3. DESIGN APPROACH

Free Wheelie is intended to provide increased mobility to manual wheelchair users at a low cost. This device is a kit that is easily attached to a standard manual wheelchair and gives it the functions of an electric wheelchair. During early project development, several requirements, constraints, and standards were identified that needed to be congruent with the design. The three chief requirements are battery life, weight capacity, and ergonomic controls. Of the constraints, the most crucial are the budget of $1000, the two-semester design period, and the size of the kit.

Multiple solutions were considered in the early stages of design for Free Wheelie. The final solution is a kit that includes a controls and user interface subsystem, an adjustable arm subsystem, and a motorized wheel subsystem. The control panel includes controls and a touch screen that allow the user to move the electronic arm to deploy the electronic wheel, which will provide enough power to transport users not exceeding 350 lbs. These components convert a manual wheelchair into one with electric capabilities, allowing the user the flexibility to switch between manual and powered control. The following subsections cover the overall design choices that were made during the development of Free Wheelie and how the device meets the set requirements.

3.1. Design Options

Multiple solutions for Free Wheelie were considered during the preliminary research phase of design. Determining the most effective course to implement the kit led to many changes when trying to finalize the design that would most efficiently meet all the requirements set for the project. When considering the electronic wheel subsystem, the focus of the subsystem was to ensure that the system is capable of handling the propulsion of the chair when in use by a person not exceeding 350 pounds. Regarding the adjustable arm subsystem, the core problem that needed to be addressed was the smooth deployment of the wheel and the strength to retract the wheel when not in use by the customer. The design of the control subsystem went through multiple phases to reach a point that would lead to the most ergonomic design for seamless form for the user. After team discussion and brainstorming, two main designs emerged that meet most of the requirements set forth by the team. These two designs are further explored in the following sections.

3.1.1. Design Option 1

Option 1 considered during the prototyping for the wheelchair conversion kit involved a two-wheel design that utilized the main wheels to control both the direction and movement of the chair. This design focused on simplifying the control mechanism by integrating the steering and propulsion into one single system. Additionally, this design included two mechanical arms (one for each wheel) beneath the wheelchair that deployed to lower the wheels to the ground. This would make the electronic propulsion system stable by dividing the required force between two wheels. However, this option was deemed less viable, as placing the wheels at the center of mass would require both pulling and pushing forces, along with additional motorized components that would further drain the battery.

3.1.2. Design Option 2

Option 2 considered during the prototyping for the wheelchair conversion kit involves a one-wheel assembly coupled to a stepper motor. The wheel itself is electronically powered and controls the forward and backward motion, while the stepper motor couples to a wheel fork to turn the wheel. This approach was most effective for reducing the overall weight and minimizing the complexity of turning and propelling the wheel system, making it the best choice to achieve Free Wheelie's design requirements.

3.2. System Overview

At a basic level, Free Wheelie, when powered on, takes an input from the user on the action they want the device to perform, and the device in turn processes the user input to perform those actions. Figure 3-1 shows a simple black box diagram of how the device functions. The major inputs involve power supplied by a 21 V battery and user inputs. The output of the device includes control of the speed and direction of the wheelchair and deployment of the wheel arm up or down.

Fig. 3-1: Basic System Overview for Free Wheelie (Level 0)

Figure 3-2 shows a more detailed overview of the Free Wheelie. The different subsystems are closely analyzed and graphically expanded to show their relation to the inputs and outputs and the microcontroller.

