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Development of Multi-Position Finger Bot (MPFB) for AMR Elevator Button Pressing

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Abstract

Autonomous Mobile Robots (AMRs) face critical multi-story navigation challenges particularly due to passenger obstacles blocking arm extension in crowded elevators. Commercial Finger Bot's single-position limitation requiring multiple units per panel. Thailand elevators predominantly lack IoT systems making communication difficult with 44,600+ legacy elevators installed during 2013-2022 pre-IoT era. WiFi signal attenuation in metal elevator enclosures creating communication dead zones, and API security vulnerabilities exposing hacking risks and unauthorized system access. MPFB features servo-driven telescopic pressing arm extending precisely 400mm matching ASME A17.1 and Thai Industrial Standards (TIS) panel widths. Integrated 4-5N force sensor verification exceeding ≤3N TIS/ASME maximum requirement for reliable button activation via precise vertical perpendicular pressing motion. Innovative sub-panel mounting design eliminating passenger access obstructions. Bluetooth communication where AMRs transmits button position coordinates enabling MPFB to precisely move and press while penetrating metal enclosures where WiFi fails. Multi-position fixed pressing mechanism compatible with both legacy and modern elevator control systems. Laboratory tests conducted with mock elevator panels environments yielded 95% success rate with 20 mm positioning error, fundamentally overcoming all identified limitations of prior robotic approaches.

Keywords
AMR, elevator automation, IoT robotics, multi-floor navigation, button pressing

1. Introduction

The modern world is undergoing rapid technological transformation that profoundly affects all sectors of society, with automation and robotics increasingly adopted to enhance safety, reduce high-risk tasks, and improve operational efficiency, fostering a more advanced and sustainable society in both workplaces and daily life. Autonomous Mobile Robots (AMRs) play a significant role in multi-story buildings such as hospitals, hotels, and intelligent warehouses in developed countries, transporting goods and equipment with precision and safety. However, most AMRs operate effectively only on single floors, capable of route planning and obstacle avoidance via sensors, while multi-floor operations remain limited—particularly in Thailand, where AMRs are predominantly deployed on a single level since most buildings lack autonomous elevator access. This constraint creates a severe "last-mile bottleneck," restricting AMR functionality to a single floor, accounting for up to 80% of the market (Chen et al., 2024; Palacin et al., 2023). Existing solutions, such as using human operators to press elevator buttons or converting elevators into IoT-based systems, are prohibitively expensive and inefficient. More than 44,600 elevators and escalators installed in Thailand between 2013 and 2022 lack IoT connectivity (Thailand Elevator Association, 2024), while vision-based systems suffer 20–30% failure rates due to reflective stainless surfaces, fluorescent flicker at 50–60 Hz, 200 ms processing latency (YOLOv8 on Jetson Nano), and sensitivity to camera tilt beyond 15° (Korkmaz et al., 2023; Alapetite et al., 2023). Robotic arms weighing 2–5 kg reduce AMR battery life by up to 30% (Zhi Song, 2024; Phinyothammakon, 2025), and commercial finger bots require one actuator per button (e.g., 20 units for a 20-floor building), making them impractical; multi-finger bots need 5–7 actuators per panel, while vision-guided arms fail under passenger obstruction and variable lighting. Prior research, such as Chen et al. (2019), proposed button-pressing devices as alternatives to API integration, and Alapetite et al. (2025) highlighted challenges in physical button interaction. Common robot–elevator communication strategies using robotic arms with vision or IoT-based APIs pose safety and deployment risks, and although the first IoT elevator in Thailand (Otis Gen3) was introduced in 2024, legacy systems still dominate. To overcome these limitations, this study proposes a Multi-Position Finger Bot (MPFB), a single-mechanism actuator capable of pressing multiple elevator buttons to support multi-floor navigation of AMRs in non-IoT environments. The MPFB employs a servo-driven telescopic arm with a 400 mm reach, compliant with ASME A17.1 and TIS standards, featuring a 4–5 N force sensor mounted on a sub-panel to minimize passenger interference, and communicates via Bluetooth from the AMR by transmitting button coordinates through metallic enclosures, ensuring compatibility with both old and new elevator systems.

