Robotic Arm For Household Automation

ECE 445 Design Document - Spring 2026

Project #19

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Contents

1 Introduction

1.1 Problem

People with limited mobility lose independence in day to day actions such as pouring a glass of water or making coffee. These aren't out of norm tasks in any way and that's why losing them can be so hard.

When you can't do basic actions your day becomes shaped around what your body can actually do instead of what you want to do in the moment. When your normal activities require a caregiver, normal living turns into needing constant dependence.You need to time your needs around someone else which leads to hesitance in asking for help or choosing to go without what you want because it feels easier than asking again. Over time, those moments of not being fully in control of your own simple preferences can be discouraging.

When everyday actions become requests you can feel like your dignity is compromised, and simple actions you used to do without a second thought are taken away. Even with supportive caregivers, the emotional weight of needing help with basic things can be draining and destroy you mentally over time.

1.2 Solution

What we propose is a robotic arm capable of performing those day-to-day tasks. The demonstration will be for one of those many simple tasks: pouring a drink.

To delve into the details, we propose a 6-DoF robotic arm that is fully actuated. The sensors will include cameras for vision detection, Time of Flight for basic depth detection and strain gauge amplifiers to measure the force applied. This project will also need a more powerful on-board computer to deal with data processing from the pcb + microcontroller sensor array and vision algorithms to accurately create commands through inverse kinematics to drive the robotic arms motors.

1.3 Visual Aid

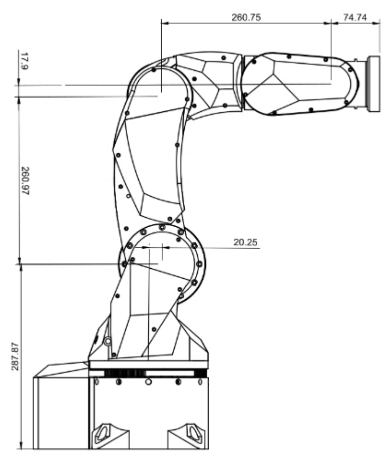

Figure 1:Arctos Arm which we use as a basis for the arm design. Reproduced from [1]

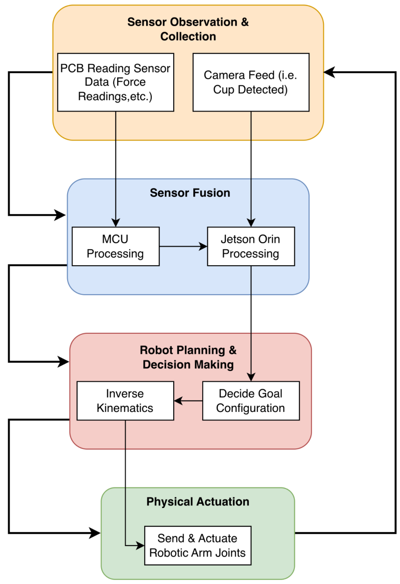

Figure 2: High Level Visual Aid of Solution Control Stack (Created By Author(s))

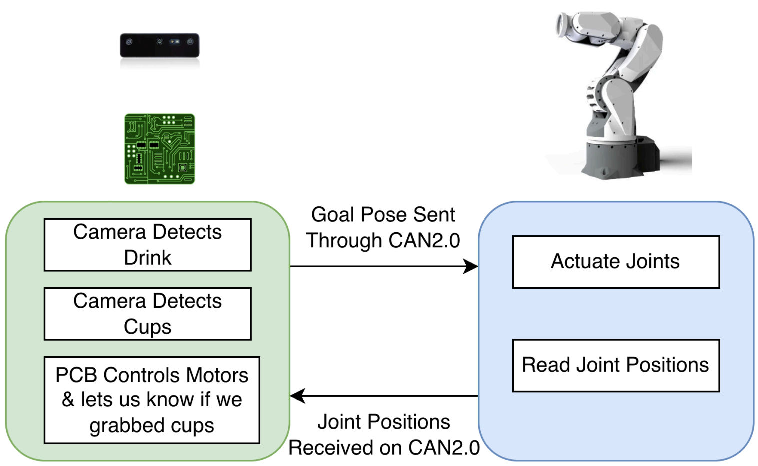

Figure 3: High Level Demo Flowchart Reproduced from [1], [2] ,[3]