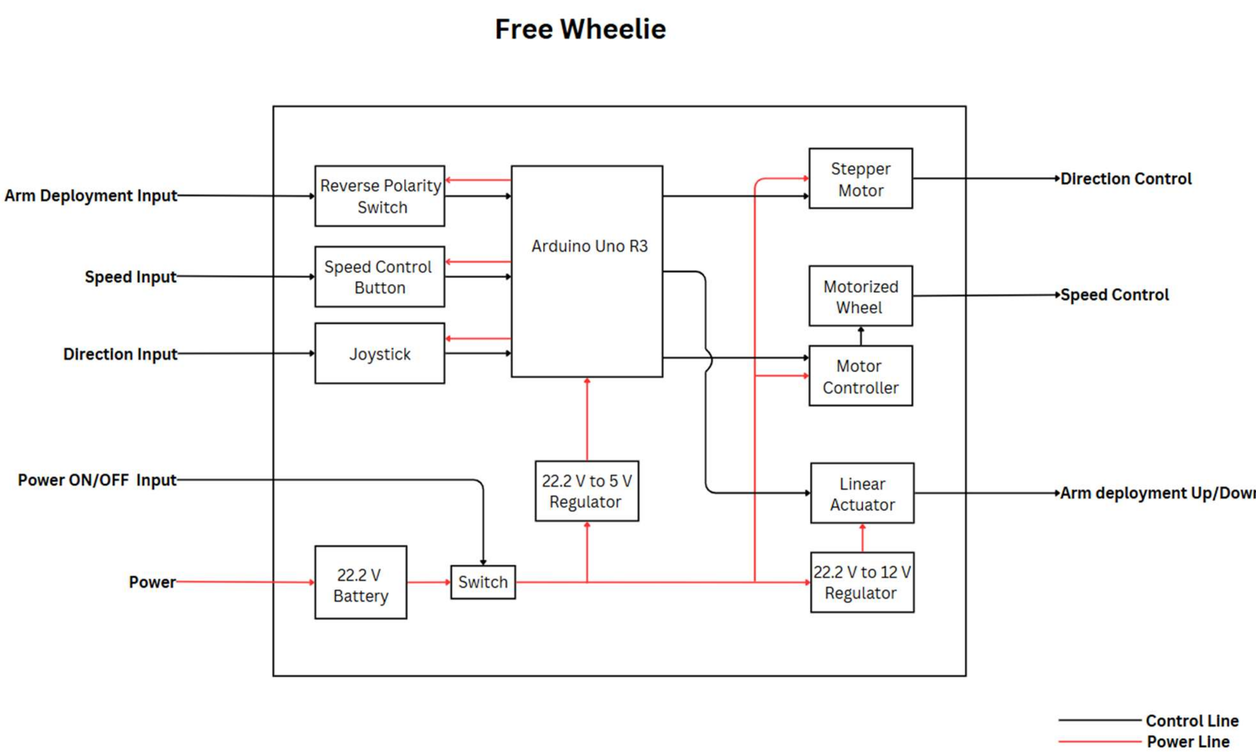

Fig. 3-2: Free Wheelie Functionality (Level 1)

Free Wheelie operates entirely based on user input. Once powered on, the microcontroller processes these inputs and controls various output mechanisms and devices accordingly. The entire system is powered by a battery, which only delivers power when the system is active.

3.2.1. Microcontroller

For Free Wheelie, several microcontrollers were considered to meet the product's functional demands. Table 3-1 shows the different microcontrollers that were compared based on their technical and financial aspects to ensure they would be a good fit for the product's needs.

Table 3-1: Microcontroller Options

Microcontroller	Programming Language	I/O pins	PWM	Price	Power Consumption
Required	High Level Language	> 5 analog, 10 digital	Yes	< $50 USD	Minimal
Arduino Uno Rev3 [1]	C/C++ (Arduino IDE)	6 analog, 14 digital	Yes	~$28 USD	25-50 mA (Idle: 25mA)
Raspberry Pi 4 Model B (4GB) [2]	Python, C/C++, many others	40 GPIO pins (digital only)	Yes	~$63 USD	400-500 mA (Idle: 400 mA)
ESP32 DevKitC [3]	C/C++ MicroPython	12 analog, 30 digital	Yes	~$9 USD	160-250 mA (Idle: 20-30 mA)

Arduino Uno Rev3 was decided among all the options as the best fit for the complexity of the product. Its low power consumption along with sufficient technical features for our product needs were key factors in making the decision. Figure 3-3 illustrates the selected microcontroller.

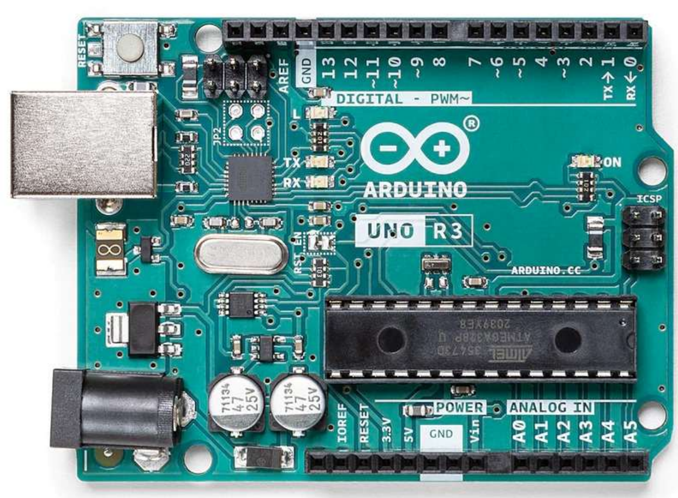

Fig 3-3: Arduino Uno Rev3 Microcontroller [1]

The Arduino Uno Rev3 was chosen for this project primarily because of its low power consumption compared to other options on the market. With typical consumption ranging from 25 to 50 mA during normal operation, it provides an efficient solution for our battery-operated, standalone product without concerns about excessive battery drain. Since our product aims to maximize battery life for the user, minimizing energy consumption through thoughtful component selection was a key priority. The 5V power output from the Arduino Uno is sufficient to operate the sensors in the product. Additionally, it offers the necessary number of digital and analog I/O pins required for the Free Wheelie. The number of pins can be easily expanded if needed by combining two Arduino Unos. The simple architecture of the microcontroller, along with its ease of use and extensive library and support resources, allows for straightforward development without requiring complex power management techniques. This makes it a practical choice for low-power, basic I/O tasks like reading sensors and controlling actuators. Overall, the Arduino Uno ensures that Free Wheelie performs reliably in long-term deployments, enhancing the longevity and sustainability of the product.

