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ABSTRACT

In this comprehensive engineering project proposal, we carefully design, structurally implement, and rigorously analyze the end-to-end operational paradigm of the Smart Waste Bin. This system represents an autonomous, completely offline, and localized intelligent waste classification and high-speed automated sorting machine, natively conceptualized, designed, and developed by Novera Team. Traditional modern smart waste management frameworks currently available in today's global commercial market demonstrate an absolute, rigid, and highly vulnerable dependency on continuous remote cloud computing infrastructure, centralized data storage systems, and persistent remote API web server handshakes. These cloud-reliant structural dependencies inherently introduce significant data transmission latencies, structural networking bottlenecks, bandwidth throttling, and critical cybersecurity risks. Most catastrophically, they result in total system operational downtime and complete hardware failure whenever deployed in localized environments that lack robust, uninterrupted network coverage or high-speed cellular links.

The innovative decentralized engineering architecture proposed in this work fundamentally shifts all real-time computational overhead and neural deep learning model processing workloads entirely away from external remote infrastructure. Instead, it embeds these heavy mathematical tasks into completely localized hardware edge processing environments through an integrated, high-performance Raspberry Pi 5 microcontroller single-board unit. The embedded hardware system is structurally architected to perform real-time, automated object pattern recognition and physical sorting tasks across four primary decoupled physical material waste streams: high-density plastic polymers, organic paper/cardboard products, scrap ferrous and non-ferrous metals, and generic remaining other mixed household waste items.

Object classification tasks are accomplished strictly inside local volatile memory slots using compressed, optimized convolutional neural networks running via native execution frameworks. Once the categorical identity of the introduced material is successfully established by the embedded computer vision subsystem, high-speed physical sorting and routing actions are executed via a custom-engineered, industrial-grade mechanical dual-axis Tilt Mechanism assembly. This structural physical assembly is driven by a heavy-duty NEMA 17 stepper motor paired with a high-resolution silent motor driver board interface to eliminate operational vibration, mitigate resonant frequencies, and maximize geometric positioning accuracy. The system directly translates the mathematical categorization output indexes into dynamic step-and-direction electrical pulses, orchestrating instantaneous angular adjustments of the sorting platform.

To optimize the physical storage capacity and volumetric efficiency within the global chassis configuration, the internal compartment is divided into a structured, space-efficient symmetric 2x2 grid quadrant collection matrix. This layout utilizes interlocking structural partition walls constructed from 1.5mm galvanized steel to prevent mechanical shifting and zero out cross-contamination risks during fast material drop sequences. Within this quad-compartment matrix, each individual sub-bin is uniquely dimensioned to yield an individual volume of approximately 53 liters of refuse. By segregating the storage volume into four isolated sectors, the design successfully consolidates a total internal volumetric capacity comfortably exceeding 212 liters before requiring manual evacuation cycles, system maintenance interventions, or structural emptying routines. This massive payload capacity ensures the standalone edge node can operate continuously in heavy public urban environments with extended standalone reliability.

Dynamic user experience configurations, multi-threaded tracking telemetry data, local capacity tracking metrics, and hardware health profiles are embedded directly onto an integrated, ultra-responsive 7-inch capacitive touch screen graphical display interface framework governed by high-performance rendering software stacks. In classical embedded designs, rendering

responsive graphical interfaces on resource-constrained single-board computers often introduces severe processing bottlenecks, leading to interface freezing and dropped frames when the processor is simultaneously evaluating machine learning models. To prevent this performance degradation, the Novera UI pipeline relies on high-speed hardware-accelerated graphics libraries that compile the visual layout directly into low-level native code. This decoupling enables the micro-system to refresh complex interface elements—such as real-time material scanning animation states, multi-compartment fill-level indicators, and continuous structural health telemetry metrics—at maximum frame rates with negligible overhead.

To resolve the critical engineering problem of automated point gamification, decentralized user engagement, and secure user incentive distribution within a 100% disconnected local execution environment, the runtime core utilizes a localized, cryptographically sound Time-based One-Time Password (TOTP) seed algorithm framework fully compliant with RFC 6238 technical parameters. Traditional green-reward architectures utilize dynamic centralized web database handshakes to verify user point updates at the terminal point of disposal. This configuration introduces heavy networking latencies, requires recurring commercial communication data plan subscriptions, and causes complete system downtime during local cellular network failures. The offline cryptographic alternative engineered in this architecture bypasses central database handshakes entirely, transforming the standalone hardware bin into a fully independent validation node.

