ECE445 SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

Automatic Sorting Robotic Arm for Table Tennis Balls

Team #52

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Revised May 21, 2026

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1 Introduction

1.1 Problem Statement

Training and laboratory table tennis balls are often stored together after repeated use. White and yellow/orange balls can become mixed, even though ball color affects visual contrast in play and practice. The International Table Tennis Federation specifies legal table tennis balls as white or orange and matt [1]. If a coach, student, or lab user wants a consistent ball color for a drill or demonstration, manually separating a mixed container of balls is repetitive and slow.

The final project therefore targets a compact automatic two-color sorting system for common white and yellow/orange table tennis balls. The demonstrated design focuses on color-based sorting using a color sensor and a servo-driven mechanism. This scope keeps the core embedded-control and robotic-actuation objective while matching the hardware that could be tested end-to-end.

1.2 Solution Overview

The proposed final system uses an Arduino Uno R3 as the single controller, a TCS34725 color sensor as the sensing element, four positional servos for the sorting arm, one continuous-rotation servo for the feeder, and an LM2596 buck-converter module for the regulated 5 V supply rail. The Arduino Uno R3 provides the digital I/O and PWM-capable pins needed for this servo-driven prototype [3]. The TCS34725 reports red, green, blue, and clear-channel readings over I2C [2]. The Arduino normalizes the RGB readings by the clear channel and classifies each ball as white, yellow/orange, or unknown.

The mechanical sequence is also intentionally simple. A continuous-rotation feeder servo advances one ball, the program waits for the ball to settle at the sensor, the color sensor is read, and the sorting arm releases the ball to the left or right output region based on the classification. Unknown readings are released after a short delay rather than deliberately assigned to either color bin. The final build uses a 12 V input source stepped down by an LM2596 module to a regulated 5 V rail for the controller and servos [6].

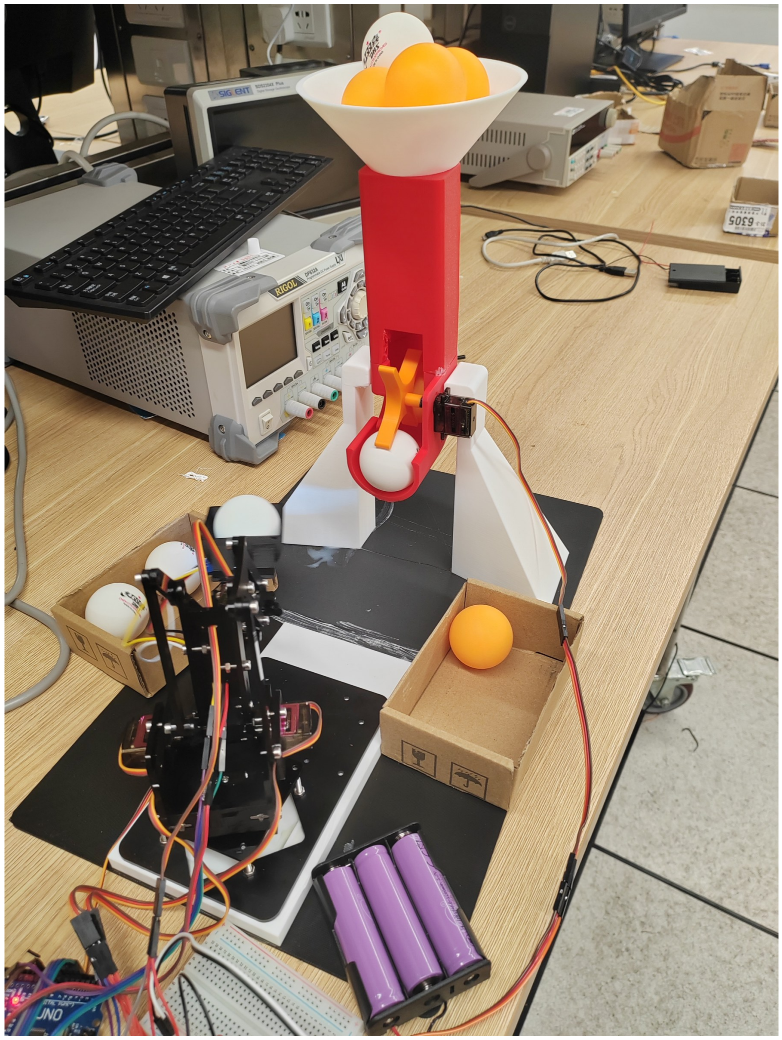

Figure 1: Final prototype in use: a feeder presents balls to the color-sensing and sorting region, and the servo mechanism directs them to the output regions.