1.4 High Level Requirements

1. 75% Success rate in pouring a drink in normal indoor lighting conditions
2. Robot shall detect human and obstacle collision and stop within 200 ms
3. Robot Accuracy is within 50mm in the control loop

2 Design

2.1 Block Diagram

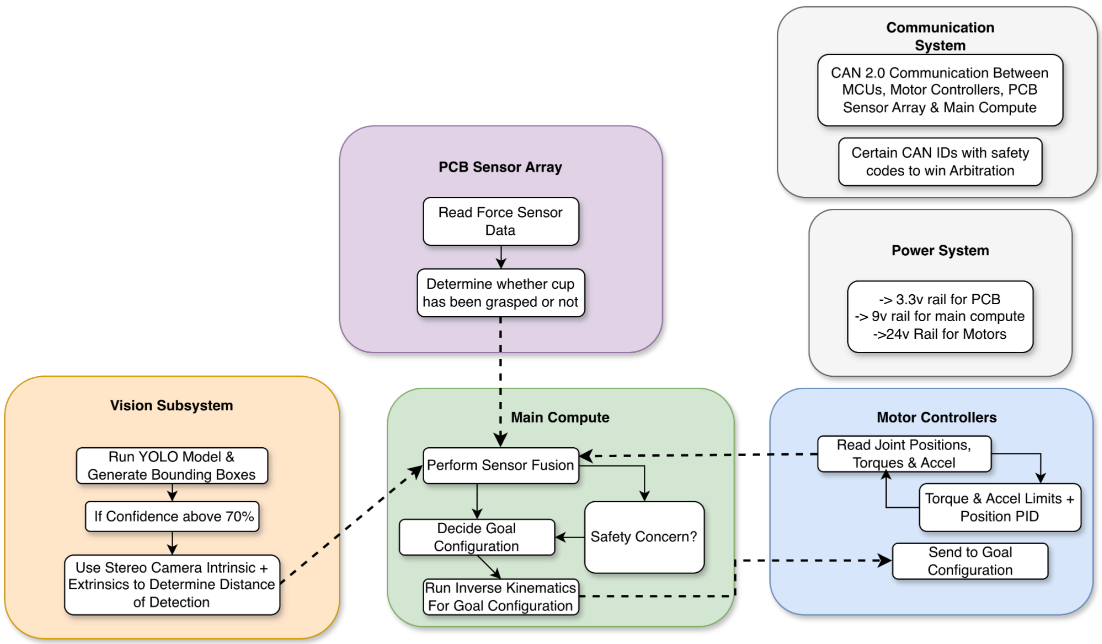

Figure 4: System/Subsystem Block Diagram (Created By Author(s))

This Block Diagram consists of multiple systems/subsystems to get a robotic arm that can successfully grab and pour drinks.

First, the main computer which consists of a Jetson Orin Nano the primary purpose of this subsystem is to intake all data both raw and preprocessed to understand the scene. From there it will decide the goal configuration based on sensor information based on whether we have a safety concern or not. Then we run inverse + forward kinematics to send the desired position to the bus.

The Vision subsystem is relatively simple from a high level overview, it takes the camera feed runs inference on a YOLOvX model then if the confidence is above 70% find the distance to the detection and report it to other main compute algorithms.

The PCB sensor array utilizes strain guage amplifiers to determine whether the cup has been grasped or not. This input is piped to the main computer for sensor fusion and decision making.

The Motor Controllers are a vital part of our safety as well as control stack. They will be enforcing torque and acceleration limits while running a PID controller to ensure precise joint positioning. The Main computer sends joint positions to the motor controllers which will then move motors to said configuration.

The Communication system is key in getting all components to talk to each other, this will be its own PCB component just to handle communication. The PCB for this component will involve heartbeat checks to each component as well as allow the main controller, PCB sensor arrays, and motor controllers to have proper communication over CAN2.0A.

The Power subsystems main goal is to provide power to each component with the proper power specifications.

2.2 Subsystem Overview

Vision Subsystem:

- Detect cups and detect glass used to pour into cups with a custom tuned Yolo family model.
- Helps us take the scene and estimate pose for pouring the water into the cups
- Use stereo cameras to find the difference in perspective for the proper distance to our bounded object.