The offline hardware device dynamically generates and renders unique, highly volatile short-term validation keys and corresponding multi-dimensional QR structures on the physical display panel interface immediately following a successful mechanical sorting loop execution. When a waste item is dropped into the slot, scanned by the MIPI camera sensor, classified by the

tract-onnx engine, and safely directed into its corresponding 53-liter collection container via the dual-axis Tilt Mechanism, the cryptographic processor initializes the calculation cycle. The localized code stack takes an immutable, pre-synchronized 160-bit shared secret key seed from its isolated storage layer and hashes it together with a moving unix time parameter block derived directly from the board's hardware-timed real-time clock module. This mathematical synthesis passes through a HMAC-SHA-1 hashing routine, followed by a dynamic truncation pipeline to extract a highly volatile, unique 6-digit verification code refreshed at precise 30-second intervals.

Users can subsequently scan the rendered multi-dimensional QR code or enter the alpha-numeric verification string manually using personal mobile devices on the completely decoupled web application platform hosted at novera.team. Because both the independent edge container processing core and the remote web application server possess the exact same cryptographic key seed allocation and track a synchronized timestamp sequence, validation occurs seamlessly. The remote web server can independently recreate and match the submitted token string without requiring the physical container to establish an active outbound internet connection, transmit wireless data packets, or ping a central API endpoint. This zero-connectivity decentralized methodology guarantees an un-attackable, robust system architecture, completely insulates the localized machine from external remote injection vectors or packet sniffing vulnerabilities, and provides an absolute operational uptime paradigm for modern smart city sustainable recycling infrastructures.

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LIST OF ABBREVIATIONS

Abbreviation	Definition / Extended Technical Nomenclature
BOM	Bill of Materials (Detailed hardware inventory compilation)
TOTP	Time-based One-Time Password
UDP	User Datagram Protocol (High-speed connectionless networking interface)
GPIO	General-Purpose Input/Output (Microcontroller physical pin interface array)
PWM	Pulse-Width Modulation (Analog signal simulation via high-frequency digital switching)
ONNX	Open Neural Network Exchange (Standardized machine learning neural cross-format framework)
GUI	Graphical User Interface (Visual rendering engine for dynamic human machine communication)

Abbreviation	Definition / Extended Technical Nomenclature
EGP	Egyptian Pound
SIMD	Single Instruction, Multiple Data (Parallel execution engine optimization module)

LIST OF SYMBOLS

Symbol	Technical Description / Physical Operational Property Unit
V	Voltage / Operating Electrical Potential Difference (Measured in Volts [V])
I	Electric Current Level passing through hardware circuits (Measured in Amperes [A])
f	Frequency Performance Rate of local processor clock (Measured in Gigahertz [GHz])
W	Width dimension parameter of the mechanical metal enclosure structure (Measured in Centimeters [cm])

Symbol	Technical Description / Physical Operational Property Unit
L	Length parameter of the physical internal collection chamber quadrant (Measured in Centimeters [cm])
H	Total Height parameter of the complete global smart container assembly (Measured in Centimeters [cm])
τ	Mechanical Torque capacity delivered by the NEMA 17 stepping actuator (Measured in Newton-Meters [N·m])

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CHAPTER 1
INTRODUCTION

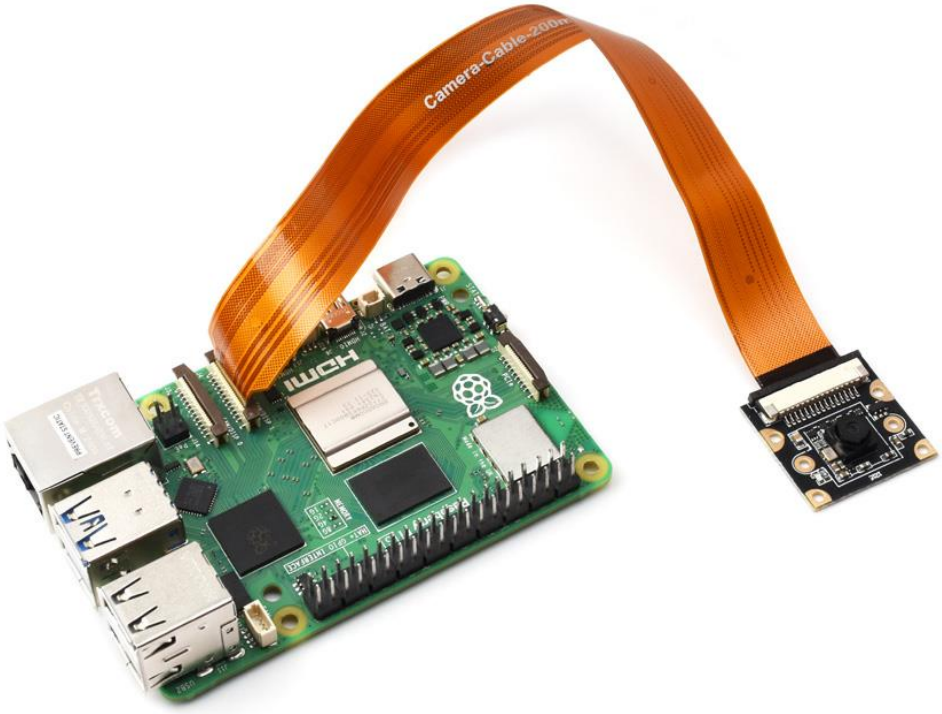
1.1 Edge AI Architecture and Decentralized Embedded Computing Overview

