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Development and Functional Demonstration of a Modular Conveyor-Based Embedded Automation Platform

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Abstract— **Conveyor-based automation systems are widely used in industrial environments for material handling, sorting, and inspection processes. However, many prototype implementations are application-specific and lack a reusable mechanical platform that supports multiple embedded control configurations. This limitation increases development time and reduces scalability for rapid automation experimentation. This paper presents the development and functional demonstration of a modular conveyor-based embedded automation platform designed to support flexible sensor and actuator integration. The system incorporates a hybrid two-phase stepper motor with a microstepping driver and an Arduino-based control architecture to provide adjustable conveyor motion. The mechanical structure consists of an aluminum frame with a 100 cm belt length, 15 cm belt width, and 3 cm roller diameter to ensure compact yet stable operation. Functional demonstration was conducted through eight independent embedded automation implementations involving different sensing and actuation mechanisms. The platform successfully supported eight embedded automation configurations using the same mechanical frame, belt, roller assembly, motor, and driver. The implementations demonstrated the feasibility of integrating different sensing, actuation, communication, and control mechanisms without modifying the conveyor's mechanical core. The results indicate that the proposed conveyor system provides a reconfigurable foundation for embedded automation prototyping, suitable for classroom or laboratory settings.**

Index Terms— **Conveyor system, embedded prototype, modular automation platform.**

I. Introduction

Conveyor-based transport mechanisms are fundamental components in industrial automation systems, particularly in material handling, sorting, inspection, and packaging processes [1, 2]. The integration of embedded controllers with conveyor platforms enables flexible automation configurations that can be adapted to various industrial tasks [3]. With the growing accessibility of low-cost microcontroller technologies, small-scale automation prototypes are increasingly developed for industrial experimentation and rapid system prototyping [4].

Although numerous studies have demonstrated application-specific automation systems using conveyor mechanisms, most reported implementations focus on single-purpose designs. The underlying conveyor structure is rarely treated as a reusable modular platform capable of supporting multiple embedded configurations. In many small-scale prototypes, mechanical drive adequacy and structural scalability are assumed rather than analytically examined, despite the critical impact of factors such as belt tension, friction, and torque on system reliability [2]. Furthermore, limited discussion is provided on whether a compact conveyor system can consistently support diverse sensing and actuation mechanisms without structural redesign. As a result, practical evidence regarding the development of a scalable and reusable conveyor-based embedded automation platform remains limited.

To address this gap, this paper presents the development and functional demonstration of a modular conveyor-based embedded automation platform for repeated use across different automation applications. The contribution does not lie in introducing a new individual sensor or actuator, but in demonstrating platform-level reusability across eight functionally distinct configurations. The system integrates a hybrid stepper motor drive and a compact mechanical structure to provide adjustable conveyor motion under practical hardware constraints. An analytical estimation of torque capability and motion characteristics is conducted to examine mechanical feasibility under light-load conditions. The main conveyor core, which includes the aluminum frame, belt, rollers, motor, driver, and motor coupling, remained unchanged across all eight implementations, whereas only the sensors, removable actuator modules, and software-defined control logic were changed. This combination of analytical torque assessment and physical implementation across eight automation scenarios distinguishes the proposed platform from single-purpose conveyor prototypes developed for one specific application.

II. Literature Review

Conveyor-based automation systems form a critical infrastructure in modern industrial material handling, packaging, and sorting environments. Conveyor-driven production lines are central to flexible manufacturing systems

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and cyber-physical production environments, where reliability and throughput stability are essential [5, 6]. Belt conveyor mechanisms remain prevalent due to their mechanical simplicity, scalability, and ease of integration into automated workflows [7].

