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Senior Design Project

Smart Laundry FoldBot

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Chapter 1

Introduction

1.1 Problem

In response to the growing demand for household automation, this project focuses on the development of an intelligent T-shirt folding machine capable of efficiently handling scattered clothes. While existing solutions can only fold flattened garments, our objective is to bridge the gap by creating a system that can retrieve T-shirts from a basket, identify the shape of T-shirts, automatically flatten them, and apply specific folding methods to handle them. Our machine can automatically grasp, flatten and fold clothes, liberating people from tedious steps. Compared to existing solutions on the market, the machine possesses strong competitiveness compared to other machines on current markets.

1.2 Solution

Our proposed solution involves the development of an automatic T-shirt folding machine equipped with advanced vision algorithms and robotic manipulation techniques. By leveraging vision models, the system will be able to recognize the shape of the T-shirts and flatten the clothing according to its shape. The mechanical design will incorporate flexible gripping mechanisms and folding boards capable of adapting to different T-shirt dimensions and materials. Through iterative testing and refinement, we aim to create a reliable and efficient solution that streamlines the T-shirt folding process, ultimately saving time and effort for users. A brief figure depicting our system for visual aid is shown in Figure 1.1.

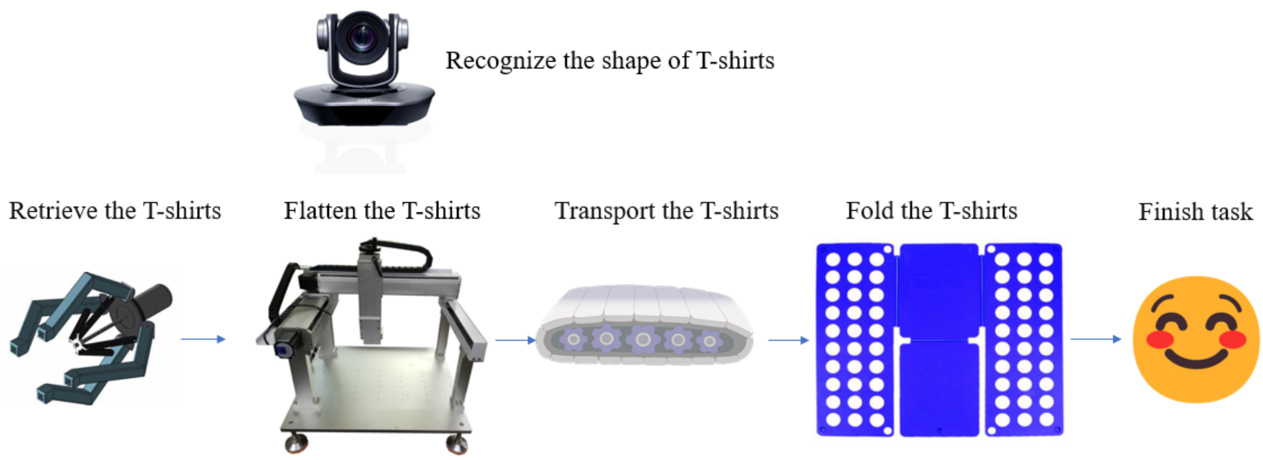

Figure 1.1: Control System Flowchart

1.3 High-Level Requirements

1. Visual Model Technology: Our visual model employs deep learning algorithms to achieve an 85% accuracy rate in feature recognition and 90% in image segmentation accuracy. Posture analysis maintains an error margin within ±2 degrees, significantly enhancing the finesse and accuracy of complex object form analysis.

2. Robust Reinforcement Learning Algorithm: Our reinforcement learning algorithm simulates main environmental disturbance factors (Variability in Garment Types and Materials, and unpredictable Garment Positions and Conditions) and integrates these into the source environment model for simulation, enhancing strategy transfer robustness and reducing operational error rates by 10-15% compared to before optimization. Particularly in garment handling, the algorithm ensures effective prevention of new creases in most operational scenarios, improving efficiency and the quality of treatment.

3. Robust Integrated Mechanical and Electronic Control System: The control system achieves precise response times of less than 10 milliseconds and ensures performance deviation remains below 1% during extended operations (such as continuous operation for 3 hours). This system is especially suitable for tasks requiring high precision control, like garment folding, significantly reducing the likelihood of creases during operation and markedly enhancing operational accuracy and efficiency.