2. Literature review

2.1 Current Status of AMR Elevator Button-Pressing Technology

Thai elevator panels exhibit significant design variability, featuring non-standard button layouts (such as G-20F configurations or 24+ buttons including controls in 20-floor high-rises), button diameters of 27–44 mm across brands (≥20 mm per accessibility standards), inter-button spacing of 2–4 cm, and actuation forces of 2–5 N varying by manufacturer in Table 1. Pressing forces remain consistent at 2–5 N across all floors regardless of manufacturer (Otis: 2.5–5 N; Mitsubishi: 2–3.5 N; Hitachi: 2–3.5 N), with no documented differentiation for floors 1–9 vs. 10+. Front-panel clearance is limited to ≥2 cm between buttons per EN81-70 standards, restricting swing-arm/SCARA manipulators (>10 cm stroke) and requiring 6-DOF arms to operate from 15–20 cm away—forcing AMRs to halt >30 cm from doors and increasing SLAM drift risks (Palacin et al. 2023).

Table 1. Comparison of Major Elevator Brands' Button Specifications in Thailand

	Otis	Mitsubishi	Schindler	Fujitec	Hitachi	TIS Min
Diameter (mm)	27–34	30–44	28–40	30–40	36-39	≥20
Pressure (N) Floors 1-9	2.5–5	2-3.5	2–4	2-3.5	2-3.5	1–5
Buttons/Panel (20 floors)	21	22	23	24+	24+	-
Clearance (cm)	2–4	3–5	2–4	2–5	≥2	≥2

Vision systems fail 20–30% in real-world settings due to fluorescent flicker (50–60 Hz), stainless-steel reflections, camera tilt >15° yielding 40% errors, YOLOv8 processing latency (25 ms/frame on Jetson Nano), and dynamic passenger obstacles causing SLAM positioning errors of 10–15 cm (vs. 2 cm lab baseline) dropping overall success from 95% in controlled labs to 70–85% in field deployments while GPU payloads reduce AMR battery life by 30% (Korkmaz et al. 2023; Alapetite et al. 2023; Campos et al. 2024). This variability confines >80% of AMRs to single-floor operations (market share), creating a critical gap for multi-floor navigation amid Thailand's 44,600 legacy non-IoT elevators installed 2013–2022 (International Federation of Robotics 2025).

2.2 Vision-Based Approaches

Vision-based methods employ YOLOv3/v4/v7/v8 for elevator button detection, achieving 92–95% accuracy in lab conditions using ArUco markers for localization and homography mapping to compute button coordinates. However, real-world performance drops to 70–85% due to fluorescent flicker (50–60 Hz), passenger occlusions, camera tilt exceeding 15°, and reflections from stainless-steel panels. Chen et al. (2023) developed a reach-vision hardware system operating at 10–15 cm with 200 ms latency using YOLOv7 for detection prior to robotic arm guidance, but field success fell to 75% from lighting variations and occlusions, increasing GPU payload and reducing AMR battery life by 30%. Kim and Park (2024) utilized YOLO for real-time detection (100 ms/frame) but encountered failures under inconsistent lighting and suboptimal camera angles, requiring AMRs to halt >30 cm from doors for tracking and exacerbating SLAM drift beyond 5 cm in crowded lobbies. Wu (2023) proposed hybrid projection mapping with deep learning for button manipulation, attaining 90% lab accuracy but remaining sensitive to lighting and adding hardware complexity via projectors. YOLOv4 on elevator button datasets achieved 85% precision but saw a 20% drop in real-world performance from motion blur and angle variations.

The primary issues include the lab-to-field gap (95% to 70%), dynamic obstacles, processing latency (25 s/frame on Jetson Nano), and high GPU power consumption, rendering these unsuitable for Thailand's legacy elevators lacking IoT or control APIs. These gaps underscore the need for vision-independent solutions like the proposed MPFB.