Communication System:

- The safety signals get highest priority, meaning they have the lowest ID to win arbitration on the bus.
- The communication system will be implemented via CAN2.0A. This is how each component in the robotic arm sends data to each other
- Each joint/link gets a unique ID on the bus for proper communication.

- CAN2.0A is ideal here because of its differential pairing which makes it more resistant to EMI that can come from motors.
- The reason why extended mode (CAN2.0B) is not used is because there isn't enough subsystems on the bus

Motor Control System:

- These are the motor drivers that physically move the robot and publish data about the motor. Will be an FOC based motor driver.

Power System:

- Converts the primary input into regulated rails for the robot
- Separates high-current motor bus from low-noise logic rails to prevent brownouts and EMI.
- Feeds the Motor Control System, Main Compute System, and all distributed Sensor PCBs
- Reports voltage & current status to Main Compute so the robot can derate or enter a safe state before power faults cause unsafe behavior.

Main Compute System:

- Determine the proper instruction to the arm
- Run Sensor Fusion based of the MCU data and Vision Data

2.3 Requirements & Verification Table

Subsystem	Requirement	Verification
Vision Subsystem	Publish 3D target pose to Main Compute at minimum of 15 Hz	Run a ROS publisher test at high load and check if the camera publishes at 15Hz, the call back will be assigned to 20 Hz.
Vision Subsystem	Depth Accuracy of +/- 10mm from 0.5m	Compare Depth readings with a high accuracy laser measurer and see how far off our readings are
Communication Subsystem	CAN bus delivers safety critical frames in at most 10 ms	Check the frequency of our bus with an oscilloscope, lowest id wins arbitration so it will follow frequency of can bus.
Power Subsystem	Sensors at 5V, Motor at 24V, and Main Compute at 9v	Read our regulated rails with a multimeter, check with oscilloscope if rails are supplying the proper power

2.4 Physical & Hardware Design

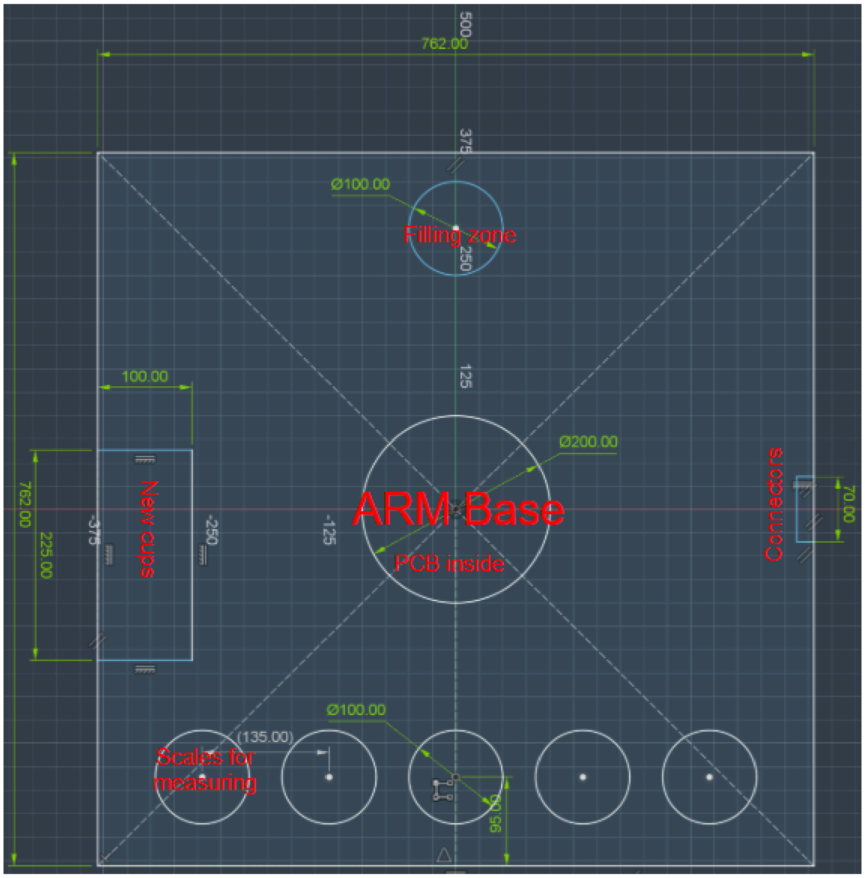

Figure 5: Hardware Diagram (Created By Author(s))

