MindMaze: An IoT based monitoring platform for dementia progression

Proposal for CM3040 Physical Computing Coursework Project

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Abstract

MindMaze is an IoT based monitoring platform that is intended to assess cognitive markers of dementia in an adult population using daily maze puzzles to allow physicians to perform longitudinal assessments on patients. Given the global prevalence and forecasted increase of dementia, there is a marked need for tools providing clinicians with diagnostic data. Moreover, given that diagnosis is challenging and existing tools lack cost-effectiveness, longitudinality, and ease of use, an IoT based solution like MindMaze may be able to provide clinicians important tools to catch disease earlier.

The proposed solution comprises a gamified diagnostic module for a patient suspected of dementia and a monitoring module for clinical review. Both are driven by Arduino UnoR4 Wifi controllers (ESP32-S3) that utilize a variety of sensors and actuators including fit-for-purpose display screens . They are bridged using a backend web application to facilitate bidirectional communication and store and visualize historical performance data for clinical review. Through integration of accessible, low cost hardware, an at-home gamified solution, and clinically validated mechanism, MinMaze aims to improve the cognitive monitoring landscape to catch disease faster to improve outcomes for dementia patients.

Background and Literature Review

This proposal defines the development of a cognition platform for those suspected of dementia onset and requiring medical monitoring of disease progression. The prevalence of conditions like dementia are on track to nearly double to almost 80 million affected individuals by the year 2030 [1] . These diseases often present as struggles with memory, attention, planning, and foresight and inevitably lead to premature death. Identifying the onset of disease is important in order to apply clinical intervention early and improve the quality of life [2]. Moreover, early detection can save lives and limit harm, as a large number of elderly injuries and fatalities occur annually due to cognitive decline [3]. However, distinguishing age-related decline from clinical definitions of dementia is a complex clinical challenge though, because physicians are short of time and longitudinal data to confidently diagnose [4,5]. Furthermore, many seniors put off assessments as they do not want to give up independence [6].

Dozens of IoT tools have been studied and evaluated on Dementia, as detailed in Salvi et al.'s meta-analysis. [7]. These tools run the gamut from detection, safety monitoring, and quality of life assistant tools. Some key examples from the analysis include:

1. **Yin et al.** [8] describes an eye-tracked stereo video monitoring tool meant for field deployment and widespread clinical use that utilized an IoT front end with

cloud enabled Machine learning assessment. While this approach had high accuracy (mid 80s) and PPV with a reasonably affordable front end system, the lack of longitudinal data prevented multiple touch points with clinicians or any establishment of a “trend” which may have helped further improve the accuracy of the system. Both this and the need for a specialized camera or sensor setup impractical for most to use at home were common limitations in this review [7].

2. **Grammatikopoulou et al.** [9] highlights work using a variety of smart home features such as cabinet open/close sensors and energy draw sensors to use lifestyle trends as a diagnostic mechanism. With mid 70s accuracy, the performance is reasonable but this technique shines in the ability to collect longitudinal data that allows for decline monitoring and progression. However, outfitting an entire home is complex and expensive, meaning it is difficult to standardize and make it cost effective as a formal solution. Again, cost effectiveness was a noted limitation in many papers found in this review [7].
3. **Rhodus et al.** [10] shows an approach to use wearable IoT solutions with Machine learning to track metrics over time. This research boasts excellent adherence due to existing infrastructure and also showed the value of continuous data tracking. However, the research was more focused on whether biometric data could be a reliable source of data for caregivers and therefore did not use a validated metric for *diagnosis.* There is no reference point for the performance of this method.

The literature explains that the need is clear for a tool that longitudinally monitors cognitive decline when recommended by clinicians to ensure timely intervention. Overall, no one solution identified has a mix of longitudinality, accessibility, and validated metrics that would make an IoT implementation shine. Furthermore, bidirectional communication between the patient and the provider, alerting for indicators of decline or dementia would be helpful for clinicians. Given these requirements, an Internet of Things (IoT) solution that optimizes the strengths of the diverse research landscape is an appropriate fit. Such a solution must have:

1. A two way interface with high adherence that relies on user input from anywhere that is internet connected and comprises an information relay to get data back to a caregiver. Something game-ified on the front end would help boost adherence.
2. An accessible and standardized IoT solution that does not require complex set up or assembly and can be standardized
3. A clinically validated test that can be randomized and repeated to track over time “daily challenges” over the course of a month to track.
4. To minimize operator involvement, data about patient performance on any assessment should send a “takeaway” alert to a doctor that is web connected to allow intervention.