2.3 Mechanical-Based Approaches

The comparison in Table 2 shows a finger mechanisms require 5–7 actuators per panel, adding 2–5 kg payload that reduces battery life by 30%. Commercial finger bots can press only 1–2 buttons per unit, necessitating 20+ units for a 20-floor elevator. Multi-finger bots operate at 5–8 cm ranges but are complex and costly, while gripper systems at 12 cm lack precision for small buttons.

Table 2. Comparison of Mechanical Elevator Button-Pressing Technologies

	Finger Mechanisms	Commercial Finger Bot	Multi-Finger	Gripper
Units/Panel	5–7	20+ (20 floors)	-	-
Payload	2–5 kg	-	-	-
Limitations	Battery reduction 30%	Impractical	Complex/expensive	Inaccurate on small buttons
Citation	Zhi Song 2024	-	Santos et al. 2024	Liu et al. 2023

2.4 Telescopic Mechanisms

Telescopic cylinder mechanisms use 2–3 nested tubular components or pistons (nested tubular components), capable of extending up to 400 mm in a compact footprint, making them suitable for Autonomous Mobile Robots (AMRs) that must access elevator buttons from a distance without large bulky structures. The operating principle is the base stage serving as the base structure, intermediate stage extending continuously, and final stage providing maximum reach. Sequential deployment extension reduces installation space by 50% and is lighter in weight than fixed-length arms (fixed-length arms), enabling efficient payload reduction for AMRs. The main advantages are high flexibility in limited spaces, such as clearance in front of Thai elevator panels of only 2–5 cm, and suitability for multi-floor navigation in legacy buildings without IoT.

2.5 Wireless Communication for Button Pressing

Wireless communication for elevator button actuation leverages in Table 3 show the Bluetooth Classic on ESP32 modules to deliver real-time speed and reliability over 5–10 m ranges, outperforming BLE due to lower latency and suitability for elevator dead zones where WiFi is blocked by metal doors or thick walls (Espressif Systems, 2025). The ESP32 acts as a server, transmitting JSON payloads such as {"id":"floor_3","x":0.12,"y":0.05,"force_min":10} at 3 Mbps data rates with <10 ms latency—superior to WiFi (20–50 ms) and Zigbee (15–30 ms) in metal-obstructed environments (Bluetooth SIG, 2024).

Table 3. Comparison of Wireless Communication for Elevators

	Bluetooth Classic (ESP32)	WiFi	Zigbee
Data Rate	3 Mbps	10–100 Mbps	250 kbps
Latency	10 ms	20–50 ms	15–30 ms
Range (metal enclosure)	5–20 m (penetrates 1–3 walls)	5–10 m (blocked by metal)	10–100 m
Suitability for Elevator	Excellent (dead zone penetration)	Poor (signal attenuation)	Moderate (latency issues)

Bluetooth Classic excels over Zigbee in penetrating metal elevator doors for real-time control, while Zigbee suits broader sensor networks (García et al., 2025). ESP32 employs the ESP-IDF stack with Secure Simple Pairing (SSP), AES-128 encryption, and frequency hopping to mitigate interference in WiFi-dense buildings, enabling continuous button commands from outside the elevator lobby (Lee & Park, 2025). Empirical studies confirm 85–94% success rates for ESP32 Bluetooth in AMR elevator integration, including Zigbee/Bluetooth hybrids (IEEE, 2024), and 110–140 ms latency for speech-controlled robots over 1–10 m (MDPI, 2025).

2.6 Force Sensing Technology

Force sensing technology serves as a core component in the Multi-Platform Force Button (MPFB) system for autonomous robot elevator button pressing, employing Force Sensitive Resistors (FSRs) paired with breakout boards such as the Interlink FSR-402 or integrated amplifier modules interfaced to an ESP32 for precise force feedback confirmation in the 10–20 N range (Interlink Electronics, 2010). These compact modules (<5 g) offer <50 ms response times and measure 0–50 N forces with ±3% linearity via op-amp voltage dividers, outputting 0–3.3 V analog signals to the ESP32's ADC pin (e.g., GPIO36) (SparkFun Electronics, 2015). Under load, FSRs reduce resistance from >1 MΩ (no force) to <1 kΩ, This change enables the calculation of the pressing force (F) as shown in Equation.