3.3. Subsystems

The prototype for Free Wheelie consists of three high- risk subsystems. The subsystems are listed below:

1. Adjustable Arm: This subsystem includes a linear actuator that deploys and retracts the electronic wheel.
2. Electronic Wheel: This subsystem includes the elements for propulsion of the chair and the ability to rotate the wheel, allowing for changes in direction.
3. Controls & User Interface: This subsystem includes a power button, a reverse polarity switch, a joystick, a speed mode button, and an LCD (liquid crystal display). These components allow the user to interact with the system by turning the system on, raising/lowering the adjustable arm, controlling the direction of the electronic wheel, selecting a slow or fast mode for the electric wheel speed, and viewing system information.

3.3.1. Adjustable Arm Subsystem

The Adjustable Arm Subsystem deploys the electronic wheel by converting a dc input into a vertical force. The arm is made up of a motor and a ball screw set. The motor converts a 21 VDC input into a rotational force. The ball screw set uses the rotational force applied to the screw to push the shaft vertically down or up.

A stepper motor was chosen to operate the linear actuator. The adjustable arm does not need to move at a high speed, so choosing a motor that has a lower speed with higher torque would be ideal for this application. The current draw from the stepper motor also proved to be less than that of the other motor option, further validating it as the best option. This motor will be operated using buttons and the Arduino Uno. Listed in Table 3-2 are the motors considered for this subsystem.

Table 3-2: Motor Options

Motor for Arm	**Rated Voltage (Volts)**	**Rated Power (Watts)**	**Rated RPM**	**Price**
Requirements	<24	<100	Low Speed	<$40
RS550 Motor [4]	21	80	25000 RPM	$14
STEPPERONLINE Nema 17 Stepper Motor [5]	12-24	48	Adjustable Speed	$14
Yaegoo Small Brushed Permanent Magnet DC Motor [6]	24	250	2750 RPM	$27

Figure 3-4 shows the stepper motor used in the adjustable arm. This stepper motor provides the amount of torque that is needed without requiring a high speed to operate.

Figure 3-4: STEPPERONLINE Nema 17 Stepper motor [5]

The adjustable arm uses a ball screw set to convert the rotational force from the motor into a vertical force to deploy the wheel. Table 3-3 shows the ball screw kits that were considered for the linear actuator.

Table 3-3: Ball Screw Set Options

Ball Screw Set	**Weight (lbs)**	**Stroke Length (m)**	**Built in Max/Min**	**Price**
Requirements	<5	0.2 < X < 1.0	Yes	<$60
Doesbot Ball Screw set [7]	4.5	0.1	Yes	$57
Uxcell linear motion ball screw SFU1605 [8]	0.76	0.25	No	$33
N\C 500mm ball screw SFU1605 [9]	3.9	0.5	Yes	$49

The N/C ball screw set that was chosen for Free Wheelie's linear actuator because it features a more compact design whilst maintaining all required parameters. Figure 3-5 below shows a visual of the N/C ball screw set.

Figure 3-5: N\C Linear Actuator [9]

The adjustable arm uses the stepper motor and ball screw set to deploy and undeploy the electronic wheel according to the user input for the subsystem.

3.3.2. Electronic Wheel Subsystem

The Electronic Wheel Subsystem consists of two main sections—the electric motor hub and a stepper motor—that are connected with a front fork to be integrated into one device. The subsystem propels the wheelchair with the use of a hub motor using a pulse width modulated signal from an Arduino Uno. This is combined with the BLDC motor controller to control the direction and braking of the wheel.

Table 3-4 shows the motor options considered for the propulsion of the wheel. The motor must possess the required power so that it is able to propel the chair while in use by an individual not exceeding 350 pounds.

Table 3-4: Wheel Motor Options

Motor	**Rated Voltage (Volts)**	**Rated Wattage (Watts)**	**Diameter (in)**	**Price**
Requirements	< 24	< 500	< 12	< $75
DNYSYSJ Hub Motor [10]	24	350	12	$50
VGEBY Scooter Motor [11]	36	400	10	$161
Alomejor Wheelchair Motor [12]	24	350	N/A	$219

Figure 3-6 shows the selected hub motor from DNYSYSJ. This hub motor provided the required voltage, size, and price when compared to other options with similar specifications that are closer to the required watts. This led it to be the best choice for main propulsion for the chair.

Fig. 3-6: DNYSYSJ Hub Motor [10]

Figure 3-7 shows the BLDC motor controller that allows the Arduino Uno to communicate to the hub motor using pulse width modulation. This controller allows for directional (forward and reverse) control, speed control, and braking.