Our system has an overall footprint of 30 inches by 30 inches and is organized around a clearly defined interaction and filling zone at the front, where we actively dispense beverages into user cups. At the center of the platform is the main arm structure, which serves as both the mechanical and electronic backbone of the system. The arm houses the PCBs and control hardware internally, and it manages communication with the weighing scales while also driving the LCD displays positioned in front of the interaction area. In the rear of the system, five ring-style weighing stations equipped with load cells provide precise mass measurements, allowing us to determine when drinks are full and to verify that dispensing is accurate, preventing both over-pouring and under-pouring through closed-loop feedback. In addition to these rear verification scales, a dedicated weighing scale in the filling zone ensures that each cup is filled to the user's selected level in real time. On the right-hand side of the platform, a passive mechanical storage container holds spare cups for interaction, serving as a simple, non-electronic staging area for the system

2.5 Software Design

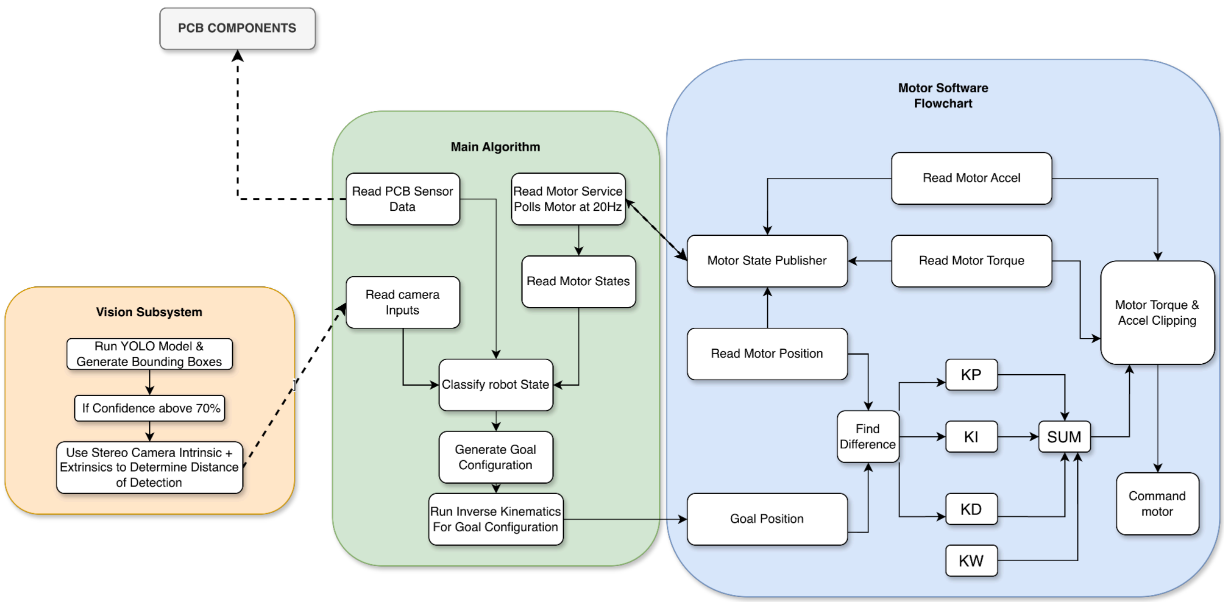

Figure 6: Software Diagram (Created By Author(s))

<u>Motor Software Control Loop:</u>

The Motor Software Control Loop consists of multiple components working together to allow safe as well as accurate operation.

In regards to safety, we need to limit our acceleration, torque and velocity. To do this, we utilize sensors on the motor driver as well as use basic kinematics to derive designated values. We then ensure that no command to the motor will actually cause unsafe behavior by limiting the torque and acceleration.