The integration of embedded control systems has significantly enhanced conveyor functionality. Programmable logic controllers (PLCs), microcontrollers, and distributed industrial control architectures enable synchronization between sensing, actuation, and transport processes [8]. In recent years, computer vision models and deep learning frameworks such as YOLO have been integrated into conveyor systems for automated inspection and sorting tasks, demonstrating high detection accuracy in industrial environments [9]. While these approaches improve classification performance, most implementations assume fixed mechanical configurations and focus primarily on algorithmic development.

Object classification research increasingly emphasizes multi-sensor fusion strategies. The integration of optical, infrared, inductive, and proximity sensing improves robustness against environmental noise and object variability [10]. However, in many such systems, the conveyor mechanism is treated as a static transport subsystem rather than a modular structural element subject to design variability.

Industry 4.0 frameworks advocate modular, interoperable, and reconfigurable production systems capable of adapting to dynamic operational requirements [11, 12]. Although these frameworks emphasize modularity at the software and communication levels, practical implementations often retain rigid mechanical platforms, limiting physical reconfigurability.

Mechanical adequacy and drive system feasibility remain less discussed in small-scale embedded automation prototypes. Stepper motors are frequently employed due to their controllability and positioning precision. Nevertheless, motor performance depends on torque margins and load characteristics [13], and in many prototype conveyor systems, torque capability is assumed from manufacturer specifications without analytical examination under modular configurations.

Simulation and digital twin approaches have been proposed to model modular automation systems prior to deployment [14]. While these frameworks provide valuable virtual evaluation tools, comparatively fewer studies demonstrate equivalent physical modular reusability across multiple sensing and actuation configurations using the same mechanical platform.

Recent studies demonstrate several directions in conveyor and modular automation research. Previous work examined conveyor-based transport scheduling in flexible manufacturing [1], whereas another work developed a PLC-controlled conveyor for a specific AI-based waste-sorting application [3]. One work introduced a modular PLC laboratory using transferable simulation kits [15] while a similar work proposed a cyber-physical material-handling framework based on digital interoperability and dynamic resource allocation [16]. As summarized in Table I, these studies contribute to scheduling, intelligent classification, automation training, and digital resource management. However, none combines a physically reusable conveyor core, multiple embedded configurations, analytical torque assessment, and physical functional demonstration. In comparison, the proposed platform retains the same mechanical and drive core across eight configurations while accommodating different sensing, actuation, communication, and control requirements.

Overall, existing literature predominantly focuses on algorithmic classification accuracy, sensor fusion robustness, or high-level modular production architectures. Limited attention has been given to analytically examining a compact conveyor structure as a physically reusable embedded automation platform demonstrated across multiple independent configurations. This study addresses this gap by integrating analytical torque feasibility assessment with functional demonstration across eight distinct embedded automation implementations.

TABLE I. COMPARISON WITH EXISTING AUTOMATION PLATFORMS

Work	Primary focus	Physical conveyor	Multiple configurations	Torque analysis
[1]	Transport scheduling	Yes	No	No
[3]	AI-based waste sorting	Yes	No	No
[15]	Modular PLC training kits	No	Yes	No
[16]	Cyber-physical material handling	Conceptual	No	No
Proposed platform	Reusable embedded conveyor platform	Yes	Eight configurations	Yes

III. SYSTEM DESIGN AND METHODOLOGY

A. Overall System Architecture

The modular conveyor platform consists of three primary subsystems: the mechanical transport assembly, the drive and motion control unit, and the embedded sensing–actuation interface. Fig. 1 illustrates the overall system block diagram.

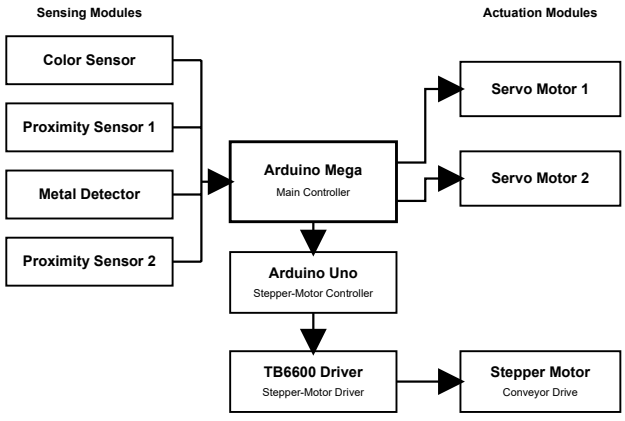


Fig. 1. Overall architecture of the modular conveyor-based embedded automation platform.