To address 3 and 4, one such an academically validated tool like mazes are well suited and could also encourage engagement given the gamification [11]. For example, the Snellgrove maze test shows that graphical puzzle activities can help with attention and visuoconstructional abilities, critical and important parts of independent living in old age. [12, 13].

Proposal

System Design

As described in the previous section, an IoT solution that meets the strengths above could be prescribed to at-risk patients or those showing early signs of dementia in order to facilitate early, accurate, and faster dementia assessment than contemporary methods. A high-level use case diagram illustrating this concept is provided in Figure 1 of the Appendix.

This will be implemented via two connected modules, one being a maze game front end for a patient suspected of dementia (“diagnostic module”) and the other a care and performance monitor for healthcare professionals (“monitoring module”). In real-world use, the front end diagnostic module would be prescribed in home settings to individuals suspected of dementia or as a routine part of testing, with the monitoring module used to update a caregiver with critical updates and test failures.. A web app information broker (“backend”) shall be used to communicate information using a REST based approach with JSON used to represent states and transfer data. At home testing is common practice in clinical use, with accepted technologies like continuous glucose monitors and holter monitors.

The diagnostic module will have a Sharp Memory LCD display with a varying maze that can be put on the screen and pushed from the backend in order to ensure memory efficiency and refresh rate can be maintained . Further, a joystick from the class materials can be used to control the user through the maze, along with a notification system that will comprise an LED light and ultrasonic sensor that shall alert the user when they are nearby if a new maze is ready for completion or there is a need to call their doctor about results. Meanwhile the monitoring module will consist of a small RGB LCD for information that will share patient performance data from the maze assessment. It will also contain a similar notification system that is triggered when the user is nearby using an ultrasonic sensor. As necessary, the RGB LED can be used with multiple colors and a duty cycle to convey acceptable or unacceptable assessment results.

Both modules shall be driven by Arduino UnoR4 Wifi (ESP-S3 type microcontrollers) that were purchased for this course. The decision is an optimization so they are cheap to manufacture but capable of processing graphical information. In a real world implementation, the monitoring module could be adapted to handle communications with multiple diagnostic modules (physicians usually have multiple patients), but given timeline limitations we will create a one to one rather than a many to one relationship between modules. **This design is captured in Figure 2 of the** Appendix.

Requirements Specification and Testing Plan

To fulfill the design description above and guide development, a rigorous requirement specification was created. This set, along with the verification tests for each is described in the appendix section, **tables 1 and 2.**

Implementation Progress

Given that the design of this project utilizes new components not explicitly discussed yet in the module, including an LCD memory display and a joystick, I wanted to derisk the implementation of these components. I sourced a memory display [14] and created an Arduino sketch to display various line vectors on the display. The code provided by Adafruit and their libraries were used as reference [14,15] to help learn the function calls to draw to this display.

Then, I studied and adapted code related to algorithmic creation of mazes [16] in order to prove that the screen size would be appropriate for the use case. Through trial and error, I was able to generate mazes based on multiple parameters that will serve as a good foundation for dynamic creation of Snellgrove mazes. I proved that the display is fit-for-purpose, although the through-hole design of the screen means connections are quite loose so solder joints will be a required next step.

Lastly, I wanted to derisk motion input. To do so, I configured wiring for joystick and wrote code to draw and track a cursor position and update it using the ESP's ADC. Here, I had to make sure motion wasn't overly staggered or fast for reasonable human interaction. I showed smooth, reliable motion of a cursor based on inputs, though finer parameters still need to be fine tuned. Overall, I believe this project will be technically feasible in the time allotted and evidence of this implementation can be found in figures 3-7 of the appendix.