1.3 High-Level Requirements

The complete system shall meet the following high-level requirements:

(1) **Color sorting accuracy:** The system shall sort white and yellow/orange table tennis balls with at least 90% end-to-end success over a mixed 10-ball trial set. Unknown readings shall not be intentionally sent to either color bin.

(2) **Sorting throughput and motion:** After initialization, the system shall complete a 10-ball sorting trial in approximately 70–80 s under normal operation, and the sorting arm shall return to the ready pose with the gripper closed after each ball.

(3) **Power stability:** The LM2596-regulated rail shall remain within 5.0 V $\pm$ 0.25 V during normal operation, and the controller shall not reset during feeder or sorting-arm motion.

2 Design

2.1 Block Diagram

Figure 2 shows the final modular design. The Arduino Uno R3 is the central controller. It receives color data from the TCS34725 over I2C, commands the five servos through PWM-style servo control signals, and executes the sorting sequence. The 12 V source is regulated to a 5 V rail through the LM2596 buck converter.

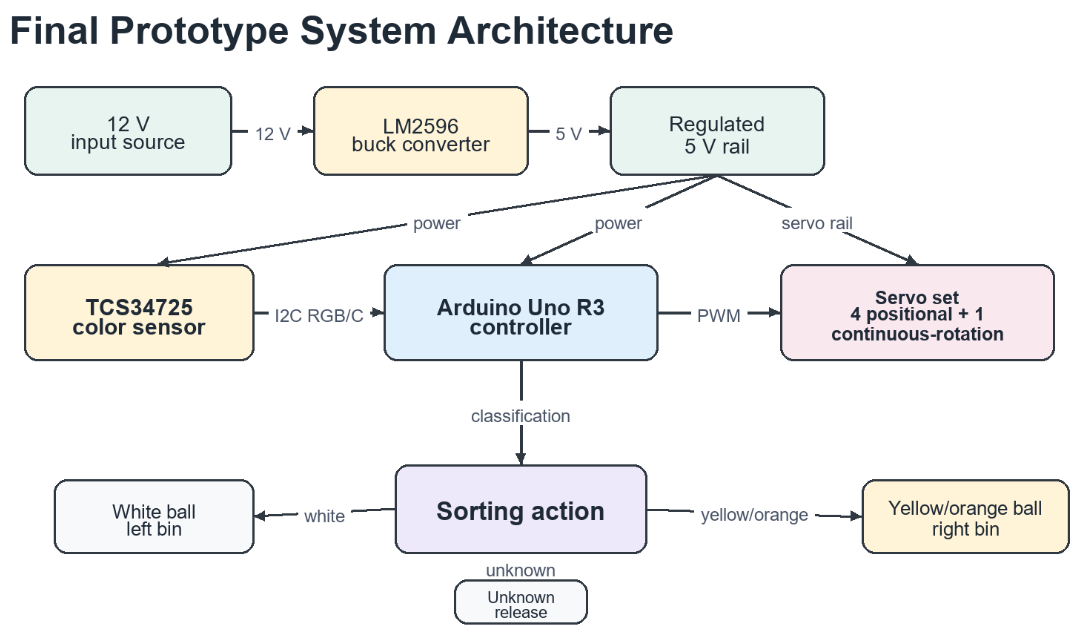

Figure 2: Block diagram of the final TCS34725-based table tennis ball sorter.