The Arduino Mega functions as the main controller, receiving input signals from the integrated sensors and generating commands for the Arduino Uno and auxiliary actuators. The Arduino Uno serves as the dedicated stepper-

motor controller, receiving motion commands from the Arduino Mega and generating the step and direction signals supplied to the TB6600 driver. The TB6600 stepper driver regulates the current supplied to the hybrid two-phase stepper motor, which drives the conveyor belt. The mechanical structure is constructed using aluminum profile framing to provide structural rigidity and modular mounting capability. The conveyor belt has a total length of 100 cm and a width of 15 cm, supported by rollers with a diameter of 3 cm. The compact dimensions enable laboratory-scale implementation while maintaining sufficient surface area for object transport and actuator placement.

The drive system employs a hybrid two-phase stepper motor (Model 17HS6001) rated at 0.7 N·m torque with a 1.8° step angle. The motor is controlled via a TB6600 microstepping driver interfaced with the Arduino Uno microcontroller. Motion parameters such as belt speed and direction are adjusted programmatically by modifying the step pulse frequency and direction signal.

Across all eight implementations, the physical conveyor frame and drive system remained unchanged. Variations were introduced only through software-defined control parameters and modular actuator attachments fabricated using 3D printing. This approach demonstrates structural reusability without mechanical redesign.

B. Analytical Torque and Load Feasibility

To examine mechanical feasibility, an analytical estimation of torque-based load-driving capability was performed using motor specifications and roller geometry. The relationship between motor torque and tangential force at the roller surface is expressed as:

$$F = \tau / r \quad (1)$$

where: τ = rated motor torque (0.7 N·m)

r = roller radius (0.015 m)

Using the rated motor torque and assuming direct torque transmission to the drive roller, the ideal tangential force at the roller surface is approximately 46.7 N. For practical operation, the available tangential force must exceed the force required to overcome belt and roller resistance, object friction, and acceleration. This condition may be expressed as

$$F_{available} > F_{resistance} + ma \quad (2)$$

where $m$is the transported mass and $a$is the conveyor acceleration. Since the transmission efficiency, friction coefficients, dynamic motor torque, and transported mass were not experimentally measured, the actual payload capacity cannot be determined from this calculation. Therefore, the calculated 46.7 N represents only a theoretical upper-bound estimate of drive feasibility and should not be interpreted as the rated or experimentally verified payload capacity of the conveyor.

C. Modular Actuator Integration and Motion Control

The conveyor platform was designed to support modular add-on components. Sorting gates, diverters, dispensing mechanisms, and object-handling attachments were fabricated using 3D printing and mounted onto the fixed aluminum frame, as shown in Fig. 2. These actuator modules are interchangeable and application-specific, while the primary transport structure and drive system remain unchanged. The standardized mounting framework enables reconfiguration without structural modification.

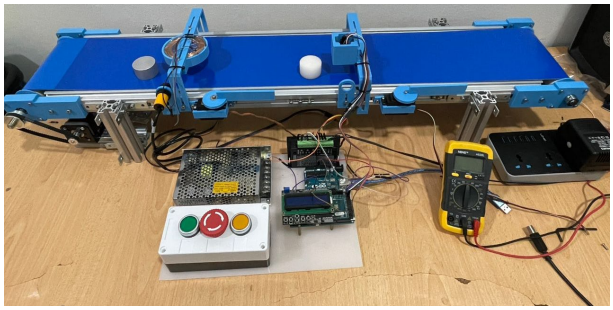


Fig. 2. Conveyor platform with modular actuator systems.

