen in Figure 1 below. Ultimately, the price, core processor, memory capacity, and number of UART channels compatible with DMA led the team to proceed with the STM32F091RCT6 as the microcontroller of choice for this project.

To begin with, the core processor of each microcontroller was considered. While the STM32F091x and the Teensy 3.0 both use ARM Cortex processors, the ESP32 uses the Xtensa LX7 processor. Because the team has experience working with the ARM cortex series, the ARM Cortex core was prioritized over the Xtensa LX7 core. Additionally, the ARM Cortex clock speed of 48 MHz was determined to be sufficient for this project; any core with higher clock speed would be unnecessary and lead to greater power consumption.

When looking at memory, non-volatile and high capacity memories were desired. While all three considered microcontrollers offer access to non-volatile flash memory, the STM32F091x offers the greatest memory capacity with 256 Kbytes. This specification was prioritized over the 16 Kbytes offered by the ESP32 and the 128 Kbytes offered by the Teensy 3.0.

The number of built in timers was also considered when identifying a microcontroller for this project. While the exact number of timers needed for this project wasn’t known at the beginning of the project, it was recognized that the STM32 and the Teensy 3.0 outperform the ESP32 in terms of built-in timers. These microcontrollers offer 12 and 11 timers respectively, which satisfied the needs for this project.

Prior to identifying which interfaces would be used to communicate between the PC and the microcontroller, wifi was considered. This led the ESP32 to be one of the team’s top three choices given its built-in wifi module and known reputation for IoT applications. In the end, the team chose to establish communication between the PC and the microcontroller over UART in contrast to wifi for stability and speed. This further enforced interest in the STM32F091x microcontroller, as it has 8 UART channels in contrast to the 3 UART channels possessed by the ESP32 and the Teensy 3.0. This allows the team greater freedom when interfacing with components.

Direct memory access was an additional important specification for this project. This project warrants an extensive amount of data being received by the microcontroller at high speeds. To ensure that this data is stored effectively, the team plans to use UART with DMA to store the data so that it can be used to influence the motion of the motors. It was identified that the STM32F091x offers 12 DMA channels in contrast to the 2 DMA channels offered by the ESP32 and the 4 DMA channels offered by the Teensy 3.0.

Finally, the price of each microcontroller was considered. Without price considered, the STMF091x and Teensy 3.0 were favorable over the ESP32 for their high-performance specifications and interfaces. Upon considering the price of these microcontrollers, the STM32F091x was chosen as it is only 1/3rd of the price of the Teensy 3.0 and offers greater features and flash memory capacity. The team’s experience with this microcontroller and compatible IDEs further validated this choice [4].

*Figure 1: Analysis of Microcontroller Specifications*

| *Feature* | **STM32F091RCT6 [1]** | Teensy 3.0 [2] | ESP32-S3-Wroom [3] |
| --- | --- | --- | --- |
| Core | ARM Cortex M0 | ARM Cortex M4 | Xtensa LX7 |
| Max. Clock Speed | 48 MHz | 48 MHz | 240 MHz |
| Flash Memory | 256 Kbytes | 128 Kbytes | 16 Kbytes |
| # Built-in Timers | 12 | 11 | 4 |
| # UART channels | 8 | 3 | 3 |
| # DMA Channels | 12 | 4 | 2 |
| Price | $5.36 | $19.00 | $3.90 |

1.2 Analysis of Component 2: Camera

In order for the air hockey playing robot to perform at its full potential, a proper camera must be chosen. The camera is the component that will be outputting the video frames that contain information about puck and mallet location. The three sensors being compared in this section are the *ELP High Speed Wide Angle Global Shutter USB Camera* [5], the *OptiTrack Flex 3* [6], and the *Raspberry Pi Camera Module 3* [7]. The main characteristics to consider include framerate, latency, and cost.

The framerate is an important specification to evaluate because of the specific application in this project. The table needs to be captured at a frequency high enough to determine the movement of the puck before it reaches the opposite side of the table. A low framerate would make calculations difficult because of the seemingly random movement of the puck. The *ELP* camera has a framerate of 90 frames per second, the *Flex 3* has a framerate of 100 frames per second, and the *Raspberry Pi Camera* has a maximum frame rate of 120 frames per second. Purely based on framerate, the *Raspberry Pi Camera* is the optimal choice.

The next characteristic to evaluate is the latency. This is an integral piece of the camera for this usage case because the entire focus is on timing. If the camera cannot get the image to software fast enough, the puck will be in a completely different location than it was in that picture. The latency needs to be as low as possible to ensure that the data being processed is not outdated. The latency of the *ELP* camera is 60 milliseconds on average. The *Flex 3* outperforms the *ELP* in this category with a latency of 10 milliseconds. The *Raspberry Pi Camera* does not compete with the other two options because of its 200 millisecond latency. The *Flex 3* is the optimal choice for this category.

Cost is the final main factor to consider when looking at these cameras. With a budget of $425, it is important to buy components that will fulfill the minimum requirements and do not provide any unnecessary functionality that would go unused and drive up the price. The *ELP* camera is priced at $80 on Amazon, the *Flex 3* is priced at $659 on the *OptiTrack* website, and the *Raspberry Pi Camera Module 3* is priced at $25.