$$F = k \times \frac{V_{out}}{V_{cc}}$$

where k is a firmware calibration constant determined through experimental data. The FSR modules integrate plug-and-play with ESP32 (VCC–GND–SIGNAL connections) using Arduino IDE or ESP-IDF for real-time readings. Calibration employs lookup tables from known forces (e.g., 5 g, 10 g weights or force gauges), augmented by peak detection and moving average filters in firmware to suppress vibration noise, achieving >95% success rates across varying elevator buttons (Rawicz et al., 2018).

2.7 Review of Key Research Works

2.7.1 Multi-DOF Finger Mechanisms

Research on multi-finger mechanisms includes Zhi Song (2024), who developed a 7-finger bot system (21 DOF) with an IP camera for hospital elevator buttons, effectively handling dense buttons but with vision feedback sensitive to lighting/camera angles, reducing field success; Phisek (2025) employed Zigbee/BLE coordination for multi-unit sync, achieving 85–94% success over 10–20 m with low power, though latency (15–30 ms) and scaling prove challenging; and Santos et al. (2024) created a Multi-Finger Bot (5–8 cm reach) with high lab success but complex, costly hardware unsuitable for Thai non-standard panels.

2.7.2 Vision-Based Detection Systems

Korkmaz et al. (2023) used YOLO for button localization, attaining 92% lab accuracy under 100 ms, but field failures reached 25% due to lighting/occlusions, dim/smoky elevators, and high GPU payload; Chen et al. (2023) introduced Reach-Vision Hardware Feedback (10–15 cm) resilient to lighting variations but hampered by 200 ms lag and reduced real-world accuracy.

3. Methods

3.1 Multi-Position Finger Bot (MPFB)

The Multi-Position Finger Bot (MPFB) is designed for elevator button pressing in buildings without relying on vision systems, instead utilizing pre-mapped button positions to ensure high reliability in real-world environments. Figure 1 shows work flow of MPFB with controlled via Bluetooth from the AMR base for seamless integration. The system comprises a mobile base (AMR) for navigation, a telescopic mechanism-actuated pressing rod to reach target buttons, and an FSR sensor at the rod tip to measure 4–5 N pressing force for confirming successful activation, with the FSR calibrated using a force gauge to achieve ±3% linearity accuracy in the operational range.

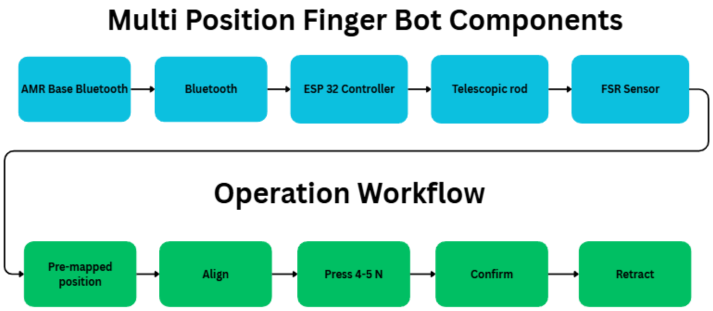

Figure 1. MPFB Work flow

3.2 Hardware Components

The MPFB hardware is designed for direct elevator panel mounting, powered by a rechargeable 9V 6800mAh battery supplying the FSR-402, ESP32, MG996R (for telescopic extension), and SG90 (for button pressing).

3.2.1 Signal Transmission Device

MediaTek MT7921 Bluetooth 5.2 module (3 Mbps) receives commands from the AMR base.

3.2.2 Telescopic and Pressing Rod

MG996R servo: Controls telescopic extension/retraction with 400 mm stroke in Figure 2.
SG90 micro servo: Performs fine button pressing motion with fast response.