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Appendix

Tables

ID	Functional Requirement	Verification Test
1	Diagnostic Module shall be able to render a display with Snellgrove Maze when provided the data	Confirm that expected maze appears on the screen upon wake when an incomplete one is available
2	Diagnostic module shall be able to alert the patient when a new maze prescription is available	Confirm that notification LED triggers without waking the screen when an incomplete maze is available.
3	Diagnostic module shall wake the screen and alert when a patient is nearby if there is an uncompleted maze to be completed	Confirm that ultrasonic sensor proximity casues the screen to wake and populate with an expected maze (see 1)
4	Diagnostic module should allow a user to move a cursor on the screen in 2D space	Confirm that an onscreen cursor appears on wake. Confirm that movement of the cursor matches that of the joystick motion
5	Diagnostic module shall alert the user when a maze has been successfully completed	Confirm that at maze completion, a success message appears to the user and the screen turns off.
6	Diagnostic module should track the time a user takes to complete the maze	Upon maze completion, confirm that the time for completion is written to a JSON or similar data structure
7	Upon maze completion, the diagnostic module shall transmit the data related to maze completion time and a completed status.	Confirm that upon maze completion, data received by backend includes a success message and data related to completion time
8	Monitoring module shall be able to alert the caregiver when a maze prescription result from patient is available	Confirm that upon maze completion and within 5 minutes, monitoring module's notification lLED triggers without waking the screen when a maze has been completed
9	Monitoring module shall display the latest patient's result to the caregiver by waking the screen and showing latest results when the caregiver is nearby	Confirm that ultrasonic sensor proximity casues the screen to wake and populate with the most recent maze completion results (success/failure with time)
10	Backend shall be able to receive maze completion results and trigger an alert to the monitoring module	See 7 and 8
11	Backend and monitoring module shall provide a web interface that show historic patient data entries	Confirm that the web portal for the backend is able to show data related to historical maze completions
12	Backend shall be able to transmit new maze layouts to the diagnostic module for completion	Confirm that expected maze layout (test 1) occurs for at least 3 unique mazes

Table 1: Functional Requirements and Relevant Verification Testing for this project

ID	Non-Functional Requirement	Verification Test
14	Diagnostic and Monitoring modules shall utilize LED light to communicate alerts	Confirm that LED lights exist and are able to turn on/off reliably on the devices
15	Diagnostic module shall use a joystick style sensor to receive user input for movement of a cursor	Confirm that only a 2 axis joystick sensor with push button is used for user input on the diagnostic module.
16	Backend, Diagnostic Module, and Monitoring Module shall receive and transmit requests in JSON or similar JSON based data structure	Confirm that compatible JSON data structures are utilized for data in the backend. Confirm that all data on modules are encoded into JSON before use outside of the module.
17	Diagnostic and Functional Modules shall use an ESP based microcontroller to govern features	Confirm that the microcontrollers are ESP-based.
18	Diagnostic Module screen shall use an LCD style display to maintain a refresh rate fast enough to provide a "game-like" experience.	Confirm that there is no human noticeable lag or stutter between input of maze cursor and screen feedback
19	Diagnostic Module controls should be accessible enough to be used by an elderly population	Confirm that no overly small or high-dexterity joysticks or buttons are used.

Table 2: Nonfunctional Requirements and Relevant Verification Testing for this project