Chapter 2

Design

2.1 Block Diagram

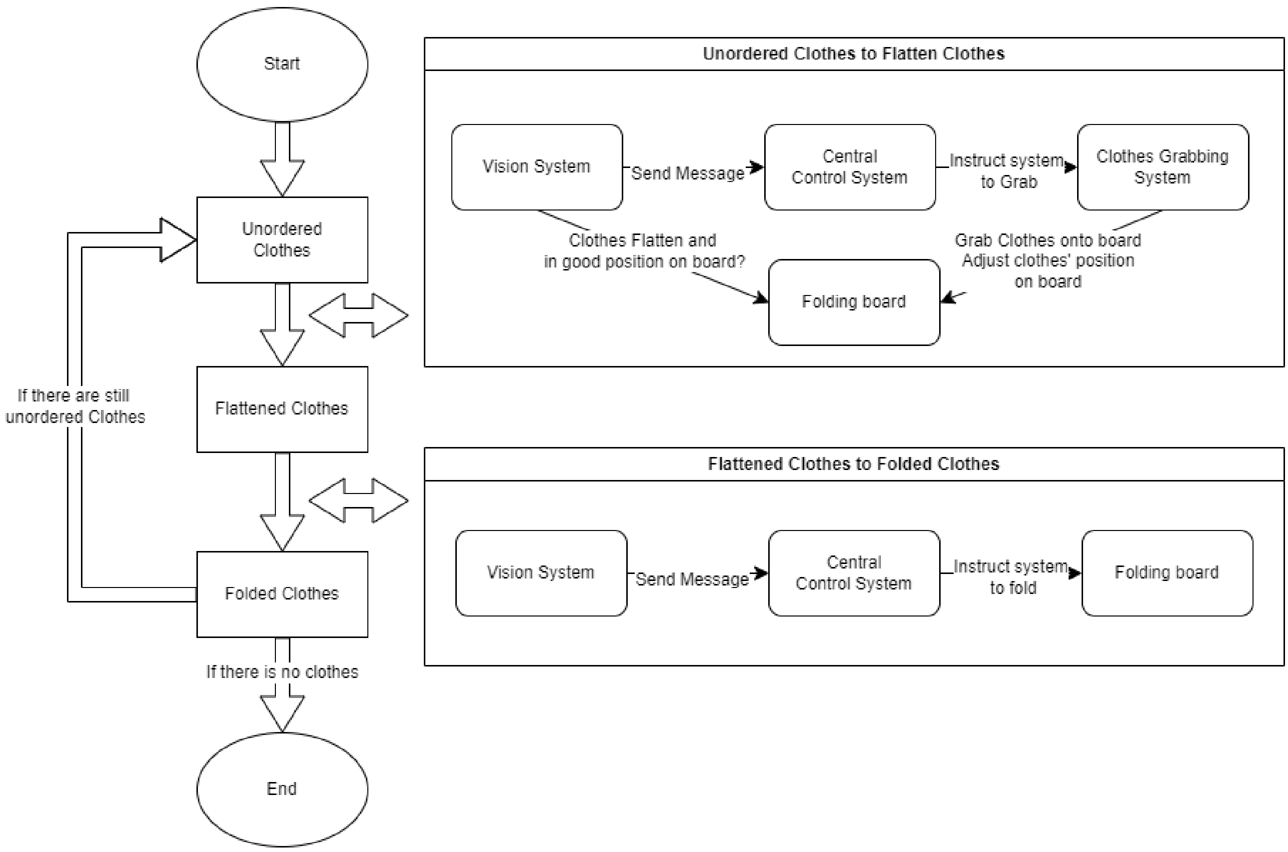

Figure 2.1: System Functionality Illustration

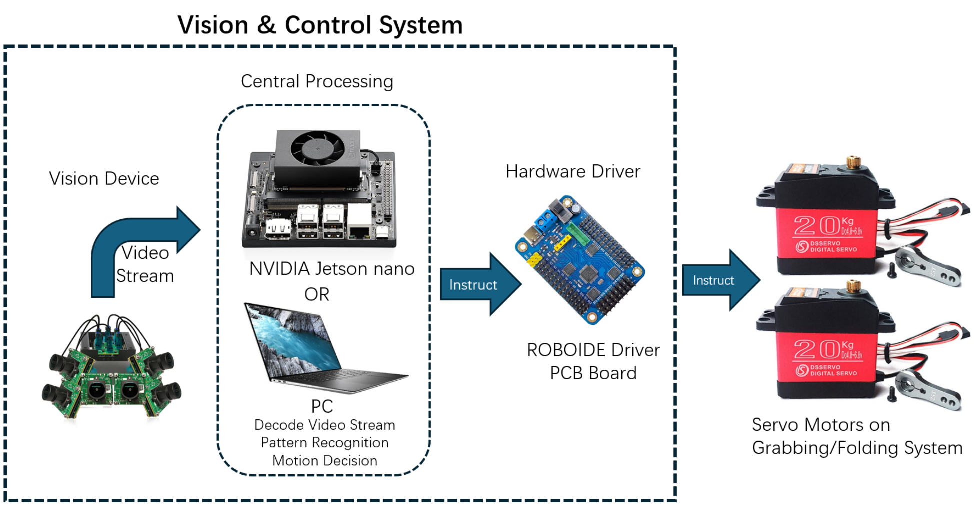

Figure 2.2: Vision and Control System Design

2.2 Subsystem Overview

2.2.1 Subsystem 1: Grabbing System

Purpose and Components: There is academic research on using Deep Reinforcement Learning and Computer Vision to classify and flatten clothes. Sun, Li (1) has shown deep reinforcement learning's promising capability for flattening Wrinkled clothes. Y Tsurumine (2) has shown deep reinforcement learning's capability for clothes smoothing. Cychnerski (3) has shown neural network's capability for clothes detection.

The first subsystem is designed to grab loose clothing from a clothes basket and transport it to the second subsystem, the folding system. The fetching system comprises a six-axis manipulator and a visual recognition device. The visual recognition device can automatically identify the shoulder of each piece of clothing. Subsequently, the robot accurately grabs the clothes' shoulders and transports them to the folding system.

Operation and Interaction:
Our design uses two symmetrical six-axis robotic arms to symmetrically grab T-shirts. After successful grasping, linear slide rails are used to transport the entire garment to the folding mechanism.
The clothes picked up by the robot will pass over a long roller device located in front of the folding system. The long roller device will ensure that when the robot arm places the clothes on the folding system, the clothes will always remain flat (not curled); when the robot arm releases the clothes, the clothes will be flat on the folding plate.