The operational sequence of the conveyor platform follows the structured control logic illustrated in Fig. 3. The system begins with initialization, during which baseline parameters such as motor configuration and sensor states are established. The stepper motor speed and direction are then defined through software control before conveyor motion is initiated.

During operation, the system continuously monitors sensor inputs to detect the presence of objects on the belt. If no object is detected, the conveyor continues normal transport motion. Upon object detection, sensor data are acquired and processed using predefined decision logic. Based on classification results, the corresponding actuator is triggered. After actuation is completed, conveyor motion resumes and the monitoring loop continues for the next operational cycle.

The embedded motion control strategy was implemented directly within the Arduino microcontroller environment using a software-driven pulse generation approach. Stepper motor motion is achieved by generating controlled step pulses delivered to the TB6600 driver through digital output pins. The conveyor speed is regulated by adjusting the time interval between successive step pulses, allowing programmable velocity control without hardware modification. Directional control is achieved by toggling the driver direction signal based on application requirements.

The embedded program follows a loop-based polling architecture. Within the main execution loop, the system repeatedly performs step-pulse generation, sensor monitoring, and actuator-control operations. Conditional logic structures are employed to evaluate sensor inputs and trigger corresponding actuator outputs when predefined criteria are met.

For configurations requiring temporary belt stoppage (e.g., object sorting or sequential handling), motion control is momentarily suspended by halting pulse generation, followed by actuator activation and subsequent resumption of transport motion. In configurations requiring continuous operation (e.g., RFID routing), the conveyor continued operating while the controller periodically checked identification data and executed the corresponding routing decision.

This software-defined motion strategy enables (1) adjustable conveyor speed through pulse interval modification, (2) bidirectional transport via direction signal control, (3) event-triggered actuation without structural redesign and (4) integration of diverse sensing modalities within a unified control loop.

By implementing motion control at the software level rather than through dedicated hardware timing modules, the system preserves simplicity while maintaining functional flexibility. This approach reinforces the modular design objective, wherein control adaptability is achieved primarily through programmable logic rather than mechanical alteration.

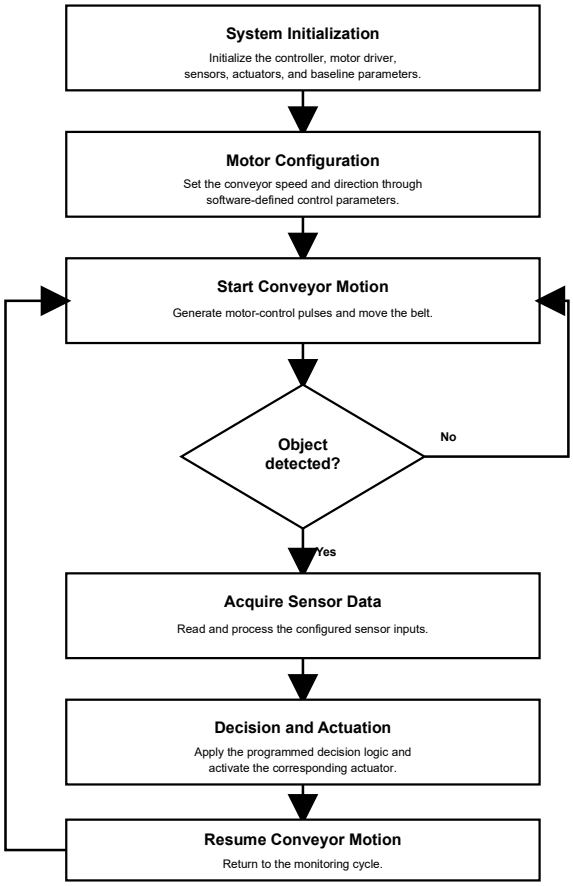


Fig. 3. General control flow of the conveyor system.