2.2 Color Sensing and Control Subsystem

The color sensing subsystem consists of the TCS34725 module and the Arduino Uno R3. The sensor is mounted near the ball inspection location so that each ball surface is measured after the feeder presents it. The software reads raw red, green, blue, and clear-channel values. The clear channel is used as a brightness reference:

$$R_r = \frac{R}{C}, \qquad G_r = \frac{G}{C}, \qquad B_r = \frac{B}{C}. \tag{1}$$

Yellow/orange balls are identified when the red ratio is greater than the green ratio, the green ratio is greater than the blue ratio, and the red-to-blue separation exceeds a calibrated threshold. White balls are identified from the measured ratio pattern in the final geometry, where the blue and green ratios are higher than the red ratio. A reading is treated as unknown when the clear channel is too low or when neither calibrated color rule is satisfied.

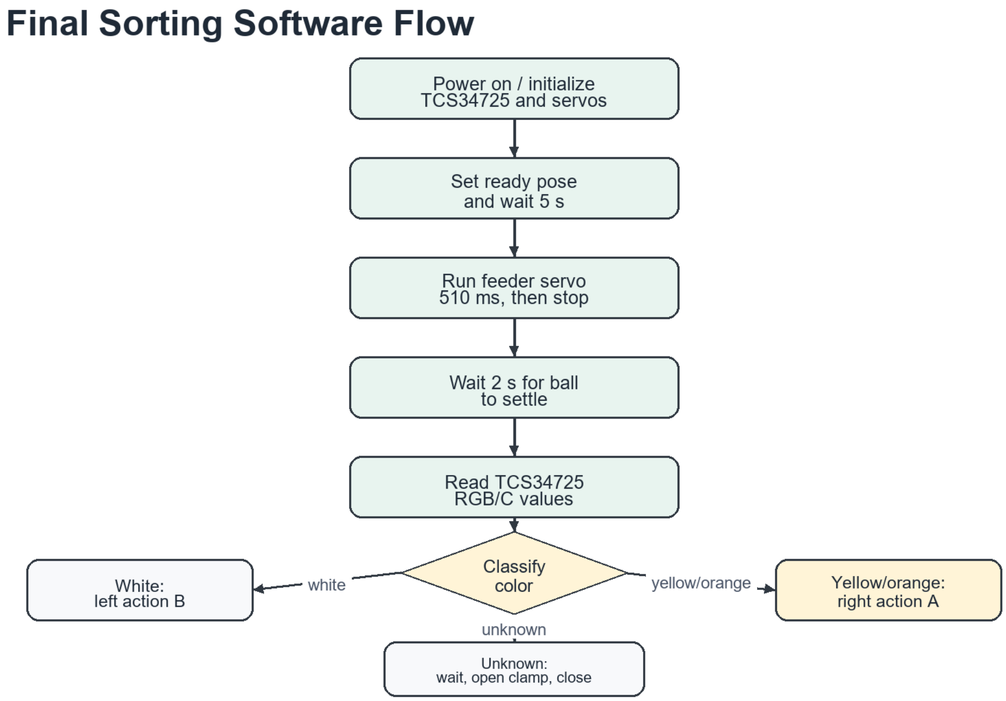

Figure 3: Software flow for the final feeder, sensing, classification, and sorting loop.

Table 1: Color sensing and control subsystem requirements and verification.

Requirement	**Verification**
The TCS34725 shall report a nonzero clear-channel value and valid RGB/C readings at the sensing location before a sorting command is executed.	Open the serial monitor during sensor testing and record RGB/C values for white and yellow/orange balls. A valid test requires stable nonzero clear-channel readings and repeatable ratio patterns.
The software shall classify yellow/orange and white balls using calibrated ratio thresholds and shall return unknown when neither color rule is satisfied.	Test a mixed set of balls and record the printed class. Success requires at least 90% end-to-end sorting success over the mixed test set and no deliberate assignment of unknown readings to a color bin.
The Arduino shall execute the full feeder-sense-sort loop without needing an external computer after programming.	Power the prototype from the regulated rail and run repeated cycles without serial input. Success requires autonomous operation after reset.

2.3 Feeding Subsystem

The feeding subsystem uses one continuous-rotation servo. This is different from a standard positional servo: the command value controls speed and direction rather than a target angle [5]. In the final calibration, a command near 90 stops the servo and a command of 100 rotates the feeder. The final program runs the feeder for 510 ms at the calibrated value, then returns the servo command to the stop value. After feeding, the software waits 2 s so the ball can settle at the sensing location.

Table 2: Feeding subsystem requirements and verification.

