SmartCart: Experiment Design & Results

April 25, 2025

System Components

- RFID reader (MFRC522) for product ID
- Load cell with HX711 for weight verification
- Color sensor (TCS3200) for aisle detection
- Ultrasonic sensors (HC-SR04) for obstacle detection
- Temperature sensor (DS18B20)
- Gesture sensor (APDS9960) for touchless control
- Hall effect sensor for security
- Accelerometer (MPU6050) for movement monitoring and trip detection
- LCD display and LED matrix for user interface
- IR sensor (TCRT5000) for user presence and power saving

Experiment Design

Experimental Setup

The experiment was designed as a controlled study with both quantitative measurements and qualitative user feedback. Testing was conducted in a simulated retail environment.

Test Objectives & Methodology

We followed a systematic approach to evaluate each component individually before testing the integrated system:

1. Component-level testing in isolation
2. Subsystem integration testing
3. Full system evaluation under simulated shopping scenarios
4. Edge case and longevity testing

Component Level Testing

Each sensor and component was tested individually using controlled test benches before system integration:

- **RFID Module:** Tested with standardized RFID tag set at various distances (0-10cm) and angles. Each tag was scanned 10 times per configuration to establish baseline recognition rates.
- **Load Cell:** Calibrated using a precisioned known weight (200g) after tare, then tested loads with and without movement.
- **Color Sensor:** Calibrated against printed A4 color papers for the five target colors, then tested under various lighting conditions (300-700 lux) measured with a digital light meter.
- **Gesture Sensor:** Programmed-tweak its sensitivity, then evaluated with 3 participants performing each gesture 10 times at different distances and speeds.
- **Ultrasonic Sensors:** Calibrated against known distances using a precision-meter stick, then tested with objects of different materials.
- **Accelerometer:** Calibrated on stationary values ($a = 0$ m/s^2) by average value as bias after filtering noise. The tests were done by free-falling and calculating the norm of the acceleration vector, which should equal $1g$.
- **Temperature Sensor:** Calibrated using an ice-bath and verified against a calibrated reference thermometer (lab) across the operational range (0-50°C) with particular focus on the critical threshold (22°C).
- **Gyroscope:** Calibrated on stationary upright position with no rotation ($w = 0$ rad/s^2) . Tested by rotating 90 degrees in 1 second first by Pitch, then by Roll.

All sensors were subjected to repeatability testing with at least 10 measurement cycles to ensure consistent readings across multiple trials. Measurement results were statistically analyzed to determine average values, standard deviations, and outlier frequencies.

Component	Success Criteria
RFID Scanner	>95% successful scans at angles within 5cm
Weight Sensor	Weight accuracy within ±15g
Color Sensor	Correct aisle identification >88%
Gesture Control	>85% gesture recognition accuracy
Ultrasonic Sensors	Obstacle detection within 10cm (97%+ accuracy)
Acceleration Sensor	Absolute Bias $\leq \pm 0.05\,g$ (95% of readings or ±2 bound.) after startup auto calibration calibration
Security Features	Detects 97% of unauthorized removals
Angle Estimator	Pitch/roll error $\leq \pm 1^\circ$ when still; angle drift $< 1^\circ$ over 2 min without external reference
Overall System	Reliable operation for >2 hours

Testing Environment

Testing conducted with ambient lighting 400-600 lux, temperature 22-25°C, on smooth tile flooring with simulated aisles using colored A4 papers and RFID-tagged products.

Feature Level Testing Approach

- **Scan Testing:** Products with tags were scanned at distances from 0-10cm and angles of 0°, 45°, and 90°. Double-scan confirmation was tested with varying delays (300-500ms).
- **Weight Missmatch Testing:** Products of known weights were added sequentially and in combination. Cart was tested both stationary and in motion to measure movement effects. Intentional weight discrepancies were created to test mismatch detection sensitivity.
- **Aisle Detection Testing:** The cart was navigated through simulated aisles marked with color-coded paper. Transitions between colors were timed and success rates recorded. Tests were repeated under three lighting conditions (300, 500, and 700 lux).
- **Gesture Control Testing:** 3 participants performed each gesture (up/down/left/right) 10 times at varying distances and speeds. Recognition success was recorded along with false positives and gesture confusion rates.
- **Obstacle Detection Testing:** Objects of different materials were placed at measured distances in front of the cart. Detection accuracy and response times were recorded for static and moving objects approaching.
- **Tipping Over Detection:** Pitch and Roll angles were tested at desired angles 20°, 25°, and 30°. Response time tests were repeatably done where one setup had 3 seconds to reach desired angles, and the other 1 second.
- **Security Testing:** Simulated theft attempts were conducted by removing products, passing the cart through neodymium magnets, and tilting the cart. Alert triggering time and response was measured.
- **Integration Testing:** Complete shopping scenarios were simulated with predefined tasks (product scanning, navigation, list management). Task completion rates and system errors were recorded.
- **Speeding Detection:** A car with a calibrated speedometer was used to test acceleration from 20 m/s to 40 m/s at fixed pedal positions ($a = 0, 0.46, 1.32, 2.3$ m/s^2). Despite lower repeatability, repeated runs on the same road gave consistent results.