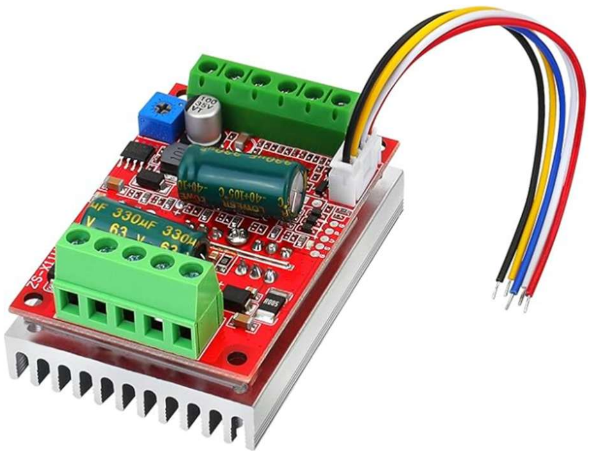

Fig. 3-7: BLDC Three-Phase Brushless Motor Controller [13]

Table 3-5 shows the motor options considered for the front fork motor. The front fork motor must possess the ability to rotate the front fork in both directions to effectively turn the wheel when it is attached to the front fork.

Table 3-5: Front Fork Motor Options

Motor for Wheel Fork	**Step Angle (Deg)**	**Holding Torque (Nm)**	**Rated Amps (A)**	Price
Requirements	< 1.8	< 1.0	< 2.0	< $ 40
STEPPERONLINE Nema 17 Stepper Motor [5]	1.8	.6	2.0	S14
57A1 Nema 23 Stepper Motor [14]	1.8	1.3	2.8	$27
TwoTrees Nema 17 Motor [15]	1.8	.4	1.5	$6

Figure 3-8 shows the selected stepper motor for the front fork from STEPPEROMLINE. This stepper motor has a step angle of 1.8 and provides the closest holding torque without exceeding the rated amp when compared to others in a similar price range, making it the best choice for the wheel fork motor.

Fig. 3-8: STEPPERONLINE Nema 17 Stepper motor [5]

Figure 3-9 below shows the front fork that is used to connect the stepper motor and hub motor into one complete device. This was chosen as it was a universal wheel fork for e-bike wheels.

Fig 3-9 Aluminum Front Fork [16]

The combination of hub motor and stepper motor creates a system that is able to deliver a smooth drive and allow for directional adjustment during everyday operations.

3.3.3. Controls & User Interface

The controls and user interface subsystem includes all the elements that allow the user to interact with the system. It is the bridge between the system and the user, allowing communication between the two to ensure proper operation. The hardware components of this subsystem include a panel with a power button, mode button, speed control button, and a joystick controller. The controls receive input from the user, and the Arduino Uno microcontroller processes the data. The LCD screen then visually outputs several pieces of information about the power status of the system, status of the battery, mode, and speed to the user.

Components for the subsystem were compared with several others available on the market to find the optimal fit to our requirements. The following paragraphs discuss the functions of these components in detail.

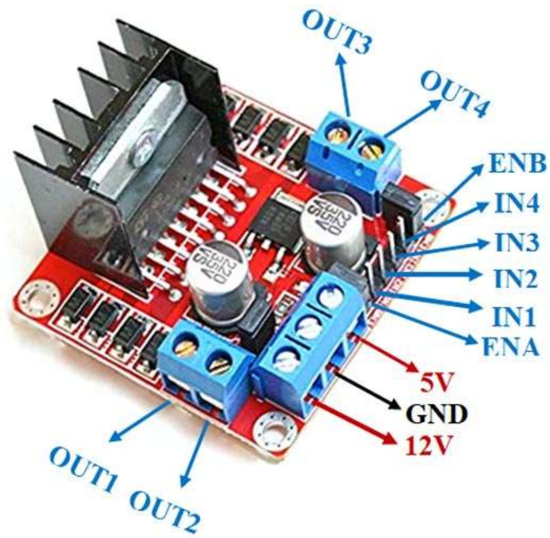

Fig. 3-10: L298N Motor Driver [17]

The L298N Motor Driver shown in figure 3-10 was selected for this project to effectively control both the speed and direction of the stepper motor used for direction control. Additionally, it is energy-efficient and provides regulated voltage to power the Arduino. All four output pins are being used to control the two-phase stepper motor. The 12V pin supports voltages within the range of 5 to 35V, which allows the module to take power directly from the 22.2V system battery. The 5V pin supplies voltage to the Arduino. The ENA and ENB pins have jumpers on them, which enable stepper motor control. All four IN pins receive digital control signals from the Arduino [18].

Fig. 3-11: Joystick Module [19]

This joystick module shown in figure 3-11 was selected due to its diverse microcontroller compatibility, which includes Arduino. It consists of two potentiometers, both of which send an analog signal to

Arduino within the range of 0 to 1023. The potentiometers are orthogonal to each other, enabling one to be used for x values and the other for y values [20]. Figure 3-12 details these values below.