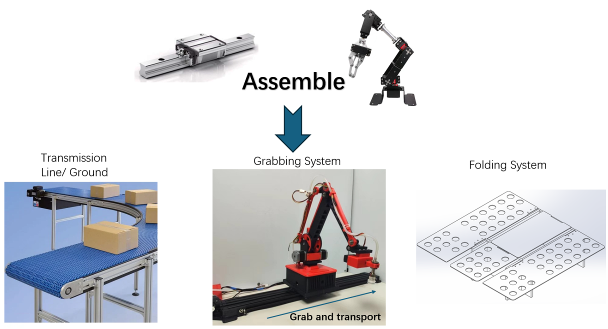

Figure 2.3: Grabbing System Interaction

Figure 2.4: Grabbing Design Illustration

2.2.2 Subsystem 2: Folding System

Purpose and Components: This subsystem automatically identifies the clothing size and folds them according to the preset parameters. It consists of core boards and expansion plates. There are existing folding machines like FoldiMate (4), which is an innovative implementation of folding a well-arranged T-shirt. But there is no implementation for a randomly arranged T-shirt. The Folding and Stacking system is functionally the same as the FoldiMate.

Core Boards

The primary folding mechanism includes four specialized boards, each powered by an electric motor, designed to fold 180 degrees to facilitate sequential folding of clothing. These are:

- **Left Core Board:** Positioned on the left side, folds 180 degrees to the right, folding the left portion of the clothing.
- **Right Core Board:** Located on the right side, folds 180 degrees to the left, mirroring the action of the left core board.
- **Center Lower Core Board:** Situated below the central part of the clothing, folds upwards 180 degrees, folding the lower part of the garment.
- **Center Upper Core Board:** Located above the central part of the clothing, also folds upwards 180 degrees, completing the fold by folding the upper portion of the garment.