To allow accurate operation we utilize a Position Integral Derivative controller (PID). This control system has three main gains to it KP,KI,KD. KP is the position error gain, KD is the change in error over time gain, and KI is the sum of the error over time gain. With the integral control part however, if we have our system take longer to converge our sum of these three terms shoot up. This is where KW comes into play, KW simply clips our integral value of the sum to ensure our system maintains stability and converges to the right solution.

Vision Subsystem:

The vision subsystem will utilize the Luxonis OAK-D S2 camera feed piped into a YOLOvX model for perception, and finally utilize stereo depth properties to find depth.

The YOLOvX model will take the same model architecture utilized by a normal YOLO model but then we will retrain the architecture to specifically classify objects that are of our interest. We also plan to ignore detections below 70% confidence because we want to be more sure of our scene before setting a goal to grab an object. If we go for low confidence detections, false positives may cause safety issues.

As for depth perception, we will utilize geometry to help the robot understand the depth of the scene. Utilizing stereo rectification we can reproject left and right planes into a common plane parallel to the line between both the camera centers. Then we can create a depth map calculating the pixel block disparity by comparing the left and right camera components. This core understanding is what allows us to find out how far away objects detected from our model are.

Main Algorithm:

The main algorithm involves multiple steps before sending a proper command to the robotic arm motor controllers.

The first step is properly understanding the scene and what the robotic arm is currently in the process of doing. In order to properly classify our state, we must read data from our camera, PCB sensors, as well as our joint states. Utilizing these sensor readings, we classify our robot into a state that follows a simple FSM model.

1. Detecting Specific Drink
2. Picked Drink Up
3. Detect Cup
4. Get Close to Cup
5. Pour
6. Finished Pouring
7. Detect Empty Drink Slot
8. Return Drink
9. Done

The purpose of classifying these states is to help the robot understand what it is doing and how to act upon its sensor readings. After classifying the state, we generate a goal configuration of our arm based on the sensor readings and then formulate that into proper joint positions through inverse kinematics.

2.6 Tolerance Analysis

Variables:

R_allow = Minimum lateral offset at the instant we start pouring.

R_cup = Cup inner radius.

R_stream = The stream radius/uncertainty.

R_margin = The rim safety margin accounting for things like cup movement, buffer or outside environment factors.

Formula: R_allow = R_cup - R_stream - R_margin.

Some components that can cause us to be outside of R_allow include, the vision subsystem having inaccuracies, the PID Loop on our motor FOC control being unstable ,kinematic error, and EMI interference on signals causing improper judgement.

3 Cost and Schedule

3.1 Cost

Part:	Number of:	ID number:	Link:	Manufacturer:	Total:
Arctos Arm	1	WES2876	Link	West3d	300
PCB	1	0000001	NA	In-House	75
Load Cells:	2 (8 total)	XM782345390	Link	ShanHJ	32
Filament:	1 (4kg total)	HGK1072347	Link	SUNLU	43
Plywood	1	202093792	Link	Home Depot	35
Labor	$20*200H total	NA	NA	NA	4000
Grand total:					4485

3.2 Schedule

Milestone:	Date ETA:	Date Final:
CAD completion	2/25/2026	2/25/2026
PCB completion and DRC PASS	2/28/2026	3/05/2026
Assembly of Arm	03/05/2026	03/10/2026
Completion of Weight scales	03/10/2026	03/15/2026
Completion of Passive Cup Disp	03/25/2026	03/30/2026
Initial whole system assembly	04/01/2026	04/01/2026
Successful one-of-run	04/05/2026	04/07/2026
Completes multiple interactions	04/10/2026	04/12/2026
Finalized and works	04/15/2026	04/15/2026

4 Ethics And Safety

4.1 Positive Contribution to society

Our device contributes to society in two meaningful ways. First, from an entertainment and educational standpoint, it is designed to function as an engaging and interactive demonstration platform, with the goal of inspiring young engineers and students to further pursue their interests in STEM. By presenting robotics and control systems in a tangible, hands-on format, the device makes advanced engineering concepts more accessible and exciting. Beyond education and inspiration, the system also has clear assistive applications. It can be deployed in environments where users struggle with fine motor skills, such as post-stroke patients or individuals with Parkinson’s disease. For these users, the device can simplify a common daily task and significantly reduce physical strain, ultimately improving independence and overall quality of life.