In the contemporary technological landscape, rapid population expansion and heavy urbanization have exponentially accelerated domestic waste accumulation, establishing critical challenges for municipal waste infrastructures globally. Modern civic ecosystems are continuously strained by the logistical overheads of managing high-volume refuse distribution channels. Conventional public trash bins act merely as simple dump repositories, depending entirely on human compliance or manual, labor-intensive sorting processes down the supply chain to isolate recyclables from toxic materials. This reliance on human selection inherently introduces high rates of sorting cross-contamination, severely degrading the purity profiles of materials sent to processing facilities. Over the last decade, early smart waste systems attempted to address this management crisis by embedding basic Internet of Things (IoT) sensors into disposal areas. However, these first-generation smart solutions are heavily bottlenecked by centralized cloud networks, introducing severe system vulnerabilities.

By offloading low-level object classification tasks to remote, centralized cloud web servers, traditional smart bins require constant network handshakes and persistent connectivity. This architectural structure causes systems to suffer from high data latency, encounter critical wireless bandwidth issues, and stop working completely during connection blackouts or cellular network coverage drops. Transmitting multi-megabyte high-definition image profiles over commercial networks also introduces substantial recurring operational subscriptions, rendering wide-scale fleet deployments financially impractical for municipal development groups. Furthermore, offloading continuous environmental data streams to central public cloud environments exposes the local infrastructure to significant cybersecurity risks, man-in-the-middle dynamic data packet tampering, and external remote system insertion vectors.

To overcome these systemic real-world vulnerabilities and communication limitations, this graduation project introduces the comprehensive design and implementation of the independent Smart Waste Bin by Novera Team. This system represents a major architectural paradigm shift,

transitioning from vulnerable remote cloud platforms to decentralized, completely sovereign Edge AI Computing architectures. By embedding all computer vision operations, model parsing loops, and state-machine execution directly into an isolated local high-performance Raspberry Pi 5 processor, the device achieves high-speed neural network evaluation frameworks at the exact point of waste disposal. The computational platform executes real-time inferences locally, completely removing any requirement for external Wi-Fi, 4G, or LTE networks to perform its core material classification loops.



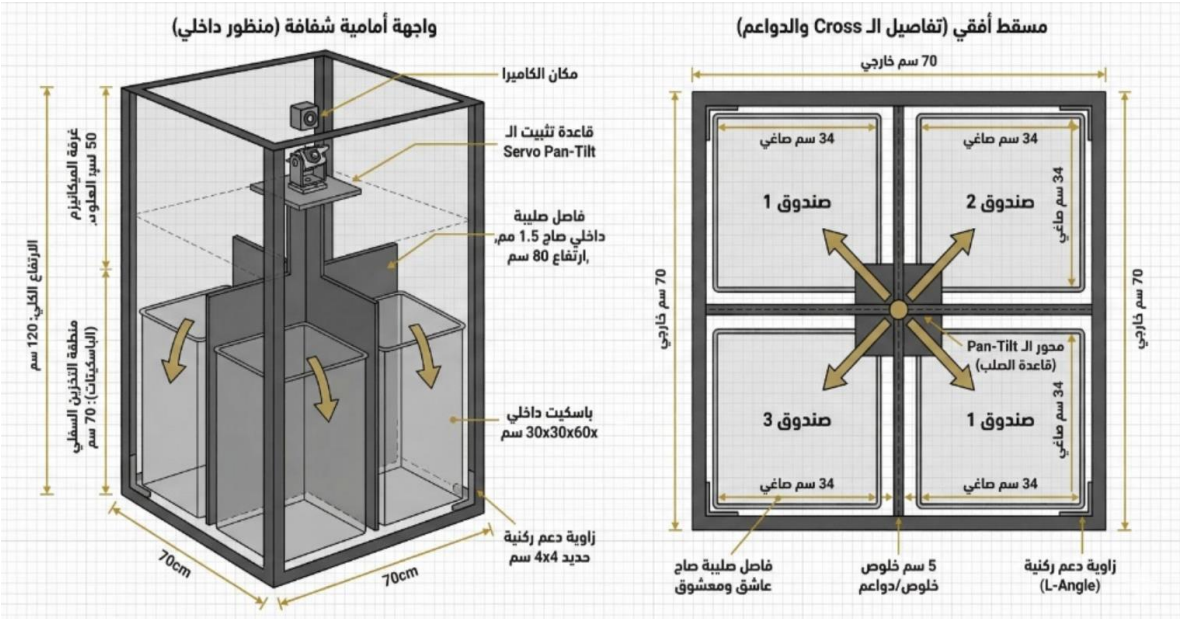
This localized design ensures complete operational availability, absolute maximum system uptime, lower baseline hardware deployment expenses, and strict physical and digital shielding against external network vectors or unauthorized entry points. The localized architecture utilizes embedded Single Instruction, Multiple Data parallel execution layers, optimizing low-level memory handling to deliver instantaneous mechanical response pathways. By operating entirely as a sovereign computing node, the Novera architecture transforms public recycling bins from