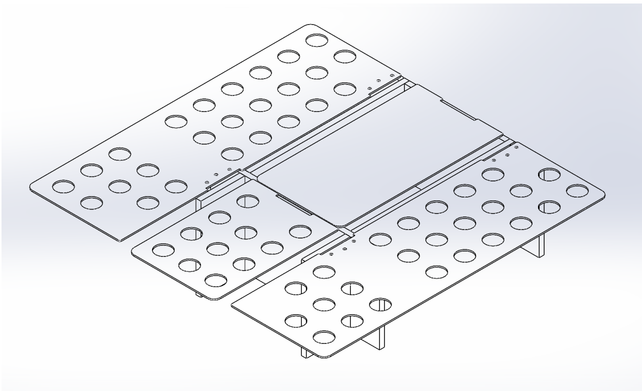

Figure 2.5: Folding Board Illustration

Expansion Plates

This part consists of three adjustable plates to provide flexibility for handling various clothing sizes and types:

- **Left Expansion Plate:** Adjacent to the left core board, extends or retracts to accommodate different clothing sizes.
- **Right Expansion Plate:** Positioned next to the right core board, adjusts for the parts of the clothing that exceed the right core board.
- **Lower Expansion Plate:** Located below the central lower core board, ensures a complete and neat fold by adjusting for clothing parts that extend beyond the board.

Conclusion: These two subsystems enable our automated folding device to perform its function in an efficient and hassle-free manner. The Cloth Grabbing System ensures clothes are prepared for folding, while the Folding System adapts to various clothing sizes for precise folding.

2.3 Subsystem Requirements

2.3.1 Requirements for the Grabbing System

The grabbing system is tasked with the automated handling of T-shirts post-dryer, involving precise grabbing, effective flattening, and accurate placement on a folding mechanism. This system combines mechanical design and control algorithms to manage variably positioned and oriented garments.

- **Fetching Role:**
  - **Requirements:**
    - *Grasping Stability and Speed:* The claw mechanism must ensure a stable grasp on T-shirts moving at speeds up to 10 cm/s within a 2-meter square operational area. The system shall maintain a minimum grasping efficiency of 99.5%, with a tolerance for dropping garments not exceeding 0.5%. Testing conditions include a range of T-shirt sizes (S, M, L, XL) and materials (cotton, polyester, blends).
    - *Visual Recognition System:* Must accurately determine T-shirt position and orientation with a precision threshold where the deviation from the target grabbing point is less than 1 cm, achieving this accuracy within 1.5 seconds for 96% of operations. The system should adapt to variations in lighting conditions within a luminance range of 200-800 lux.
- **Flattening and Placing Role:**
  - **Requirements:**
    - *Flattening Effectiveness:* Achieve a flattening outcome where residual wrinkles are less than 1 cm in height, and the process duration does not exceed 4 seconds per T-shirt, with a process reliability of 98%. The mechanism must adjust its flattening strategy based on pre-identified T-shirt material characteristics.
  - **Methods:**
    - Mechanical mechanism design to incorporate adjustable pressure plates with feedback control to modulate force based on the T-shirt's fabric type and detected wrinkles. This system should self-calibrate for different garment thicknesses within 3 operational cycles.
    - Implementation of a reinforcement learning algorithm for intelligent clothing flattening, designed to optimize flattening paths and pressure application points. The algorithm requires a maximum of 5 learning iterations to adjust to a new T-shirt type, with a subsequent operation efficiency improvement target of 20%.

2.3.2 Requirements for the Folding System

The folding system encompasses an electric mechanism designed for precision folding of T-shirts and their orderly stacking. This system leverages an electromechanical approach to ensure consistent and accurate folding, followed by stacking in a predefined arrangement.

- **Folding Clothes:**
  - Requirements:
    - *Operational Force and Speed:* The system must generate adequate force to manipulate T-shirts, with folding arm rotational speeds adjustable between 0.4 rad/s and 1.2 rad/s. The system shall achieve a folding precision where the variance from the intended fold line is less than 0.8 cm, with a consistency rate of 99% across all T-shirt sizes.
  - Mechanism: A servo-driven electro-mechanical system with integrated sensors for real-time fold quality feedback, enabling dynamic adjustment to fold parameters to maintain accuracy under varying load conditions.
- **Stacking Clothes:**
  - Requirements:
    - *Alignment Accuracy:* Stacked T-shirts must exhibit a high degree of alignment, with each subsequent layer aligning within a tolerance of 1.5 cm of the one below it, and necklines uniformly oriented. This specification aims for a 98% success rate in stack uniformity, accounting for all standard T-shirt sizes.
  - Purpose: To ensure a systematic and orderly stacking process, facilitating subsequent handling, storage, or packaging activities with minimal manual adjustment requirements.