Figures

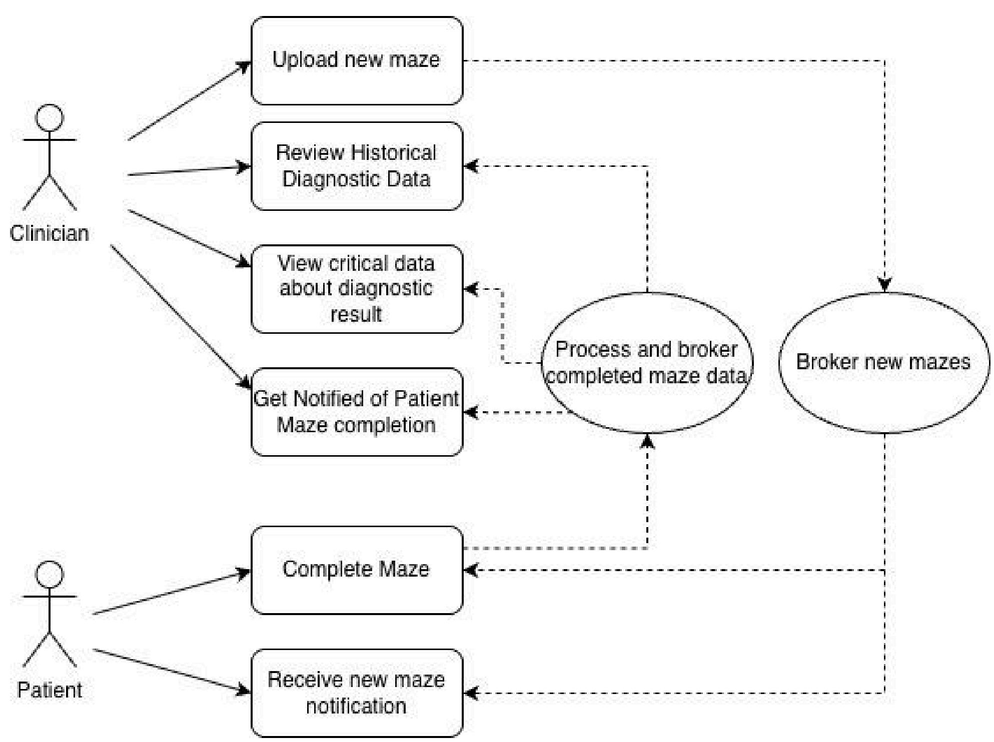

Figure 1: Use case diagram for both intended end users (physician and patient) for the described project. Dotted lines and ovals represent backend tasks that the user has no interaction with.