4.2 Engineering Standards of Project

- IEEE 7000-2021
  - For Ethical Values & System Design
  - Applies to our project because our product must uphold an ethical purpose
- IEEE 7001-2021
  - Transparency for our testing on autonomous systems
  - Applies to our project because our tests should be transparent so people know the limitations of our system
- IEEE 1872-2015
  - Used for robotics and automation with planning and task or environment representations
  - Relevant to our project because our robot plans its actions based on its classified state in the main algorithm

4.3 IEEE/ACM Code Application to our project

- Safety First: Safety Signals have the lowest CAN-ID, so they win arbitration meaning they send the signals to the bus instead of anything else.
- Transparency & Predictability: All tests will be publicized, so there will be complete honesty and transparency about the limitations of our robot.
- Responsible Testing: We supervise each test and ensure that people are not endangered by tests. We will also ensure that tests provide conclusive data about robot edge cases.

4.4 Safety Concern Mitigations

Our project uses an ARCTOS robotic arm to move and position dispensing components for filling cups. While the system involves electromechanical motion, it has been intentionally designed to minimize risk to both users and developers through conservative mechanical choices, low-voltage operation, and multiple physical safeguards.

Mechanical Safety:

The ARCTOS arm selected for this project is a lightweight, low-force robotic arm intended for educational and light-duty applications. It is not capable of generating high torque or high-speed motion that would pose serious injury risks. Motion speeds will be software-limited to further reduce kinetic energy during operation.

To further mitigate physical contact risks, all hard edges on the arm structure and surrounding frame will be padded with compliant foam or rubber materials. The interaction zone will be clearly defined and limited strictly to cup placement. The arm's range of motion will be restricted in software to prevent unintended sweeping outside of its intended operating envelope. An easily accessible emergency stop mechanism will be included to immediately disable motor power if triggered.

Because the arm is used strictly for cup positioning and dispensing tasks, it does not handle heavy payloads or perform high-force interactions. The system is therefore inherently low-risk from a mechanical standpoint.

Electrical Safety

The entire system operates below 36 V DC, which significantly reduces electrical hazard risk. No high-voltage AC systems are used. Additionally, the system will not operate at high amperage levels.

All wiring will be properly insulated and secured with strain relief. There will be no exposed wires, terminals, or conductive leads accessible to users. All electronics, including PCBs and power distribution components, will be fully enclosed inside an electrically insulating protective housing. Proper grounding practices will be followed where applicable, and fuses or current-limiting protection will be implemented in the power path to prevent fault conditions.

The use of low-voltage DC systems ensures compliance with standard laboratory safety practices for educational electromechanical devices.

Human Interaction Safety

The device is designed for safe interaction in a controlled demonstration environment. Users will only interact with the filling zone by placing cups on a designated platform. They will not need to access internal electronics or mechanical subsystems.

The system will be supervised during operation. A Safety Manual will be provided outlining startup procedures, shutdown procedures, emergency stop instructions, and safe interaction boundaries. The device will always be powered down during maintenance, inspection, or hardware adjustments. Developers will follow standard laboratory safety protocols when assembling or modifying electrical components.

Risk Classification

This project does not involve flying vehicles, high-voltage systems, high-power industrial actuators, pressurized systems, or hazardous chemicals. All design decisions prioritize minimizing stored energy, limiting mechanical force, and enclosing electrical components.

Safety Documentation

A formal Safety Manual will be produced prior to demonstration. It will include electrical system specifications and voltage limits, mechanical motion limits and speed restrictions, emergency stop procedures, maintenance and inspection checklists, developer handling procedures, and a pre-demonstration safety verification checklist.

We believe that our low-voltage architecture, enclosed electronics, padded mechanical surfaces, limited-force arm selection, and supervised operation sufficiently protect both users and developers from unsafe conditions. The system is intentionally designed as a low-risk, educational-grade robotic platform with layered mechanical and electrical safeguards.

5 Citations

[1]"DIY 3D printed robotic arm," *ARCTOS*. https://arctosrobotics.com/

[2]"OAK-D S2," *Luxonis*, 2025. https://docs.luxonis.com/hardware/products/OAK-D%20S2

[3] *Istockphoto.com*, 2025. https://www.istockphoto.com/illustrations/pcb-board (accessed Feb. 28, 2026).