Requirement	**Verification**
The feeder shall advance balls using one continuous-rotation servo and shall stop between sorting cycles.	Observe 10 repeated feeder cycles. Success requires the servo to stop after each 510 ms command interval and remain stopped during sensing and sorting.
The feeder shall present no more than one ball to the sensing and sorting region in normal operation.	Run five 10-ball trials and record jams or double-feed events. Success is met when at least three 10-ball trials finish without manual intervention and without double-feed.
The ball shall be given a settling delay before color measurement.	Inspect the control code and time the loop. Success requires the 2 s delay to occur after feeder motion and before the TCS34725 reading.

2.4 Sorting Arm Subsystem

The sorting arm uses four standard positional MG90S servos. These servos are controlled by commanded angles within their limited travel range, and the MG90S form factor was selected because it is compact and provides enough torque for lightweight table tennis ball handling [4]. In the final motion profile, the base servo selects the output side, the gripper opens and closes to release the ball, and the upper-arm and forearm servos remain in their calibrated ready positions to improve repeatability. This simplified final sequence was selected after testing showed that unnecessary upper/lower arm movement reduced mechanical reliability.

Table 3: Final servo mapping and calibrated roles.

Pin	**Servo type**	**Function**	**Calibrated command**
D3	Positional	Base rotation	90 deg center, 45 deg right, 135 deg left
D4	Positional	Upper arm	90 deg ready, held fixed in final sequence
D5	Positional	Forearm	90 deg ready, held fixed in final sequence
D6	Positional	Gripper	100 deg closed, 45 deg open
D9	Continuous-rotation	Feeder	90 stop command, 100 for 510 ms feed command

Table 4: Sorting arm subsystem requirements and verification.

Requirement	Verification
The base servo shall direct yellow/orange balls to the right action and white balls to the left action.	Run controlled color tests and observe the base-servo direction. Success requires yellow/orange detections to use the right action and white detections to use the left action.
The gripper shall close to the calibrated closed command before the next cycle and open during release.	Observe repeated cycles and check code constants. Success requires the gripper to return to the 100 deg closed command after release.
The arm shall return to the ready pose after each ball.	Run 10 cycles and observe the final pose after each cycle. Success requires D3 at 90 deg, D4 at 90 deg, D5 at 90 deg, and D6 closed before the next feeder command.

2.5 Power Subsystem

The power subsystem uses a 12 V input source followed by an LM2596 buck-converter module. The LM2596 stage provides the regulated low-voltage rail used by the Arduino and servos while keeping the power stage off-the-shelf and easy to verify.

Figure 4: LM2596 buck-converter module used to regulate the 12 V input source to the 5 V system rail.

Table 5: Power subsystem requirements and verification.

Requirement	Verification
The regulator output shall be between 4.75 V and 5.25 V before and after connection to the circuit.	Measure the LM2596 output with a digital multimeter before connection and after connection at idle. Success requires both measurements to fall inside the tolerance range.
The regulated rail shall remain inside 4.75–5.25 V during visible servo motion.	Measure the rail during feeder and sorting-arm motion. Success requires the observed voltage to remain inside tolerance and no controller reset to occur.
The wiring shall share a common ground between the controller, sensor, power module, and servo supply.	Inspect wiring continuity and confirm stable sensor readings and servo commands during operation. Success requires no intermittent resets or lost sensor readings.

