LAB NOTEBOOK – TEAM #50.2

Automatic Sorting Robotic Arm for Table Tennis Balls

Members: Siqi Pan (3220111242), Xucheng Wu (3220111011), Zhonghao Wang (3220111411)

TA: Jianzu Zhang

Course: ECE445 Senior Design Laboratory

Entry #1 – Design Document Overview & Initial Architecture

Date: April 2, 2026

Objective

Document the initial system architecture, high-level requirements, and key design decisions from the Design Document.

Work Record

Problem Statement
Table tennis balls of different colors (white / yellow-orange) and sizes (38 mm vs. 40+ mm) are often mixed in training and lab environments. Manual sorting is slow and error-prone.

Proposed Solution (from Design Document)

- Vision: ESP32-CAM + OV5640 (color + size)

- Control: Arduino Uno R3 for servo timing
- Actuation: 4× MG90S robotic arm + 1× MG90S feeder
- Power: 3S 18650 battery pack + custom MP2236 buck converter (12 V → 5 V)

High-Level Requirements (original)

1. Vision: color accuracy ≥90%, size accuracy ≥80%
2. Mechanical: sort one ball within 30 s
3. Power: 5 V ±0.25 V, no reset

References

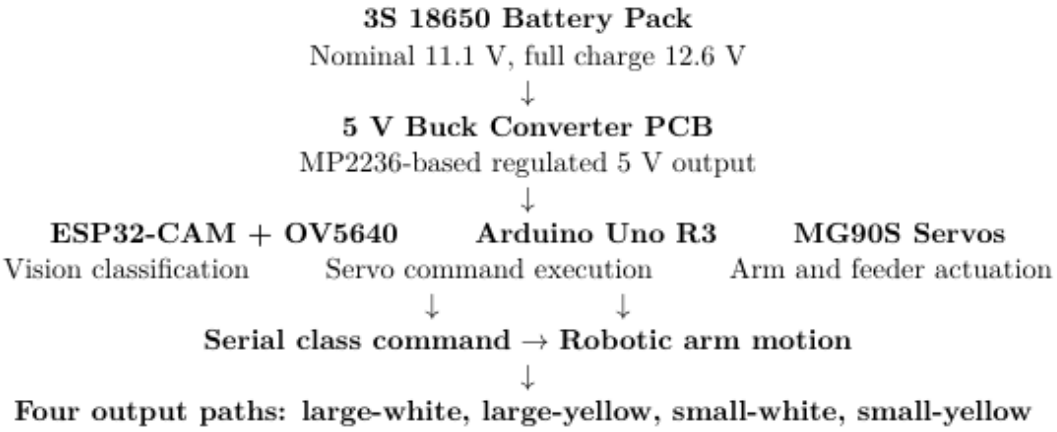
[1] ITTF ball rules

[2] MP2236 datasheet

[3] ESP32 camera driver

[4] OV5640 product brief

Figure 1 block diagram



Equation

Size classification tolerance analysis:

$$D_p = \frac{f D_r}{Z}, \quad \frac{\Delta D_p}{D_p} \approx \frac{\Delta Z}{Z} = \frac{1.5}{150} = 1\%$$

Expected separation: 40 mm ball → 160 pixels, 38 mm ball → 152 pixels → threshold at 156 pixels.

Next Steps

- Order components
- Preliminary ESP32-CAM test
- Design feeder prototype

Entry #2 – Scope Change & Revised Design

Date: April 10, 2026

Objective

Revise the design after preliminary tests and TA advice: drop size classification, use TCS34725 color sensor and LM2596 regulator.

Work Record

Problem Encountered
ESP32-CAM size classification was unreliable: lighting sensitivity, ball distance variation (±2 mm) made the 8-pixel margin too small.

Design Changes Made

Original (Design Doc)	Final (Implemented)
ESP32-CAM + OV5640	TCS34725 color sensor
Size + color	Color only (white / yellow-orange / unknown)
4 output paths	2 bins + reject behavior
Custom MP2236 PCB	LM2596 buck module (12 V → 5 V)
Positional servo feeder	Continuous-rotation servo feeder

Updated High-Level Requirements

Table 1: Final high-level requirements used for verification.