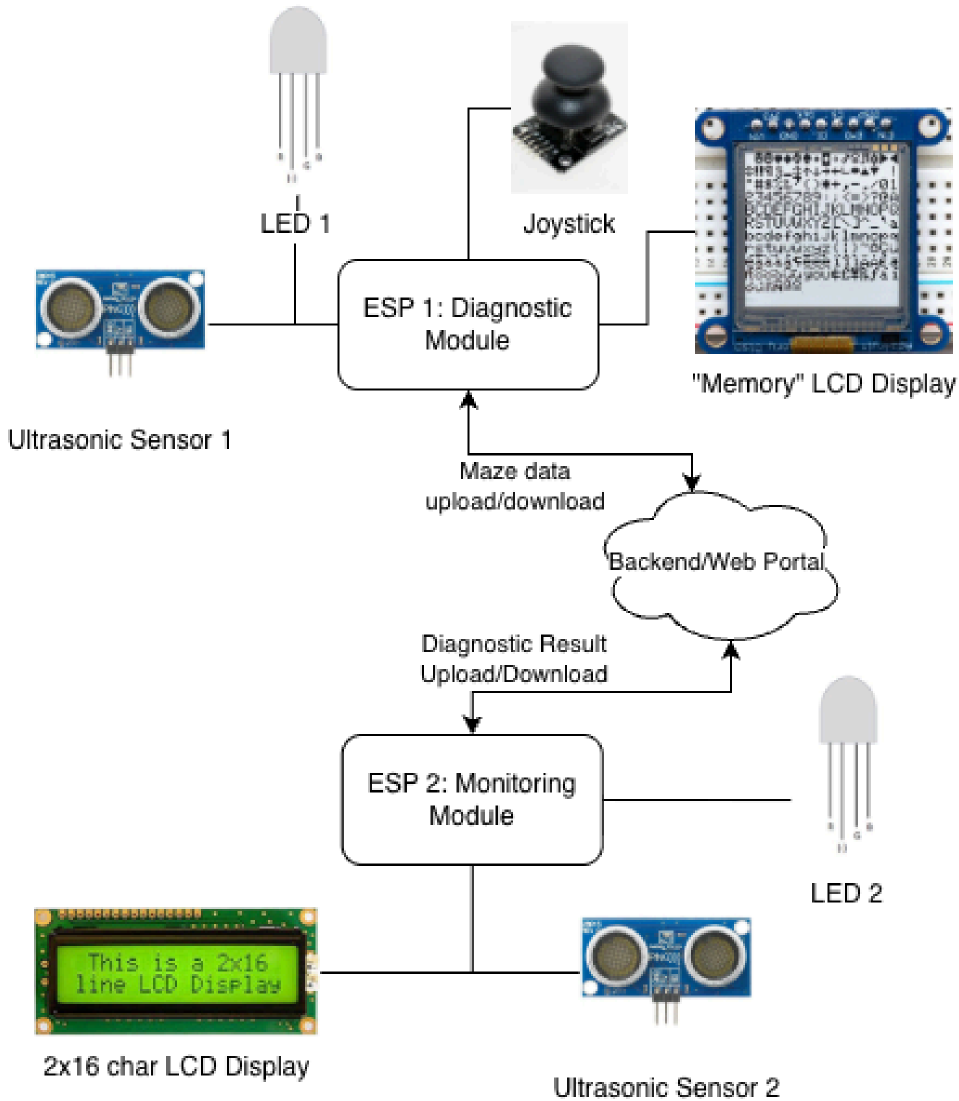

Figure 2: Design Schematic showing both Arduino R4 Wifi modules (ESP1/2), RGB LEDs, Ultrasonic sensors, and both text and Sharp Memory LCD displays, comprising 2 total ESP microcontrollers with at least 3 sensors or actuators per microcontroller.

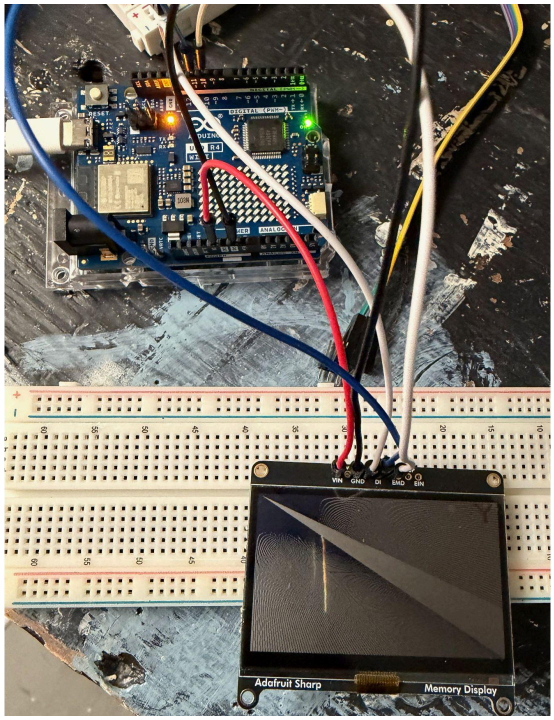

Figure 3: Example of Sharp Memory Display with ray traces only (proof of concept)

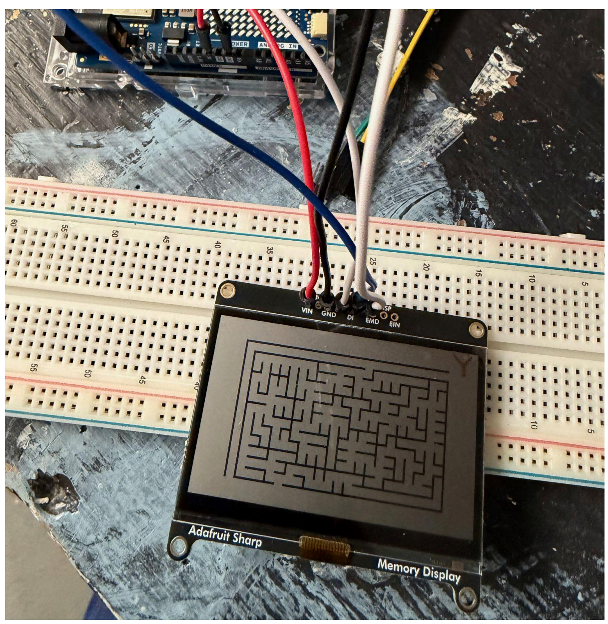

Figure 4: Example Snellgrove Maze using algorithmic maze generation (Work in progress, given the multiple exists and entrances)

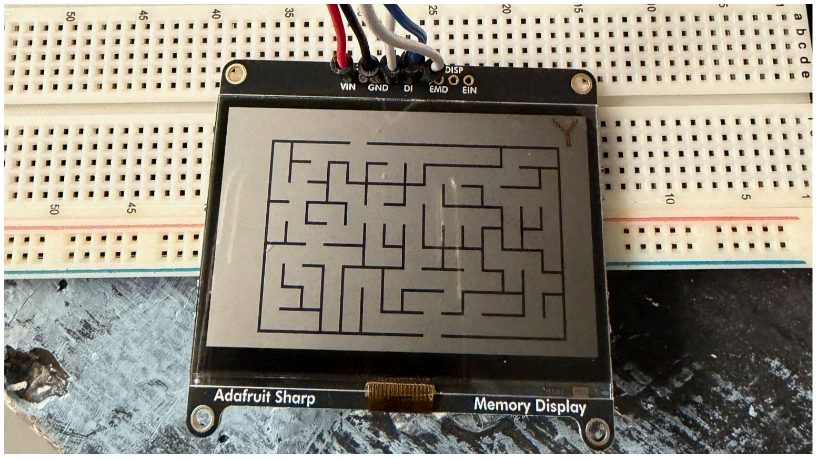

Figure 5: Optimized Snellgrove Maze (close to final algorithm for construction)