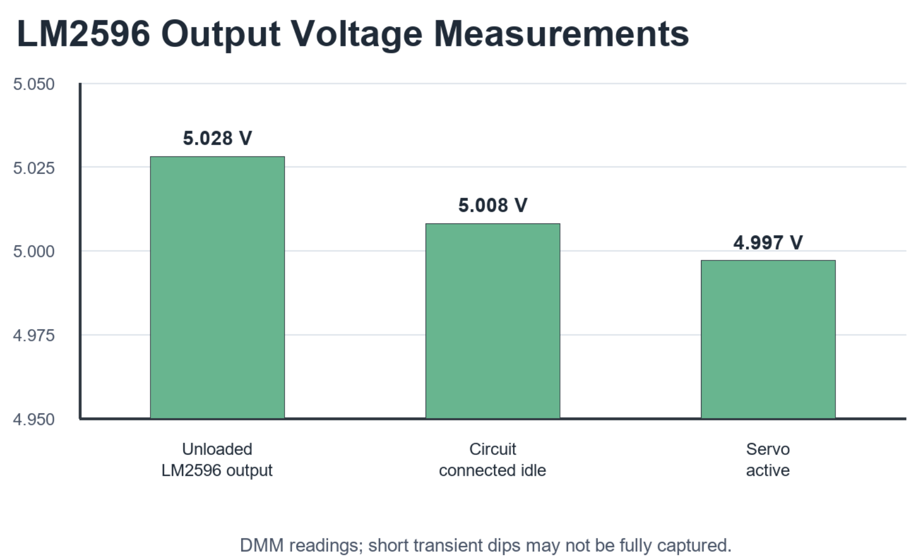

Figure 5: Measured LM2596-regulated output voltage under unloaded, connected-idle, and servo-motion conditions.

2.6 Mechanical Structure

The mechanical structure uses acrylic material for rigid plates and custom 3D-printed parts for mounts, channels, and ball guidance. Acrylic provides a low-cost and easy-to-cut base structure. 3D printing allows the feeder and gripper geometry to be adjusted around the ball diameter and servo locations. The final mechanism is intentionally compact and low speed because the target application is educational demonstration and small-batch sorting rather than industrial throughput.

Table 6: Mechanical subsystem requirements and verification.

Requirement	Verification
The frame shall support all five servos without visible bending during normal operation.	Observe the structure during repeated sorting cycles and inspect for flexing, loose joints, or servo mount movement.
The feeder path shall guide balls into the sensing region with minimal lateral variation.	Mark the sensing area and run repeated feed cycles. Success requires balls to settle in the sensor region before the color reading.
The output regions shall keep sorted balls separated after release.	Run mixed-ball sorting trials and inspect the left and right output regions after each trial. Success requires no sorted ball to cross into the wrong output region after release.

2.7 Tolerance Analysis

The most important feasibility question in the final design is whether the color threshold can reliably separate yellow/orange balls from white balls despite brightness variation. The software reduces dependence on absolute brightness by using the clear-channel-normalized ratios

$$R_r = \frac{R}{C}, \quad G_r = \frac{G}{C}, \quad B_r = \frac{B}{C}. \tag{2}$$

From the sensor tests, yellow/orange readings clustered around a ratio pattern in which $R_r > G_r > B_r$. A representative yellow/orange reading was

$$R_r = 0.4089, \quad G_r = 0.3415, \quad B_r = 0.2457. \tag{3}$$

The red-to-blue separation for this sample is

$$\Delta_Y = R_r - B_r = 0.4089 - 0.2457 = 0.1632. \tag{4}$$

The final threshold requires $R_r > G_r$, $G_r > B_r$, and

$$R_r - B_r > 0.055. \tag{5}$$

For the representative yellow/orange sample, the margin above threshold is

$$0.1632 - 0.055 = 0.1082. \tag{6}$$

This margin is large compared with the threshold itself, so yellow/orange detection is feasible under the tested lighting and geometry. A representative white-ball reading from the revised test set was

$$R_r = 0.4293, \quad G_r = 0.7276, \quad B_r = 0.9003. \tag{7}$$

For this reading,

$$B_r - R_r = 0.4710, \qquad G_r - R_r = 0.2983. \tag{8}$$

These separations support the final white-ball rule, which uses blue/red and green/red separation rather than absolute brightness. The tolerance risk is therefore not the mathematical separation between the two measured color families; it is the mechanical presentation of the ball. If the feeder releases two balls at once or if a ball misses the sensing area, the software cannot correctly sort the ball even if the color thresholds are valid. This matches the final test observations: the only non-100% trial was caused by a double-feed event.

Power tolerance was also checked numerically. The design target is 4.75–5.25 V. The measured values were 5.028 V before circuit connection, 5.008 V at idle after connection, and approximately 4.997 V during servo motion. The smallest measured value therefore has a margin of

$$4.997 \text{ V} - 4.75 \text{ V} = 0.247 \text{ V} \tag{9}$$

above the lower bound. A digital multimeter may not capture very short transients, so oscilloscope verification would be appropriate for a future higher-load version, but the measured steady values demonstrate feasibility for the final prototype.