IV. Functional Demonstration

To evaluate the structural reusability and integration flexibility of the proposed platform, the same mechanical conveyor structure was deployed across eight independent embedded automation configurations.

A. Configuration Overview

Across the eight implementations, all eight configurations retained the same aluminum frame, belt, roller assembly, motor, driver, and motor coupling, while only the sensing modules, actuator attachments, and control logic were changed. This configuration-level comparison quantifies the structural reuse demonstrated by the platform. However, trial-level measurements of accuracy, cycle time, throughput, and repeatability were not recorded; therefore, the results are limited to functional integration and mechanical reusability rather than quantitative performance benchmarking.

Table II summarizes the implemented configurations and their primary variations. Unlike single-purpose automation prototypes, the objective of this demonstration was to examine whether the unchanged mechanical and drive core could support diverse sensing and actuation requirements without structural modification. Functional demonstration was conducted by operating each configuration according to its intended sensing, decision, and actuation sequence. A configuration was considered functionally successful when the sensor detected the intended input, the controller executed the programmed decision logic, the corresponding actuator responded, and the conveyor completed the required transport sequence without modification to the mechanical core. The demonstration focused on functional integration and mechanical reusability rather than quantitative performance benchmarking.

Available project documentation recorded several quantitative operating parameters for selected configurations. For example, the C1 implementation used an RFID scan timeout of 5 s, an IR sampling interval of 60 ms, a metal-sensor debounce period of 10 ms, and a color sensor reading interval of 500 ms. Meanwhile, the C2 implementation classified objects using three height ranges of 1–5 cm, 5.1–10 cm, and 10.1–13 cm, with a reported ultrasonic reading fluctuation of approximately ±0.3 cm.

TABLE II. Summary of Automation Configurations Using the Proposed Conveyor Platform

Conf.	Application Type	Sensors / Communication Used	Actuation Mechanism	Control Variation
C1	Object sorting	IR, Color, RFID, metal	Servo diverter	Speed adjustment
C2	Size classification	Ultrasonic, RFID	Servo motor	Direction control
C3	Recycling separation	Inductive, Reflective	Servo gate	Multi-sensor logic
C4	IoT-enabled conveyor	IR, Wi-Fi	Servo actuator	Remote monitoring
C5	Temperature handling	IR temperature	Cooling fan	Threshold logic
C6	RFID-based routing	RFID	Stepper-driven gate	ID-based decision
C7	Packaging assistance	IR, Load cell	Dispensing motor	Timed actuation
C8	Dish handling	IR, Ultrasonic	Stepper arm	Sequential control

Across all configurations, only the sensing modules, actuator components, and software logic were modified. The mechanical structure, roller assembly, motor, and driver remained unchanged. Throughout all eight implementations, the aluminum frame, belt dimensions (100 cm × 15 cm), roller diameter (3 cm), and stepper-driven motion system remained identical. The hybrid stepper motor (17HS6001) and TB6600 driver were consistently used without mechanical alteration.

No structural reinforcement, belt resizing, or drive replacement was required when transitioning between

configurations. Actuator modules were mounted using standardized attachment points integrated into the aluminum profile frame. This unchanged mechanical core demonstrates that the conveyor platform provides sufficient structural stability to accommodate varying actuator loads and sensor placements under light-load operational conditions.

For each configuration, the required sensing and actuator modules were installed on the unchanged conveyor core, and the corresponding control program was uploaded to the Arduino Mega. A representative object or input was then introduced while the conveyor was operating. The demonstration sequence consisted of confirming input detection, execution of the programmed decision logic, activation of the intended actuator, and completion of the transport sequence. The conveyor frame, belt, rollers, motor, driver, and coupling were inspected during each implementation to determine whether any mechanical modification was required. The demonstrations were conducted as functional checks during configuration development without a predefined number of repeated trials or a ground-truthed performance dataset.