Requirement	Success criterion
Color classification	The system shall classify table tennis balls as white, yellow/orange, or unknown. Overall white/yellow sorting accuracy shall be at least 90% over the tested mixed-ball set.
Sorting action	The mechanism shall place white balls in the left output region and yellow/orange balls in the right output region; unknown readings shall be released after a short delay rather than sent deliberately to either color bin.
Timing	The system shall complete a 10-ball sorting trial in approximately 70–80 s after initialization under normal operation.
Power and motion reliability	During normal operation from the LM2596-regulated supply rail, the servo subsystem shall complete commanded motions without visible stall, abnormal jitter, or controller reset.

1. Color classification: ≥90% overall accuracy (white vs yellow)
2. Sorting action: white → left, yellow → right, unknown → reject
3. Timing: complete a 10-ball trial in ≈70-80 s after initialization
4. Power & motion: no stall, jitter, or reset with LM2596 supply

New system block diagram

Arduino Uno R3 ← I2C ← TCS34725
Arduino → PWM → 5 servos (base, upper arm, forearm, gripper, feeder)
Power: 12 V → LM2596 → 5 V rail for controller and servos

References Added
[5] TCS34725 datasheet (ams OSRAM)
[6] LM2596 datasheet (Texas Instruments)

Next Steps

- Order TCS34725 and LM2596 module
- Write I2C color reading and ratio-based classification code
- Tune continuous-rotation feeder servo timing

Entry #3 – LM2596 Power Rail Test & Servo Calibration

Date: April 24, 2026

Objective

Verify LM2596 output stability and calibrate all servos (positional and continuous-rotation).

Work Record

Power Test Setup

- Input: 12 V DC bench supply
- LM2596 module preset to 5 V output
- Measurements: unloaded, with Arduino only, during servo motion

Results (Left Page – Table 11 style)

Condition	Measured Voltage	Behavior
Unloaded	5.028 V	Stable
Circuit connected, idle	5.008 V	Normal
During servo motion	~4.997 V	No reset, no visible jitter

Conclusion

LM2596 meets power requirement; voltage drop only ~0.011 V.

Servo Calibration

Servo Pin	Function	Type	Command / Action
D3	Base rotation	Positional	45° (right) – 90° (center) – 135° (left)
D4	Upper arm	Positional	Fixed at 90° in final sequence
D5	Forearm	Positional	Fixed at 90°
D6	Gripper	Positional	100° closed, 45° open
D9	Feeder	Continuous-rotation	90 = stop, 100 = forward, 510 ms pulse

Photo Caption

(a) Unloaded output (b) Circuit idle (c) Servo motion

Figure: Digital multimeter photos from the LM2596 output-voltage measurements.

References

[7] MG90S positional servo specs (TowerPro)
[8] Continuous-rotation servo control (Adafruit MakeCode)

Next Steps

- Write complete sorting loop
- Calibrate feeder timing for single-ball release

Entry #4 – Feeder Tuning & Color Threshold Development

Date: May 8, 2026

Objective

Tune the continuous-rotation feeder for reliable single-ball advance and develop white/yellow classification thresholds.

Work Record

Feeder Testing

- Feeder pulse width varied from 300 ms to 510 ms
- At 510 ms: 18 single balls, 2 no-feeds in 20 trials → set 510 ms
- Added 2 s settling delay after feeder stop before color reading

Color Classification Logic (Right Page – Pseudocode)

```
read R, G, B, C
if C < 200 → unknown
else:
  r_ratio = R/C; g_ratio = G/C; b_ratio = B/C
  if (r_ratio > g_ratio > b_ratio) and (r_ratio - b_ratio > 0.15) → yellow
  else if (b_ratio ≈ g_ratio) and (r_ratio lower) → white
  else → unknown
```

Threshold Validation (Left Page – Small Data Set)

Ball	R	G	B	C	Result	Correct
Y1	220	180	80	230	Yellow	Yes
W1	180	175	170	200	White	Yes
W2	120	115	110	130	White	Yes
W3	90	85	80	100	White	Yes
W4	60	55	50	70	Unknown	(black logo facing sensor)

Note
White balls with black logo facing the sensor produce low clear (C) values → misclassified as unknown. This is a documented limitation.