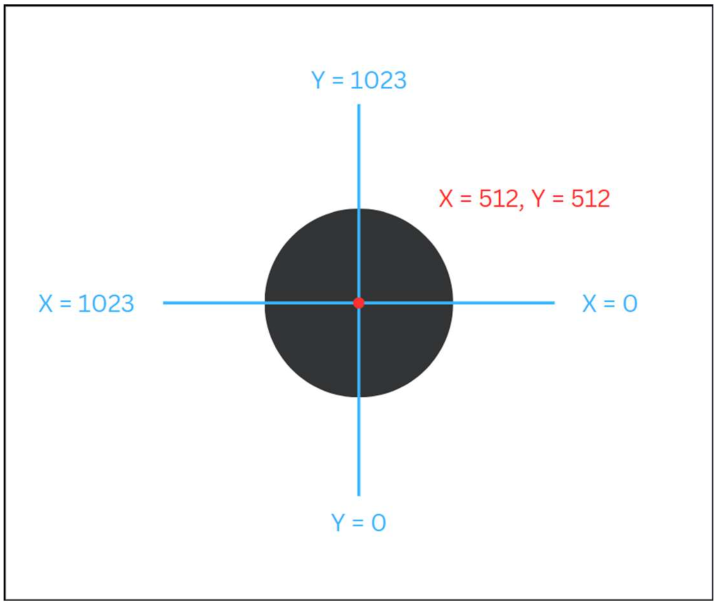

Fig. 3-12: Joystick Coordinates

Figure 3-12 depicts a top-down view of the joystick and what x and y values it sends to the Arduino Uno depending on what position it is in. In the very center, as indicated by the red dot, x = 512 and y = 512. This is the default position, and the system does not respond when the joystick is there. For any other position, the stepper motor and electronic wheel will respond in different ways, according to the Arduino code. This behavior is outlined in figure 3-14.

Table 3-6 shows several essential factors considered during the selection of the LCD, such as compatibility, reliability, price, and performance.

Table 3-6: LCD Options

LCD Display	Display Size	Interface	Voltage	Compatibility	Power Consumption	Price
Required	20x4	I2C	<=5V	Arduino	Low	<$12
HiLetgo HD44780 LCD [21]	20x4	Parallel (4 or 8 bits), I2C	5V	Arduino, Raspberry Pi, etc.	Low	~$10
Adafruit LCD [22]	20x4	Parallel (I2C available)	5V	Arduino, Raspberry Pi, etc.	Low	~$18

Sunfounder LCD [23]	20x4	Parallel, I2C	5V	Arduino, Raspberry Pi, etc.	Low	~$14

After evaluating various options available in the market, the HiLetgo HD44780 LCD 20x4 2004A was selected due to its balance of affordability, functionality, and widespread support in the maker community. The HiLetgo HD44780 2004 LCD has an exceptional cost-to-performance ratio, offering high-quality performance at an affordable price of $10. Its broad compatibility with multiple prototyping platforms, in our case the Arduino microcontroller and IDE, ensures seamless integration, while its ease of use is enhanced by clear libraries and minimal wiring requirements. The display comes with a built-in I2C module that lowers the Arduino I/O pin requirement from 7 pins to just 4 pins. The display's low power consumption makes it ideal for our battery-powered project. Additionally, the widespread use of the HD44780 controller within the maker community ensures extensive support, documentation, and troubleshooting resources, making it an ideal choice for our prototyping project. Overall, this module provides an optimal balance of affordability, functionality, and ease of integration, making it the most practical choice for Free Wheelie.

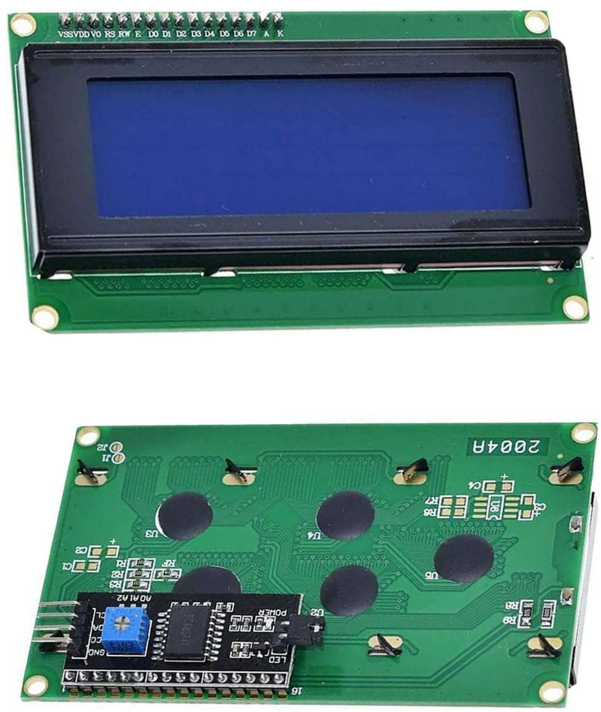

Fig 3-13: HiLetgo HD44780 LCD 20x4 2004A [21]

Figure 3-14 below is a flowchart showing the process by which these components interact in the controls and user interface subsystem.