B. Control and Actuation Variability

Although the mechanical framework remained constant, the embedded control strategies varied significantly across configurations. Variations included single-sensor detection systems, multi-sensor fusion logic, sequential actuation processes, bidirectional conveyor motion, and remote monitoring and communication integration. Representative implementations are shown in Fig. 4.

In object sorting configurations (C1 and C3), infrared and color sensors were integrated to perform material or color-based classification. These systems employed servo-driven diverter gates mounted along the conveyor edge. Upon detection, the control algorithm temporarily halted or slowed the belt motion, actuated the servo to redirect the object, and resumed transport. The implementation required precise synchronization between detection timing and actuation delay to ensure correct object routing.

In size and dimension-based configurations (C2 and C8), ultrasonic sensors were used to determine object height or geometry. For example, the dish-handling configuration (C8) combined ultrasonic detection with stepper-driven mechanical arms to redirect objects according to dimensional thresholds. These implementations required sequential control logic rather than single-trigger actuation, introducing state-based control sequences into the embedded program.

The recycling and material classification configuration (C3) incorporated inductive sensors for metal detection alongside reflective sensors. This multi-sensor configuration required conditional logic structures that processed multiple input states before actuation, demonstrating the platform's capability to support sensor fusion strategies.

In the RFID-based routing configuration (C6), object identification was performed through tag recognition. The conveyor operated continuously while identification logic determined routing decisions, activating a stepper-driven gate mechanism. This configuration emphasized logical decision mapping rather than simple threshold-based detection. The packaging assistance configuration (C7) introduced timed actuation control, where dispensing duration was calibrated based on predefined intervals. This required the control system to integrate transport motion with time-based output control rather than position-based actuation.

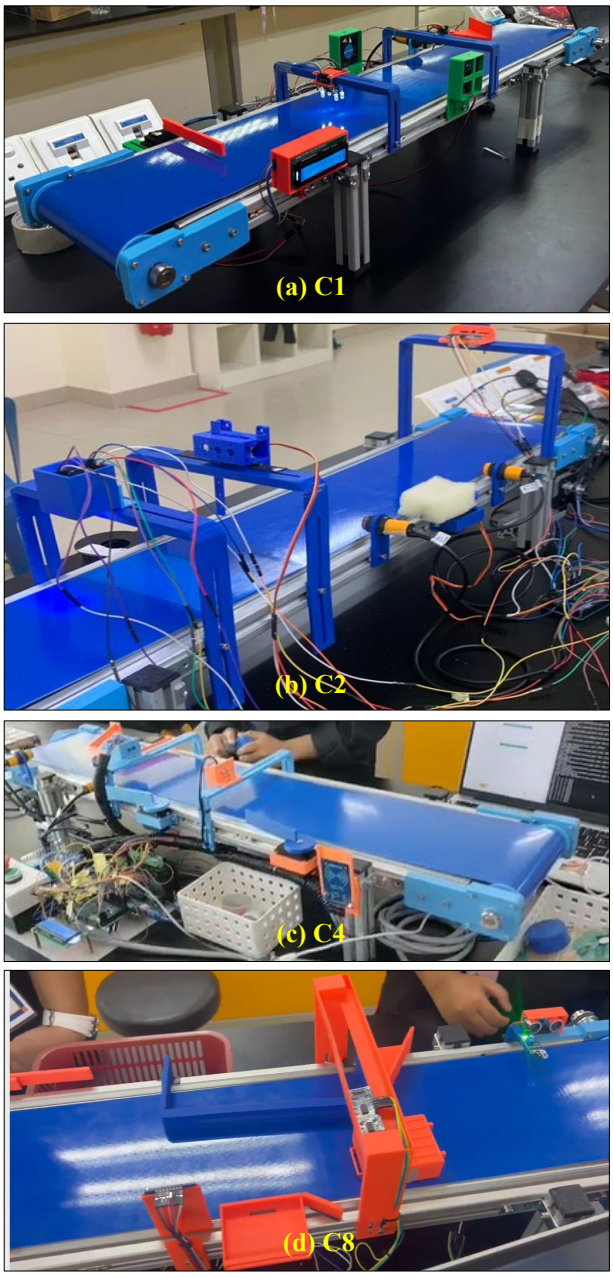


Fig. 4. Examples of automation configurations implemented using the conveyor platform: (a) C1: object sorting, (b) C2: size classification, (c) C4: IoT-enabled conveyor, and (d) C8: dish handling.