2.4 Tolerance Analysis

2.4.1 Grabbing System Tolerance Analysis

We choose a six-axis manipulator to transport and flatten clothes onto the folding board.

Assumption for Analysis

We need to grab the clothes from the ground and place them onto the folding plate. So we need a relatively large manipulator system with y-axis slides to transport the clothes. At least we should have a height of 75cm so that the T-shirt can be naturally flattened through gravity. Then we chose the largest manipulator under the budget.

Figure 2.6: Six-Axis Manipulator

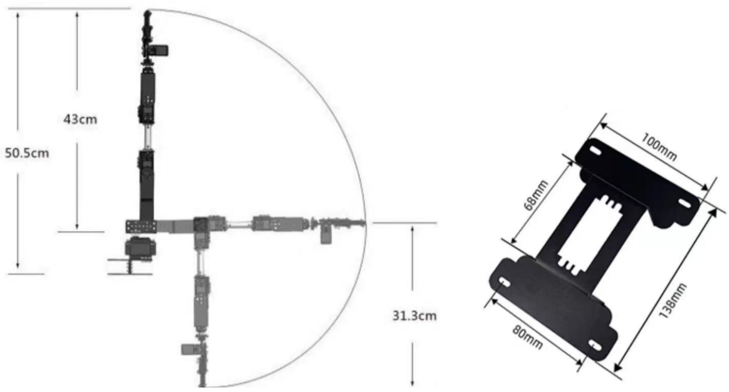

Figure 2.7: Manipulator Size

As we can see in Figure 2.7, The stroke in the z direction reaches about 75cm. The Manipulator can grab the T-shirt and make it flatten through gravity.

2.4.2 Folding System Tolerance Analysis

The folding plates are powered by steering engines and should be able to fold clothes on the plates. We aim to design four plates. Two big plates have a size of 80cm $\times$ 30cm and two small plates have a size of 40cm $\times$ 30cm. They can match the size of the clothes. We chose DS3218 steering engines and they have enough power to fold plates and clothes. The parameters of the engines are listed below.

Operating Voltage	5V	6.8V
Idle current(at stopped)	4mA	5mA
Operating speed (at no load)	0.16 sec/60°	0.14sec/60°
Stall torque (at locked)	18 kg-cm	21.5 kg-cm
Stall current (at locked)	1.8A	2.2A

Figure 2.8: Steering Motor Electrical Specification

2.4.3 Vision System Tolerance Analysis

The VRT is crucial for the system's ability to identify the position and orientation of clothing accurately. It is defined by the system's resolution and its error margin in recognizing clothing features.

Assumptions for Analysis

- The visual recognition system can decode video images of 1920*1080p at 30fps
- The system can identify clothing positions and do AI inference for $1920 * 1080 * 30 * (4\text{bytes}) = 248.83200\text{MB/s}$ computational input.

The table below lists the NVIDIA Jetson Nano specs. As we can see, Jetson Nano is capable of CV development and AI inference since its GPU can process 472 GFLOPS of floating point calculation.

Table 2.1: Jetson Nano AI Performance and Video Codec Capabilities

Feature	**Specification**
AI Performance	
GPU	128-core Maxwell CUDA core
GFLOPS	472
CPU	Quad-core A57
Clock speed	1.43 GHz
Video Codec Capabilities	
H.264	Encode and decode up to 4K at 30 FPS
H.265	Encode and decode up to 4K at 30 FPS
VP8	Encode and decode up to 1080p at 30 FPS
VP9	Encode and decode up to 1080p at 30 FPS