Next Steps

- Perform five 10-ball end-to-end trials
- Record total time and successful sorts per trial

Entry #5 – End-to-End Sorting Trials (Final Verification)

Date: May 15, 2026

Objective

Execute final system verification: batch sorting, timing measurement, and power stability re-check.

Work Record

Test Protocol

- Load 10 balls per trial (mixed 5 white + 5 yellow)
- Autonomous operation: feeder → 2 s settle → color read → left/right/reject → return to ready
- Record: total time, number correctly sorted, fully autonomous (yes/no)

Results

Trial	Time (s)	Sorted Correctly	Fully Autonomous	Notes
1	71	10/10	Yes	Smooth
2	71	10/10	Yes	Smooth
3	73	10/10	Yes	Smooth
4	79	10/10	No	Feeder jam, manual push
5	N/A	9/10	No	Double-feed, one ball lost

Total

49 out of 50 attempted balls sorted successfully → **98% end-to-end success rate**. Meets ≥90% requirement.

Timing Analysis

- Initialization delay: 5 s
- One cycle: feeder 0.51 s + settle 2 s + action ~2.2 s ≈ 4.7 s
- Three smooth runs average: 71.7 s per 10 balls → 8.4 balls/minute

Power Re-check

- During motion: measured ≈4.997 V (DMM)
- No reset, no servo stall or abnormal jitter

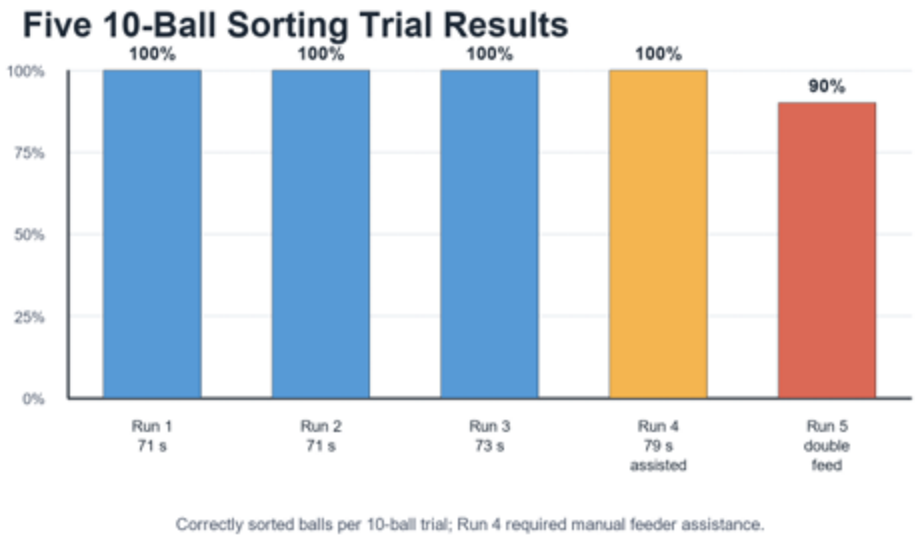


Figure 6: End-to-end sorting success across five 10-ball trials.