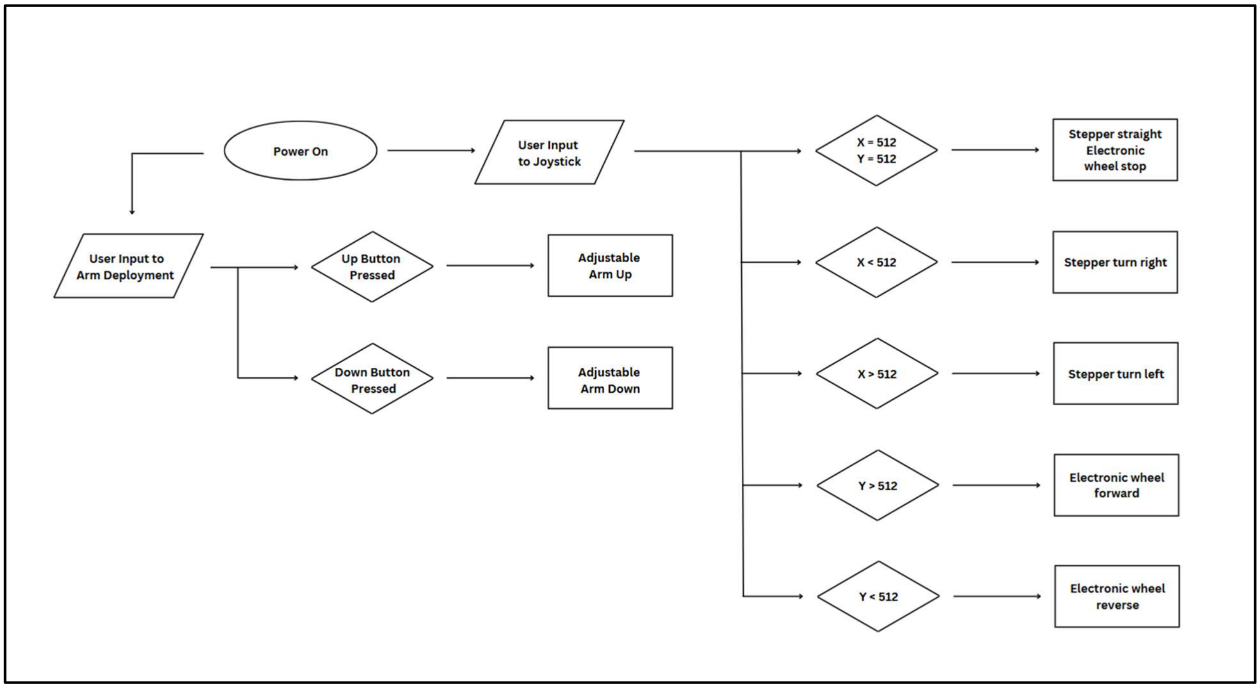

Fig 3-14: Controls Subsystem Flowchart

The user can deploy the adjustable arm and control the movement of the wheelchair as outlined above.

3.4. Level 2 Prototype Design

The completed prototype of Free Wheelie consists of the user interface, power system, and motorized components working in conjunction. The design of the system is a seamless integration of different functioning electronic parts of the wheelchair to ensure reliable performance.

3.4.1 Level 2 Diagram

Figure 3-15 showcases the final design for the prototype for Free Wheelie. The control panel is mounted on the arm of a manual wheelchair frame, and it contains all the elements for user input and output. The adjustable arm and electronic wheel are mounted on the back of a given manual wheelchair frame along with the motor controllers. The system controls and output interface with the arm and wheel through Arduino.