2.5 Subsystem Verifications

2.5.1 Grabbing System Verification

1. **Stable Grasping Capability**:
   - *Requirement*: The mechanical claw must reliably grasp clothing in 98% of attempts across a range of garment types.
   - *Verification*: Conduct a series of 100 consecutive grasping tests on various garment types and materials. Success criteria: Achieve a minimum 98% success rate.
2. **Visual Module Accuracy**:
   - *Requirement*: The visual module must identify the shoulder area of garments with a precision of 0.3cm to 0.8cm error margin.
   - *Verification*: Evaluate the visual module's accuracy on 50 different garments. Success criteria: Achieve within the specified error margin for at least 96% of garments.
3. **Stable Transportation Speed**:
   - *Requirement*: Garments must be transported at a consistent speed of 10cm/s to 20cm/s over a 2m distance.
   - *Verification*: Measure and record the speed of transportation over 2m for 30 garments. Success criteria: All measurements must fall within the specified speed range.
4. **Accurate Placement on Folding Board**:
   - *Requirement*: Garments must be placed at the center of the folding board with a tolerance of $\pm$1cm, with all collars aligned in the same direction.
   - *Verification*: Assess the placement accuracy of 50 garments on the folding board. Success criteria: 95% of garments must be correctly placed within the tolerance range.
5. **Continuous Stable Operation**:
   - *Requirement*: The system must demonstrate continuous and stable operation over a 4-hour period without performance degradation.
   - *Verification*: Run a continuous operation test for 4 hours simulating real-world usage. Success criteria: No performance decrease or operational errors should occur.

2.5.2 Folding System Verification

1. **Synchronization with Grabbing System**:
   - *Requirement*: The fold system must initiate folding only after garments are fully and correctly positioned on the folding board, achieving 100% synchronization accuracy.
   - *Verification*: Conduct 50 operational cycles to test synchronization. Success criteria: Perfect synchronization in all cycles.
2. **Wrinkle-Free Folding**:
   - *Requirement*: At least 95% of the folded garments must not exhibit visible wrinkles that deviate from the wrinkle-free standard.
   - *Verification*: Fold 100 garments and evaluate each for wrinkles against a predefined standard. Success criteria: Achieve or exceed the wrinkle-free standard for 95% of garments.
3. **Stable Removal Post-Folding**:
   - *Requirement*: Garments must be removed from the folding board without affecting the fold integrity in 98% of operations.
   - *Verification*: Remove 50 folded garments, assessing the fold integrity post-removal. Success criteria: Maintain fold integrity for 98% of the garments during and after removal.

Chapter 3

Cost and Schedule

3.1 Cost

We have purchased most of the parts that we need, since the building and assembling process are not completed, there might be new items that we need to purchase.
Table 3.1 shows the estimated cost table for this project, Please note that all concurrency unit on table 3.1 is Chinese Yuan.

Module	Item	Price	Quantity	Total
Control and Vision Module	NVIDIA Jetson Nano	800	1	800
	NVIDIA Jetson Nano Power Supply	62.9	1	62.9
	ROBOIDE Servo Driver PCB	168	1	168
	5v 12A DC Power	35	1	35
	DC 5.5*2.5 Power Plug	10.5	1	10.5
	RV Power Wire	19.8	2	39.6
	Camera(Estimated)	400	2	800
Grabbing Module	Foldable Table	72.9	1	72.9
	6-axis Manipulator with Servo	388	2	776
	Linear slide module(Estimated)	3000	1	3000
	Support for slide module(Estimated)	500	1	500
Folding Module	CNC Carbon-fiber folding board	820	1	820
	M6 Screw-Nut Set	7.35	1	7.35
	Custom Wood Board	82	1	82
	M4 Self-tapping screws	14.04	1	14.04
	L-bar	5.7	1	5.7
	Metal Hinge	2.89	8	23.12
	DS3218 20kg Servo Engine	115	4	460
	DS3218 Servo Support	8	4	32
	Servo Extension Wire	2.2	30	66
	Custom Arm for Servo(Estimated)	100	4	400
Total(CNY)		8175.11		