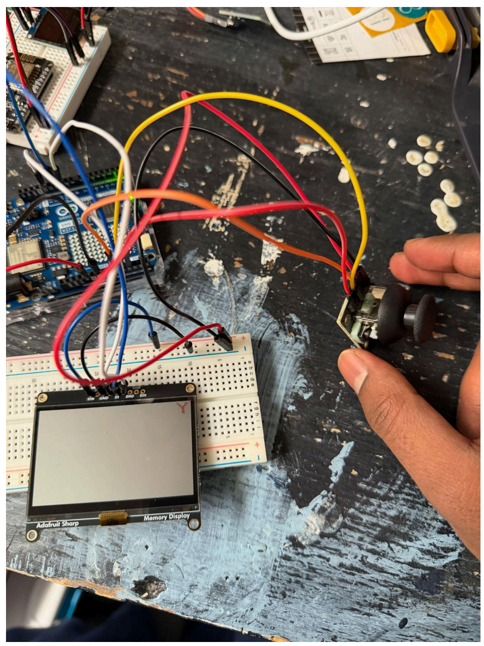

Figure 6: Joystick interface setup for input tracking

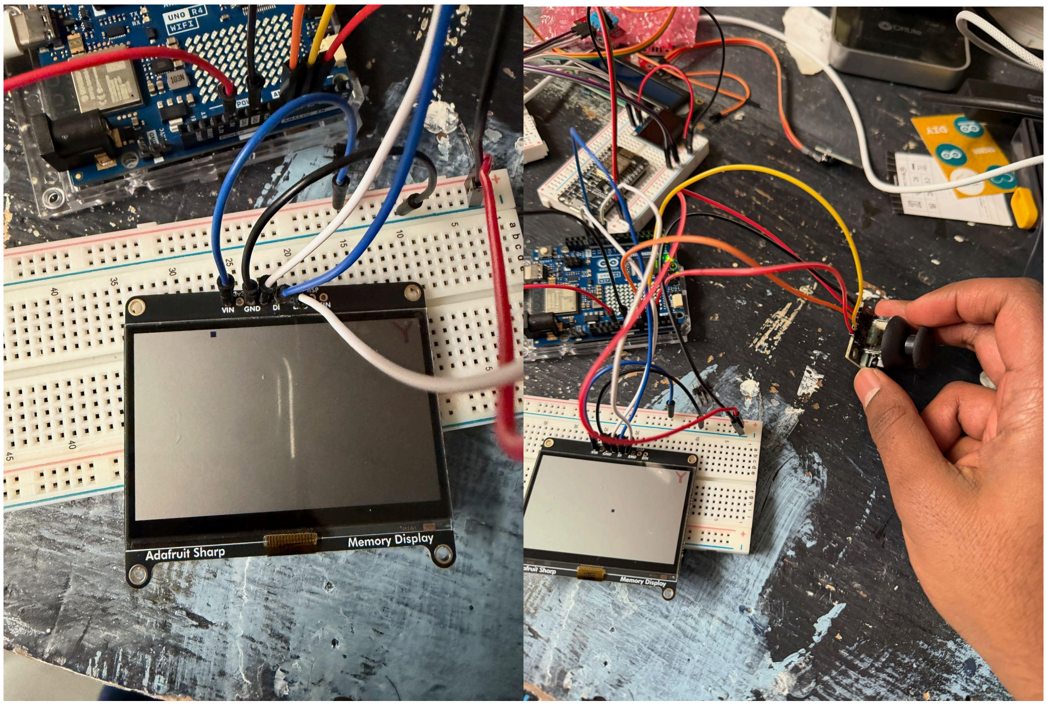

Figure 7: Evidence of joystick input responsiveness on cursor– moving the joystick down and to the right moves the cursor down and to the right.