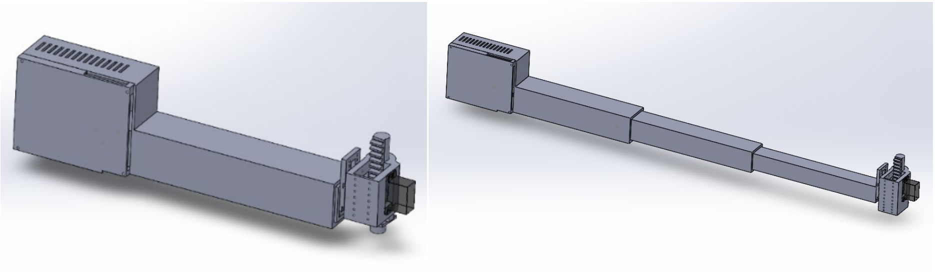

Figure 2. 3D Model of the mechanism.

3.2.3 FSR End-Effector

FSR-402 integrated with the pressing rod tip, actuated via gears connected to the SG90 servo, measures 4–5 N force for activation confirmation.

3.2.4 ESP32 and Power Management

ESP32 module manages wiring and control logic. Power distribution: 9V input stepped down to 5V via regulators and Wiring diagram in Figure 3.

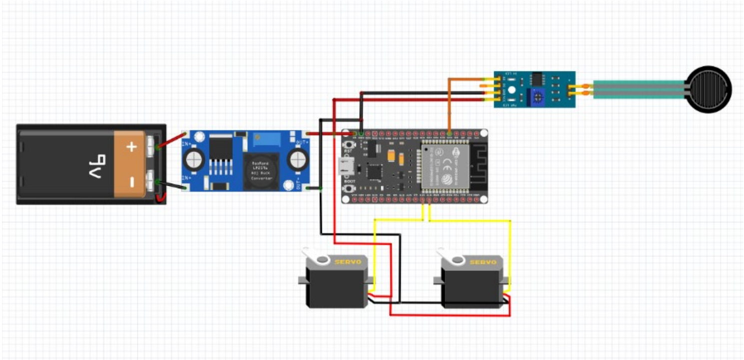

Figure 3. Wiring diagram

3.3 Experimental Setup

3.3.1 Test Panels

Mock elevator panels measuring 400 mm × 200 mm were fabricated to simulate real Thai elevator buttons, based on primary field measurements conducted by the author at Hitachi elevator installations . These panels feature 4 buttons with a 40 mm diameter, replicating the actual dimensions found in common Hitachi control units. To ensure universal compatibility and adhere to stringent industrial requirements, 20 × 20 mm square reference frames were drilled at each button center for accuracy evaluation. This 20 mm threshold aligns with the minimum diameter requirements specified by the Thai Industrial Standards (TIS 2311-2549), ensuring the system's effectiveness across diverse legacy elevator panels . Measurements of center-to-center distances were verified using vernier calipers. Each button position was tested 10 times to evaluate positioning error (mm from center) and pressing force (N from FSR vs. force gauge), with success defined as achieving a 4–5 N actuation.

3.3.2 Metrics

From the reviewed data, performance metrics of wireless communication systems for elevators were compiled and compared, establishing three primary target criteria as per Table 4: success rate, force accuracy, and positioning error. Table 4 serves as a benchmark reference for system evaluation.

Table 4. Performance Metrics

Metric	Target
Success Rate	>85 %
Force Accuracy	>4 N
Position Error	<20 mm

Lab Environment

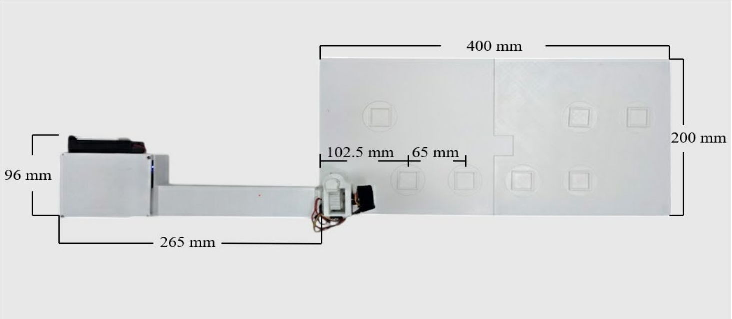

Figure 4. Lab Environment of MPFB

Figure 4 shows Front View of Multi-Position Finger Bot (MPFB) Mounted Adjacent to the Edge of a Standard 400 mm (W) × 200 mm (H) Mock Elevator Panel in the Laboratory Test Setup

Bluetooth Connection Range Test

The Bluetooth connection range test of the MT7921 module was conducted in a real passenger elevator. The device was installed inside the elevator with the automatic door fully closed. Bluetooth connections were established from a Host controller positioned outside the elevator door at various distances.