Finally, the temperature-based handling configuration (C5) employed threshold-driven control using an infrared temperature sensor, activating a cooling mechanism when predefined limits were exceeded. This introduced

environmental-response logic rather than object-classification logic.

Across these varied implementations, the same motor-driver assembly and mechanical structure supported threshold logic, multi-sensor fusion, timed actuation, sequential control, identification-based routing, and remote monitoring integration.

From a mechanical perspective, these eight configurations imposed varying dynamic conditions, including intermittent belt stopping, directional reversal, lateral servo-driven loads, sequential mechanical interactions, and additional actuator mounting mass. Despite these variations, no reinforcement of the aluminum frame, resizing of the belt system, or modification of the motor-drive coupling was required.

The analytical torque feasibility estimation presented in the previous section supports theoretical load adequacy under light operational conditions. While quantitative load measurements were not performed, repeated deployment of the unchanged mechanical core across eight distinct automation scenarios provides practical evidence of structural suitability under the tested light-load operating conditions.

Collectively, the eight configurations represent different integration requirements rather than repetitions of the same automation function. C1–C3 demonstrate object classification using single- and multi-sensor inputs; C4 adds wireless communication and remote monitoring; C5 applies environmental threshold control; C6 uses identification-based routing; C7 coordinates conveyor motion with timed dispensing; and C8 implements sequential object handling. They also employ different actuator mechanisms, including servo diverters, a solenoid gate, a cooling fan, a stepper-driven gate and arm, and a dispensing motor. Despite these differences, the same mechanical structure and motor-driver assembly supported all sensing, communication, control, and actuation requirements without mechanical redesign.

V. CONCLUSION

This paper presented the development and functional demonstration of a modular conveyor-based embedded automation platform designed for structural reusability across multiple application scenarios. The system integrates a hybrid stepper motor drive, microcontroller-based control architecture, and a compact aluminum-framed transport assembly to provide configurable motion under light-load conditions. An analytical estimation of torque-based load feasibility was conducted to examine mechanical adequacy based on motor specifications and roller geometry. The estimated tangential force of approximately 46.7 N represents a theoretical upper bound and should not be interpreted as the experimentally verified payload capacity of the conveyor. Although this estimation represents idealized conditions, it provides theoretical support for the suitability of the selected drive system for small-scale embedded automation tasks.

The platform was deployed across eight independent automation configurations involving object sorting, size-based classification, recycling separation, RFID-based routing, packaging assistance, environmental monitoring, IoT integration, and sequential handling mechanisms. Across all implementations, the mechanical frame, belt dimensions, roller assembly, and drive system remained unchanged. Variations were introduced solely through software-defined control logic and modular actuator attachments fabricated using additive manufacturing techniques.

The ability to accommodate diverse sensing modalities, control strategies, and actuation mechanisms without structural redesign provides practical evidence of physical modularity of the proposed conveyor platform. Rather than functioning as an application-specific prototype, the system serves as a reusable embedded automation framework adaptable to different functional requirements.

This study demonstrates the functional integration and mechanical reusability of the platform under the tested light-load conditions. However, it does not establish experimentally verified payload capacity, classification accuracy, throughput, or long-term mechanical reliability. Future work may include systematic experimental evaluation of cycle time, load variation effects, and long-term mechanical reliability to further quantify platform performance under extended operational conditions.

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