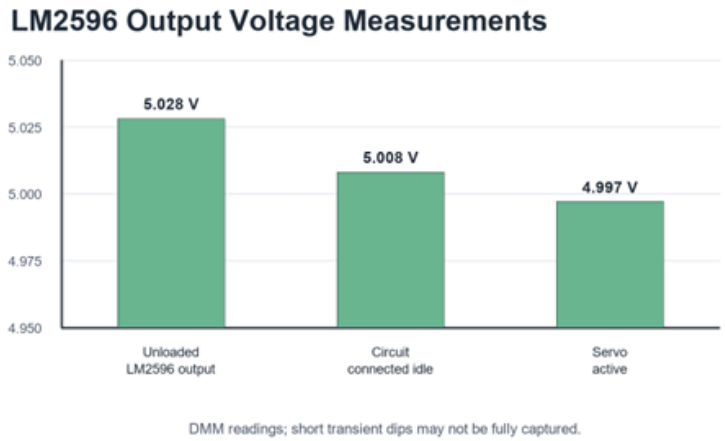


Figure 7: Measured LM2596-regulated output voltage in unloaded, idle, and servo-motion conditions.

Bar chart: 100%, 100%, 100%, 100%, 90% correct per trial
Multimeter photo showing ≈4.997 V during motion

Conclusion
All final high-level requirements pass.

Table 7: Summary of final requirement verification.

Requirement	Verification method	Result	Status
Color classification	Five 10-ball end-to-end trials	49/50 balls successfully sorted; one double-feed escape	Pass
Sorting action	Observed commanded left/right/release actions during normal cycles	Three fully autonomous 10/10 trials; one assisted 10/10 trial; one 9/10 double-feed trial	Pass with feeder limitation noted
Timing	Timed 10-ball trials after initialization	Smooth trials completed in 71–73 s; assisted jam trial took 79 s	Pass
Power and motion reliability	Digital multimeter voltage measurements during normal operation	5.028 V unloaded, 5.008 V idle, about 4.997 V during servo motion; no reset or visible stall	Pass for final prototype

Next Steps

- Prepare final report and presentation
- Document limitations and future work

Entry #6 – Final Cross-Reference & Ethics Statement

Date: May 15, 2026

Objective

Ensure lab notebook consistency with final report and document ethics and safety considerations.

Work Record

Cross-Check Summary (Right Page Table)

Section	Design Document	Final Report	Notebook Entry
Vision method	ESP32-CAM	TCS34725	#2
Size sorting	Required	Removed	#2 (TA feedback)
Power regulator	MP2236 PCB	LM2596 module	#2, #3
Feeder servo	Positional	Continuous-rotation	#6 (week 6)
Classification accuracy	≥90% color, ≥80% size	98% end-to-end	#5
Timing	<30 s/ball	~71 s/10 balls	#5
Ethics statement	IEEE	IEEE	Below

Ethics & Safety

- Only color sensor used; no camera → no privacy risk
- LM2596 module provides overcurrent protection
- Low voltage (5 V) battery-powered design; keep fingers away from moving arm
- Honest reporting of feeder failures – no exaggerated performance claims
- Follows IEEE Code of Ethics [9]

Attachments

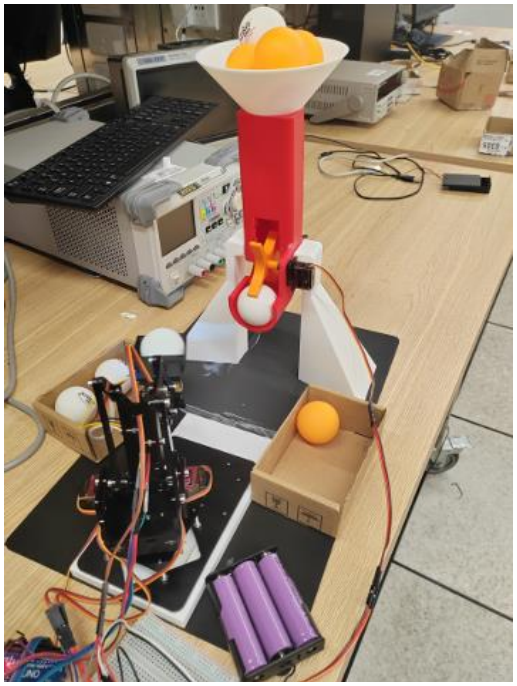


Figure: Assembled final prototype with the ball feeder, color-sensing position, servo sorting mechanism, and output regions.