Although the *ELP* camera did not outperform all options in any one category, it was still chosen to be the camera for this project. The reasoning behind this decision comes down to the ratio of latency to cost. The team decided it was not worth the extra $579 to decrease the latency down from 60 milliseconds to 10 milliseconds between the *ELP* camera and the *Flex 3*. The *ELP* Camera is also able to shoot at 90 frames per second, which is enough for puck tracking. It also has a global shutter, which is important for eliminating blur on moving objects. The *ELP* Camera is a solid choice in every category, which makes it the best choice for this project. Shown below is a table indicating the differences between the 3 options considered for the camera.

*Figure 2: Analysis of Camera Options*

| *Feature* | *ELP Camera* | *OptiTrack Flex 3* | *Raspberry Pi Camera Module 3* |
| --- | --- | --- | --- |
| Framerate | 90 fps | 100 fps | 120 fps |
| Latency | 60 ms | 10 ms | 200 ms |
| Price | $80 | $659 | $25 |
| Resolution | 1920x1080 pixels | 640x480 pixels | 1536x864 pixels |
| Connection | USB 2.0 | USB 2.0 | FPC Connector |
| Global Shutter? | Yes | Yes | Yes |

1.3 Analysis of Component 3: 7-Segment Display

*Figure 3: Analysis of 7-Segment Displays*

| [8] | Size: 19.00mm x 12.60mm x 8.00mm  Common Pin: Common Anode  Voltage forward: 2V  Current: test 20mA  Cost: $1.12 (free because it is already acquired) | This is the 7-segment display that is being used in the scoreboard’s pre-existing PCB. It already works with the scoreboard and provides a bright enough display. This display is also larger, making it easier to see. |
| --- | --- | --- |
| [9] | Size: 15.00mm x 9.20mm x 3.15mm  Common Pin: Common Cathode  Voltage forward: 2V  Current: test 20mA  Cost: $1.84 | This 7-segment display is a good alternative despite the smaller size, and has similar power requirements. However, there is very little reason to use this or any other 7-segment display when the first 7-segment display already works. |

Ultimately, what 7-segment display is used will be determined by whether the scoreboard’s PCB is reused. Since the PCB will be reused, the first 7-segment display is the obvious choice. It already works with the rest of the board and comes with no additional cost. There is no risk of messing up the board and no time needs to be taken to implement it.

1.4 Analysis of Component 4: Motors / Motor Controller Module

As steppers strike the balance of precision, speed, and controllability, we chose to go with stepper motors to drive the gantry system. This decision is further supported by nearly all CNC mills using stepper motors (which our gantry system essentially is).

As for why we chose a NEMA 23 type stepper motor over other NEMA values, this was dictated by the potential required torque for the gantry system. For a hopeful maximum acceleration of 20m/s^2, assuming an effective acceleration mass of 2.26kg (5lbs), we need a maximum force of 45.35N. For a pulley shaft diameter of 1 cm, this requires a torque of ~.45Nm. The NEMA 23 overshoots this metric but gives us ample tolerance in the event of higher effective acceleration mass, larger pulleys, or limited maximum drive current (dictated by the power supply).

For the motor drivers (as this section is dedicated to both the motors and the drivers), we have chosen to go with the manufacturer recommended drivers as we can be certain the two will work effectively together.

*Figure 4: Analysis of Motors*

| Motors | | |
| --- | --- | --- |
| Component | Description | Analysis |
| NEMA 23 Stepper Motor [10] | This bipolar Nema 23 stepper motor has 1.8 deg. step (steps/revolution).  Key Specs:  Each phase draws 2.8A, allowing for a holding torque of 1.9Nm(269oz.in).  Max voltage 48V  Cost: $29.99 | Stepper motors provide accurate motion without sacrificing much speed or power efficiency. The NEMA 23 specifically provides ample torque at a price easily doable for our project. The one downside is that individual phases must be driven separately at high voltages with pulses rather than other motor types which are easily controlled or have dedicated control logic. |
| Brushless 3 phase DC motor. [11] | Brushless 3 phase DC motor. 5200KV 3.175mm Shaft “High Speed Waterproof Motor”  Key Specs:  Watts: 900W  Max voltage: 9.6V  Max Amps: 94A  KV(RPM/Volt): 5900KV  Max RPM: 50000  Cost: $29.98 | DC motors provide very high speeds at reasonable wattages. For our application, a brushless DC motor would probably not have been accurate enough to effectively control XY motion. At a roughly $30 price point, most brushless DC motors do not come with hall effect sensors, meaning all motion correctio would need to be done in software. For our application, we need a motor capable of providing near-exact motion without the need for constant correction [13].  Additionally, DC motors require an ESC unit typically priced above drivers for other motor types. |
| Synchronous Gear AC [12] | 60RPM Reducer Motor Dual Bearing Synchronous Gear AC  Key Specs:  (1) Rated voltage: AC 115Volts  (2) Operating frequency: 60Hz  (3) Output shaft speed: 60rpm/min  (4) Rated power: 10 Watts  (5) No-load current: ≤90mA | AC motors are simply the worst type of motor for this application. These are designed to be cheap, slow, and relatively low torque motors designed for constant, mono-directional movement [14]. Needless to say, none of those criterions fit our project. |

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