Table 3.1: Total Estimated Cost for FoldBot

3.2 Schedule

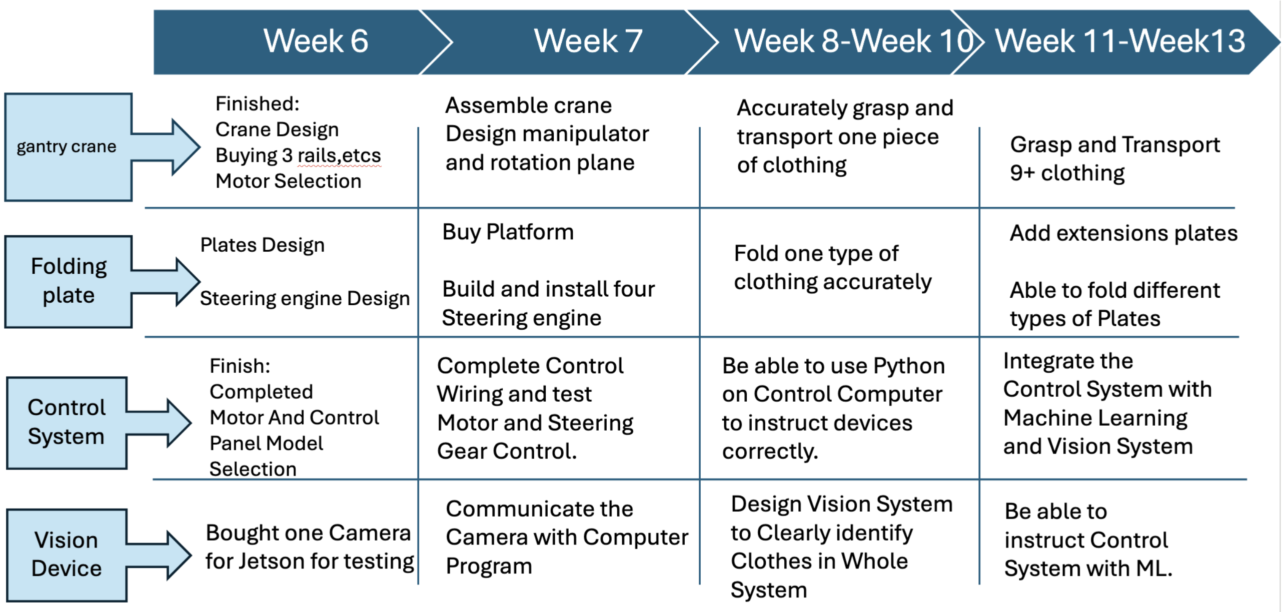

Figure 3.1: Schedule

Chapter 4

Ethics and Safety

4.1 Ethics

In alignment with the principles outlined in both the IEEE (5) and ACM (6) Codes of Ethics, our project rigorously addresses the following ethical concerns:

Social Responsibility: Our project is committed to evaluating and mitigating its impact on society, encompassing social, economic, and environmental dimensions. We pledge to assess not just the immediate advantages of our work but to anticipate and plan for potential long-term effects on the community and environment.

Fairness and Equity: We guarantee that our project operations and outcomes will adhere to the highest standards of fairness and justice, ensuring no discrimination against individuals or groups based on ethnicity, gender identity, sexual orientation, religion, or national origin. Acknowledging the potential for inherent biases, we are dedicated to identifying and rectifying these biases through conscious design and implementation strategies.

Integrity and Transparency: Our team commits to upholding the utmost levels of honesty and transparency throughout the project life cycle. This includes clear communication regarding the project's progress, and any associated risks, uncertainties, or conflicts of interest to all stakeholders, including team members, instructors, and the broader community. This commitment ensures accountability and fosters trust in our project and its outcomes.

4.2 Safety

Our project's development and implementation strictly adhere to the safety guidelines specified on the course website and relevant regulatory standards, emphasizing:

Electrical Safety: Given our project's reliance on electrical components, we prioritize electrical safety to prevent risks such as electrocution or fires. This involves ensuring proper insulation and grounding of wires, correct sizing and protection of circuits, and the provision of necessary safety equipment for electrical component handling.

Mechanical Safety: For projects involving mechanical elements, we ensure that all machinery, such as motors, is securely installed and that moving parts are safeguarded to prevent accidents. This includes implementing physical barriers and safety protocols to protect users and equipment from harm.

Laboratory Safety: Our project's development process includes stringent laboratory safety measures to protect project members from potential hazards associated with tools, equipment, and materials used. This encompasses comprehensive safety training for all project participants, availability of appropriate protective gear, and conducting all experimental activities within a controlled laboratory setting.

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