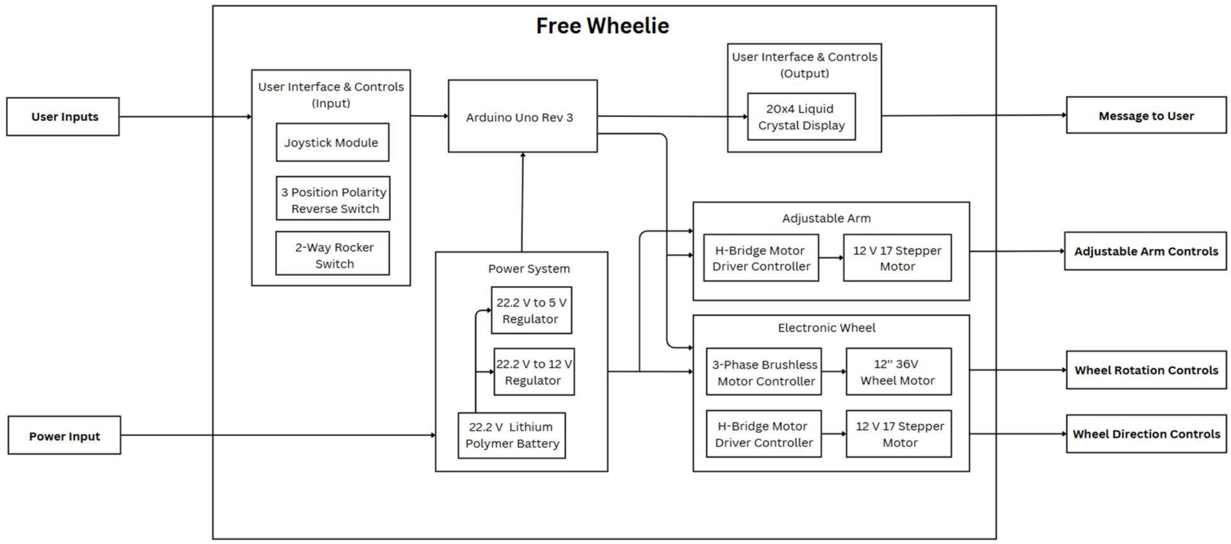

Fig. 3-15: Diagram for Free Wheelie (Level 2)

The key input of the system is identified as the power input, which comes from the power switch. The user is able to turn on or turn off the whole system through this switch that controls the power supply to all the components of the system. The power system also consists of different voltage regulators supplying ideal operating voltage to neighboring systems and their components. When powered on, the microcontroller takes in user input through the user interface that consists of switches for adjustable wheel-arm deployment and speed control and a joystick for direction control. It also sends output to the user interface through the LCD at all times to display different messages to the user regarding the status of the system. The microcontroller continuously monitors all the inputs coming in. When an output condition is met in the code, it sends out control signals to the motor system consisting of motorized components such as the electronic wheel, linear actuator, and wheel fork motor to control the wheelchair movement.

Free Wheelie's prototype system consists of different subsystems working together to give users the ability to power, control, and operate their manual wheelchair as an electronic wheelchair. Because of the limited movement and control capabilities of the users due to being in a wheelchair, it is important for the system to function reliably and provide maximum time for the users to be able to motorize the wheelchair through it. Testing each component of the system and fixing any subpar mechanisms to enhance performance is necessary to ensure the reliability and success of Free Wheelie as a market product.

REFERENCES

[1] Arduino, “Arduino Uno Rev3,” Arduino Online Shop. https://store-usa.arduino.cc/products/arduino-uno-rev3 (accessed Apr. 9, 2025).

[2] “Amazon.com: Raspberry Pi 4 Model B (4GB) : Electronics,” Amazon.com, 2024. https://www.amazon.com/Raspberry-Pi-RPI4-MODBP-4GB-Model-4GB/dp/B09TTNF8BT (accessed Apr. 9, 2025)

[3] “ESP32-DEVKITC-32UE | DigiKey Electronics,” DigiKey Electronics, 2024. https://www.digikey.com/en/products/detail/espressif-systems/ESP32-DEVKITC-32UE/12091813 (accessed Apr. 9, 2025).

[4] “RS550 21V 14 Teeth (Φ9.5mm) Replacement Motor for DIY Projects, 9.6-25V 9-15 Teeth 25000 RPM Drill and Power Tools - Amazon.com,” *Amazon.com*, 2025. https://www.amazon.com/Electric-Screwdriver-9-6-25V-Replacement-Cordless/dp/B0D8ZQFDTD/ref (accessed Apr. 23, 2025).

[5] “STEPPERONLINE NEMA 17 Stepper Motor Bipolar,” *Amazon.com*, 2025. https://www.amazon.com/STEPPERONLINE-Stepper-Bipolar-Connector-compatible/dp/B00PNEQKC0 (Accessed Apr. 9,2025)

[6] “Blocked,” Amazon.com, 2025. https://www.amazon.com/Yaegoo-Brushed-Permanent-Electric-2750RPM/dp/B0D78FX5BC/ref (accessed Apr. 23, 2025).

[7] “Doesbot Ball Screw and 12mm Optical Axis Sliding Table Apply Nema23 57BYG and Nema17 42BYG Stepper CNC 3018 Aluminium Upgrade Kit (Motor Shaft Diameter 5MM): Amazon.com: Industrial & Scientific,” *Amazon.com*, 2025. https://www.amazon.com/Doesbot-Optical-Sliding-Aluminium-Diameter/dp/B0DK312CNN/ref (accessed Apr. 23, 2025).

[8] “uxcell Linear Motion Ball Screw SFU1605 (Dia 16mm, Pitch 5mm, Length 150mm) Anti Backlash Ball Screw Kit with Metal Ball Screw Nut for CNC Machine Parts: Amazon.com: Industrial & Scientific,” *Amazon.com*, 2025. https://www.amazon.com/uxcell-Linear-SFU1605-Backlash-Machine/dp/B0CTF7Q3LF/ref (accessed Apr. 23, 2025).