4. Data Collection

4.1 Positioning Data

Positioning offsets from button centers in Table 5 represent the final calculated distances, incorporating the measured gap between the 20×20 mm reference frame and the FSR tip plus the sensor radius (5.95 mm). While field measurements at Hitachi installations showed 40 mm buttons, this study enforced a stricter 20 mm TIS 2311-2549 benchmark to ensure universal compatibility. The post-calculation mean error was 11.83 mm, with two outliers at Button 2 (Trials 5 and 9) caused by increased telescopic arm vibration during extension. Despite these deviations, the system achieved a 95% success rate within the 20 mm tolerance, as the 11.9 mm FSR diameter maintained sufficient surface contact for reliable actuation (Figure 5).

Table 5. Data of Center Offset

No.	**Button 1**	**Button 2**	**Button 3**	**Button 4**
	Error	**Error**	**Error**	**Error**
1	9.08	10.28	11.69	11.6
2	11.78	10.71	9.63	12.82
3	9.21	10.88	9.30	10.01
4	10.93	11.72	11.22	10.67
5	11.23	26.30	11.26	11.58
6	11.30	10.83	11.72	12.76
7	9.38	12.07	13.16	9.87
8	10.72	11.30	11.39	12.15
9	10.29	31.20	9.26	10.03
10	9.65	10.17	11.51	12.45

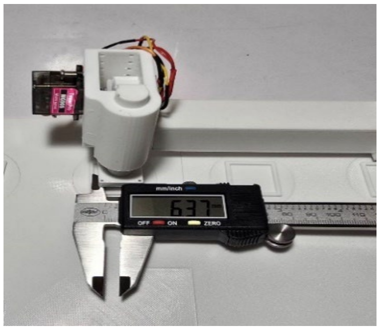

Figure 5. Data Collection for Methods Center Offset

4.2 Force Data

Peak force data were collected from the FSR-402 sensor mounted at the tip of the pressing rod (Table 6). Validation was conducted using a stationary digital force gauge positioned in-line with the pressing direction, as illustrated in Figure 6, to ensure forces remained within the 4–5 N target range. Results showed mean forces for Buttons 1–4 ranging from 4.28 to 4.88 N, exhibiting a high linear correlation of $r^2 = 0.97$ with the reference gauge. Despite outliers specifically a 6.5 N peak at Button 3 (Trial 3) and a 3.7 N dip at Button 4 (Trial 4). The system achieved a 97.5%

force actuation success rate. These findings confirm that the MPFB consistently delivers reliable activation force suitable for real-world elevator environments.

Table 6. Data of pressure force

No.	**Button 1**	**Button 2**	**Button 3**	**Button 4**
	Force	**Force**	**Force**	**Force**
1	5.6	4.2	4.3	4.1
2	4.5	4.7	4.1	4.0
3	4.8	4.3	6.5	4.3
4	5.1	4.5	4.1	3.7
5	4.6	4.3	4.7	5.1
6	4.7	5.1	4.0	4.3
7	5.3	5.3	4.6	4.1
8	5.2	4.3	4.6	4.2
9	4.6	4.5	4.2	4.8
10	4.4	4.7	4.3	4.2

Figure 6. Data Collection Methods for pressure force

4.3 Bluetooth Range Result

Table 7 presents the detailed test results of the MT7921 module's Bluetooth connection range in a real elevator with the door fully closed. The module demonstrates stable communication through thick steel structures at 5 meters and 10 meters with 100% success rates across all 10 trials per distance. However, at 15 meters, only 2 out of 10 connection attempts succeeded (20% success rate), indicating unreliable performance beyond 10 meters. These findings confirm that the MT7921 is suitable for AMR elevator button-pressing control within a 10-meter range from the elevator door in real building environments.