Quantitative data was collected using a combination of Arduino IDE Serial Monitor logging, external timers, and manual observation.

Test Results

RFID Product Recognition

- Tested at distances 0-10cm, angles 0°, 45°, 90°
- Scan success: 91% within 2 cm, 78% within 5cm, and 25% at 10cm
- Optimal angle: 0-10° from perpendicular
- Double-scan confirmation works with 650ms delay for each recognition.
- Avg. recognition time: 650ms

Product	Success	Time(ms)
Iced-Tea	78%	700
Pepsi	76%	600
Chips	79%	630

Weight Verification System

- Accuracy: ±15g static, drift 2g/day
- Movement-induced error: up to 30g during cart fast movement
- Mismatch detection: 96% success for discrepancies ¿20g
- Response time: 300ms to weight change

Test Item	Expected	Measured
Iced-Tea	535g	522g
Soda	300g	305g
Chips	34g	31g

Aisle Detection System

- Overall accuracy: 94% under optimal lighting
- Light sensitivity: drops to 58% at 300 lux
- Buffer algorithm requires 3+ readings for stability
- Most reliable: Red (92%), White (89%)
- Least reliable: Blue (62%), Black (68%)

Light	Red	Green	Blue
300 lux	88%	76%	74%
500 lux	98%	93%	83%
700 lux	96%	90%	62%

User Interaction System

- Gesture recognition: 87% overall success
- Left/Right gestures (92%) more reliable than Up/Down (82%)
- Best performance at 10-15cm distance
- Bright light reduced accuracy by 15%
- LCD readability rating: 8.5/10 from test subjects

Gesture	Success	Time(ms)
Up	81%	320
Down	83%	310
Left	93%	280
Right	91%	290

Angle Measurement System

- Accuracy: ±1° static (95 % Confidence);
- Drift $< 1°/2$ min
- Update rate: 75 Hz
- Latency 13.3 ms

Test Tilt	Expected	Measured
Small	15°	15.3°
Medium	45°	45.8°
Large	90°	89.3°

Acceleration Measurement System

- Absolute Bias $0.31 m/s^2$ (95 %)
- Maintains accuracy for lower range
- Less accurate around 1 g (gravity)
- Response time: 10 ms to acceleration change

Test Event	Expected	Measured
Drop test	$+1.0\,g$	$+1.04\,g$
Stationary test	$0.00\,g$	$0.03\,g$
Bump/Car 1.32 m/s	$+1.32 m/s^2$	$+1.38 m/s^2$
Bump/Car 0.46 m/s	$+0.46 m/s^2$	$+0.49 m/s^2$
Bump/Car 2.3 m/s	$+2.3 m/s^2$	$+2.37 m/s^2$

Security Features

- Hall sensor detects unauthorized exit with 97% reliability
- Tilt detection triggers at angles ¿10°
- Temperature accuracy: ±0.5°C
- Battery life: 4.2 hours normal use, 3.1 hours with alerts
- Solenoid lock activation on security breach within 200ms
- Remote alert signal via ESP32 with 94% reliability

Feature	Success	Time(ms)
Hall Sensor	97%	180
Tilt Alert	96%	250
Temp Alert	99%	750
ESP32 Alert	98%	420

Contributions

This project was a collaborative effort. Each team member contributed significantly to different aspects of the work:

- **Mazen Abou Said** – Handled system integration, coordinated security testing and obstacle detection.
- **Hadi Elham** – Managed hardware and tested components like RFID, gesture, and ultrasonic sensors.
- **Rawan El Hakim** – Developed weight logic and conducted analysis across all component tests.
- **Amjad Khaddaj** – Implemented Acceleration measurement with Angle estimation, and tested these systems respectively with their logic in different environments.
- **Tia Tarabay** – Oversaw user interaction testing, evaluated gesture, RFID and LCD usability, and compiled participant feedback.