[9] “500mm Ball Screw SFU1605 Diameter 16mm,5mm Pitch with Metal Ball Screw Nut for CNC Machine: Amazon.com: Industrial & Scientific,” *Amazon.com*, 2025. https://www.amazon.com/200mm-Screw-SFU1605-Diameter-Machine/dp/B08QHZQKG3/ref (accessed Apr. 23, 2025).

[10] “Amazon.com: 12’’ 24V Electric Scooter Brushless Gearless Hub Motor Wheel Motor for E-Bike Scooter Motorcycle, 350W 12 Inch E-Bike Cycling Hub Conversion Kit (US Stock) : Sports & Outdoors,” *Amazon.com*, 2025. https://www.amazon.com/Electric-Brushless-Gearless-Motorcycle-Conversion/dp/B09SCVQ3LR (accessed Apr. 9, 2025)

[11] “Amazon.com: Alomejor Electric Scooter Motor Wheel Hub 350W Rear Wheel Drive Motor Folding Electric Scooter Replacement Parts for MAX G30 : Sports & Outdoors,” *Amazon.com*, 2025. https://www.amazon.com/dp/B0BBVCH5MS/ref (accessed Apr. 9, 2025).

[12] "Amazon.com: 250W 24V Wheelchair Motor, High Torsion DC Brushed Gear Motor for Electric Wheelchair Replacement : Health & Household," *Amazon.com*, 2025. https://www.amazon.com/dp/B0BJT7K2FM/ref (accessed Apr. 9, 2025).

[13] "Amazon.com: 1PCS DC 6-60V 400W BLDC Three-Phase Brushless Motor Controller PWM Hall Motor Control Driver Board 12V 24V 48V with Forward/Reverse/Stop/Brake Function : Tools & Home Improvement," *Amazon.com*, 2025. https://www.amazon.com/BLDC-Three-Phase-Brushless-Controller-Function/dp/B0D97PN96D/ref (accessed Apr. 9, 2025).

[14] "RTELLIGENT 57A1 Nema 23 Stepper Motor Stepping 1.3Nm/184.14oz-in 6.35mm Shaft 4-Wire 2.8A 1.8Deg Low Noise for Laser/CNC Machine: Amazon.com: Tools & Home Improvement," *Amazon.com*, 2025. https://www.amazon.com/dp/B07RW6TGL3?ref (accessed Apr. 9. 2025).

[15] "Twotrees steeper motor," *Amazon.com*, 2025. https://www.amazon.com/dp/B07THK76QQ/ref (accessed Apr. 9, 2025).

[16] "Front Wheel Fork," *Amazon.com*, 2025. https://www.amazon.com/Cechoayuu-Absorber-Aluminum-Suspension-Motorcycle/dp/B0DWK6K9B8/ref (accessed Apr. 9, 2025).

[17] "L298N-Module-Pinout." *Blogspot.com*, 1.bp.blogspot.com/-0upqWEeSmbg/X-DLNFKHrUI/AAAAAAAAEps/zdenWyv94-ox2SejY_sKSZF413Iit05GwCLcBGAsYHQ/s16000/L298N-Module-Pinout.jpg. (accessed 23 Apr. 2025).

[18] ArduinoGetStarted.com. "Arduino - Controls Stepper Motor Using L298N Driver | Arduino Tutorial." *Arduino Getting Started*, arduinogetstarted.com/tutorials/arduino-controls-stepper-motor-using-l298n-driver. Accessed 12 Mar. 2025.

[19] "Joystick Module for Arduino, ESP32, ESP8266, Raspberry Pi – Analog Control Stick for Robotics and Projects, 2-Pack: Amazon.com: Industrial & Scientific." *Amazon.com*, www.amazon.com/dp/B0DQ37P5RQ?&linkCode=sl1&tag=zlufy-20&linkId=fe465532775f9cf6ce8cc30be70db732&language=en_US&ref_=as_li_ss_tl. Accessed 23 Apr. 2025.

[20] "Arduino - Joystick | Arduino Tutorial," Arduino Getting Started. https://arduinogetstarted.com/tutorials/arduino-joystick (accessed Apr. 9, 2025).

[21] "Amazon.com: HiLetgo HD44780 2004 LCD 20x4 2004A Character LCD Screen Display Module Blue Backlight with IIC/I2C Serial InterfaceAdapter : Industrial & Scientific," Amazon.com, 2025. https://www.amazon.com/HiLetgo-HD44780-Character-Backlight-InterfaceAdapter/dp/B082Y37WXG/ref (accessed Apr. 9, 2025).

[22] "198 | DigiKey Electronics," DigiKey Electronics, 2025. https://www.digikey.com/en/products/detail/adafruit-industries-llc/198/5774229?gclsrc (accessed Apr. 9, 2025).

[23] "CN0296D | DigiKey Electronics," DigiKey Electronics, 2025. https://www.digikey.com/en/products/detail/sunfounder/CN0296D/18668625?gclsrc (accessed Apr. 9, 2025).