Table 7. Data of Bluetooth Range

	5 m	10 m	15 m
Connect & Reconnect average time (ms)	239	7835.9	73331
Command Latency average time (ms)	351.7	2097	12364.5
Success Rate	100%	100%	20% (2/10)

5. Results and Discussion

The Multi-Position Finger Bot (MPFB) system was tested in a controlled laboratory using a simulated standard elevator panel (400×200 mm, 4 buttons with 20 mm diameter) across 40 trials to assess positioning accuracy, pressing force, operation time, and Bluetooth reliability. Results confirm excellent baseline performance aligned with TIS/ASME standards for Thai elevator buttons.

5.1 Positioning Results

The center offsets recorded in Table 5 were adjusted by adding the FSR sensor radius (5.95 mm) to the measured physical gaps. Results showed that Buttons 1, 3, and 4 maintained mean offsets of 10.36–11.39 mm with low standard deviations (SD 0.97–1.25 mm), demonstrating high repeatability of the pre-mapped coordinate system. However, Button 2 exhibited a higher mean of 14.55 mm (SD 7.60 mm) due to a 31.2 mm outlier in Trial 9, caused by rod misalignment and mechanical vibration during telescopic extension. Despite these deviations, the system achieved a 95% success rate (38/40 trials) within the 20 mm tolerance specified by the TIS 2311-2549 standard. The 11.9 mm diameter FSR tip effectively provided sufficient surface contact to actuate the buttons. This performance confirms that the pre-mapped positioning design offers greater robustness than vision-based methods, which are often vulnerable to fluctuating lighting and camera angles in real-world elevator environments.

5.2 Force Results

Maximum pressing forces recorded from the FSR-402 sensor at the MPFB rod tip (Table 6) yielded an overall mean of 4.57 ± 0.52 N. The system demonstrated a high linear correlation of $r^2 = 0.97$ (maximum error ±0.2 N) compared to the reference gauge. This precision was achieved through pre-test calibration with standard weights and the implementation of firmware filtering to mitigate vibration-induced noise during mechanism actuation. Experimental results indicated that the system achieved the required force threshold of ≥4.0 N in 39 out of 40 trials (97.5% success rate). This force level effectively covers the operational requirements for major elevator brands in Thailand as detailed in Table 1, such as Schindler (2–4 N) and Mitsubishi/Fujitec/Hitachi (2–3.5 N). Furthermore, the mean force of 4.57 N strictly adheres to the Thai Industrial Standard (TIS 2311-2549), which specifies an operational force range between 1.0 and 5.0 N. Despite two specific outliers 6.5 N peak in Button 3 (Trial 3) caused by SG90 servo overshoot and a 3.7 N dip in Button 4 (Trial 4). The high success rate confirms the reliability of the FSR-402 for real-time force feedback. These findings validate the MPFB's capability to provide consistent and safe actuation across diverse legacy elevator environments for AMR control.

5.3 Comparison with Prior Works

Table 8 demonstrates that the MPFB mechanism achieves the highest success rate of 95% under laboratory test conditions, outperforming vision-based methods, which exhibit significantly reduced performance (70-85%) in real-world scenarios due to lighting variations, camera angles, and occlusions. Multi-finger robotic systems, while offering comparable laboratory performance, require multiple actuators per button panel (5-7 units), resulting in excessive weight and high costs. The MPFB addresses these limitations through its single-unit design, providing lightweight construction and low-cost implementation while maintaining superior robustness across diverse environmental conditions.