3 Cost

Table 7: Estimated and actual major parts cost.

Part	**Qty.**	**Retail Cost (RMB)**	**Notes**
Arduino Uno R3	1	35	Controller
TCS34725 color sensor	1	28	Color sensing
MG90S positional micro servo	4	40	Arm joints and gripper
Continuous-rotation micro servo	1	10	Feeder actuator
12 V input source / battery holder	1	10	Input supply
Batteries	3	45	Reused in final build
Acrylic sheets	2	20	Mechanical base
3D printing filament	0.3 kg	15	Custom parts
Jumper wires and breadboard	1 set	15	Wiring and prototyping
Screws and hardware	1 set	8	Assembly
LM2596 buck converter module	1	10	12 V to 5 V regulator
Total retail replacement cost	–	**236**	–

4 Schedule

Table 8: Project schedule and division of labor.

Week/Phase	Task	Owner
Week 1	Define sorting problem, review ball-color motivation, and select initial sensing approach.	Team
Week 2	Build early servo arm test program and calibrate base, arm, forearm, and gripper angles.	Siqi Pan
Week 3	Evaluate sensing alternatives, then select TCS34725 color sensing for the final implementation.	Siqi Pan, Zhonghao Wang
Week 4	Design and print mechanical feeder, output regions, and servo mounts.	Xucheng Wu
Week 5	Integrate TCS34725 readings with Arduino sorting code and tune white/yellow-orange thresholds.	Siqi Pan, Zhonghao Wang
Week 6	Add continuous-rotation feeder servo timing and simplify the arm motion for repeatability.	Team
Week 7	Integrate the LM2596 module power path and measure regulated output voltage.	Siqi Pan
Week 8	Run five 10-ball end-to-end sorting trials, record timing, identify feeder jam/double-feed limitations, and finalize documentation.	Team

5 Ethics and Safety

The project does not collect personal data. The final design uses a color sensor that measures local reflected light from the ball surface, so no user images or personally identifiable data are recorded.

Electrical safety is important because the system uses a 12 V-class input source and a 5 V regulated rail. The 12 V source must not be connected directly to the Arduino, TCS34725, or servos. The LM2596 output should be adjusted and checked with a multimeter before connecting the circuit. A common ground must be maintained between the controller, sensor, and servo supply. Batteries should be charged only with an appropriate charger and should not be shorted during testing.

Mechanical safety is also important. The feeder, base servo, and gripper can move unexpectedly after reset, so users should keep fingers away from the sorting mechanism during operation. The system should be powered off before changing mechanical alignment, swapping balls in the sensing region by hand, or adjusting the feeder.

This design follows the IEEE Code of Ethics by prioritizing safety, reporting limitations honestly, and avoiding exaggerated performance claims [7]. The final verification data explicitly report the feeder jam and double-feed failure modes so that future users understand the remaining risks.

6 References

References

[1] International Table Tennis Federation, *ITTF Statutes 2026*. Ball color requirements specify white or orange matt balls. [Online]. Available: https://documents.ittf.sport/sites/default/files/public/2026-02/2026_Statutes_v1_consolidated_tc.pdf

[2] ams OSRAM, *TCS34725 Color Sensor*. [Online]. Available: https://ams-osram.com/products/sensors/ambient-light-color-spectral-proximity-sensors/ams-tcs34725-color-sensor

[3] Arduino, *Arduino Uno Rev3*. [Online]. Available: https://store.arduino.cc/products/arduino-uno-rev3

[4] Tower Pro, *MG90S*. [Online]. Available: https://towerpro.com.tw/product/mg90s-3/

[5] Adafruit MakeCode, *servo Write*. Continuous rotation servos interpret commands as speed and direction rather than fixed position. [Online]. Available: https://makecode.adafruit.com/reference/pins/servo-write

[6] Texas Instruments, *LM2596 SIMPLE SWITCHER Power Converter 150-kHz 3-A Step-Down Voltage Regulator*. [Online]. Available: https://www.ti.com/lit/ds/symlink/lm2596.pdf

[7] IEEE, *IEEE Code of Ethics*. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html