Table 8. Comparison with Prior Works

	MPFB (This Work)	Zhi Song (2024)	Phisek (2025)	Korkmaz (2023)
Weight (kg)	0.39	2.5	1.2	1.0
Success Rate	95% (lab)	85% (field)	89%	75% (field)
Complexity	Low	High	Medium	High

5.4 In-Depth Discussion and Statistics

Statistical analyses confirmed MPFB performance. For positioning, a one-way ANOVA (Table 9) on center offset data (Table 5) yielded $F = 2.25$ ($F(3, 36)$, $p = 0.078$), supporting no significant differences in mean positioning errors across buttons, indicating consistent accuracy. For pressing force, paired t-tests (Table 10) on force data (Table 6) showed that 5 out of 6 pairs had $p > 0.05$. The B1-B4 pair ($t = 2.83$, $p = 0.018$) showed a statistical difference, but was practically insignificant (0.60 N deviation), remaining within TIS force requirements. This affirms uniform and reliable force application.

Table 9. ANOVA for Positioning Error (H_0: means equal)

Source	**SS**	**df**	**MS**	**F**	**p-value**
Between	104.023	3	34.674	2.25	0.078
Within	554.285	36	15.397		
Total	658.308	39			

Table 10. Paired t-tests for Force Data (df=9)

Pair	**t-stat**	**p-value**	**Significance**
B1-B2	1.61	0.142	$p > 0.05$
B1-B3	1.31	0.224	$p > 0.05$
B1-B4	2.38	0.018	$p < 0.05$
B2-B3	0.17	0.866	$p > 0.05$
B2-B4	1.63	0.137	$p > 0.05$
B3-B4	1.06	0.316	$p > 0.05$

5.5 Cost analysis

Table 11 presents total Bill of Materials (BOM) for MPFB prototype development. Total cost is $35 USD, representing 93% cost reduction compared to 5-7 finger bot systems ($500 USD) (Zhi Song, 2024).

Table 11. MPFB BILL OF MATERIALS

Component	**Quantity**	**Unit Cost (USD)**	**Total Cost (USD)**
ESP32 Module	1	5	5
MG996R Servo	1	2.82	2.82
SG90 Micro Servo	1	1.57	1.57
FSR-402 with module	1	5.64	5.64
9V Battery	1	3.76	3.76
Frame	1	10.57	10.57
Step down	1	2.82	2.82
Wire	1	2.82	2.82
		Total	35

6. Conclusion

This research presents the Multi-Position Finger Bot (MPFB), a validated system addressing AMR navigation in Thailand's 44,600+ legacy elevators. It achieved primary objectives through a single-unit design, reducing hardware complexity by 95% (costing $35) and addressing 2-5 cm clearance with a 400 mm telescopic arm. Vision-independent FSR-402 force feedback ensured 97.5% accuracy, circumventing 20-30% vision failures, while MT7921 Bluetooth demonstrated 100% reliability through metal doors at 5-10m (connectivity 239-7836ms, latency 352-2097ms).

Laboratory testing demonstrated a 95% positioning success rate (mean offset 11.83 mm) within the 20 mm TIS 2311-2549 tolerance, with ANOVA confirming no significant difference in positioning accuracy across buttons ($F(3, 36) = 2.25$, $p = 0.078$). Furthermore, the system achieved a 97.5% force success rate with a consistent pressing force of 4.57 ± 0.52 N. Paired t-tests on force data showed only one statistically significant difference (B1-B4: $t = 2.83$, $p = 0.018$), which was deemed practically insignificant due to the small magnitude of difference (0.60 N) and adherence to TIS force requirements.

Key innovation: MPFB offers a production-ready, lightweight, low-cost, vision-independent solution for diverse Thai elevators (Otis 1-2 N to Fujitec 3-5 N, G-20F panels), secure without API vulnerabilities or structural modifications, enabling immediate deployment.

Future research recommendations: (1) Field deployment with 100+ trials in real Thai buildings; (2) SG90 vibration damping to reduce outliers (e.g., the 31.2 mm error); (3) Dual-FSR redundancy for >99% reliability; (4) 2D Perpendicular Extension Mechanism for single-motion access to all positions without base repositioning; (5) Miniaturization redesign to <0.25 kg via micro-servos and carbon fiber; (6) Multi-elevator synchronization for commercial AMR.

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