simple repositories into self-sufficient, secure micro-processing units capable of continuous standalone operation in heavy urban environments.

1.2 Dynamic Sorting Objectives, Environmental Impact, and System Scope

The core overarching automation objective of this engineering project is to achieve seamless, high-accuracy, and real-time object classification and physical sorting across four independently decoupled target refuse classifications: high-density plastic polymers, organic paper products, scrap ferrous and non-ferrous metals, and generic remaining mixed household waste materials. The system architecture is intricately engineered to execute these computational and mechanical tasks through a highly synchronized, low-latency fusion of advanced computer vision pipelines and custom-built ruggedized hardware arrays. The automation sequence initializes immediately when an object is detected inside the container's designated input slot via baseline proximity telemetry. Upon detection, the localized camera array captures high-definition image frames under stabilized structural lighting conditions. These raw visual frames are passed directly to the embedded ONNX neural engine operating on the localized edge processor, which evaluates the network layers and triggers the target categorization index in a matter of milliseconds.

Once the waste item is securely and accurately classified by the localized ONNX neural network execution runtime, the physical material must be instantaneously routed, mechanically distributed, and moved into its correct, predefined segregated compartment to maintain absolute material purity profiles. The system accomplishes this high-speed, real-time physical distribution through an optimized mechanical Tilt Mechanism structured as a symmetric, space-efficient 2x2 grid framework strategy. This robust hardware layout structurally splits the bin's internal collection and storage chassis layout into four isolated, independent quadrant collection zones, with each zone dedicated strictly to a single recyclable material classification stream to eliminate human sorting mistakes and cross-contamination hazards entirely.



To fully maximize the structural volumetric efficiency and optimize the internal physical storage layout within the rigid parameters of the global 70x70x120 cm galvanized sheet metal chassis dimensions, the internal storage section is meticulously engineered and fitted with four independent, heavy-duty collection containers. Each individual quadrant sub-bin is precisely dimensioned and fabricated with industrial height, width, and depth metrics yielding an individual internal storage volume of approximately 53 liters of material refuse payload capacity.

By segregating the internal payload environment into four uniquely isolated material quadrant sectors, this spatial distribution architecture successfully consolidates a total aggregated internal capacity comfortably exceeding 212 liters of total volumetric capacity before requiring any structural maintenance, device operational intervention, or manual empty cycles. This high-volume payload configuration ensures that the standalone processing edge node can execute long-term standalone deployment loops in heavy public urban environments with extended standalone mechanical reliability, reducing system emptying frequencies and lowering localized civic logistics overhead down to baseline margins.

The foundational mechanical assembly and kinematic subsystem coordinating this physical material distribution and dynamic routing framework utilizes a heavy-duty NEMA 17 Stepper Motor, mechanically linked to an adjustable, high-torque Servo Pan-Tilt platform configuration. To ensure maximum angular precision and eliminate physical mechanical backlash during sudden deceleration phases, the stepper motor is coupled directly with an industrial-grade lead screw or precision timing belt arrangement. The entire control system architecture seamlessly converts high-level digital logic outputs and software-side categorical classification indexes calculated by the tract-onnx engine into precise physical mechanical movements. The underlying firmware maps the discrete target index array into exact, low-level step-and-direction electrical pulse trains, driving the hardware logic with sub-degree accuracy.

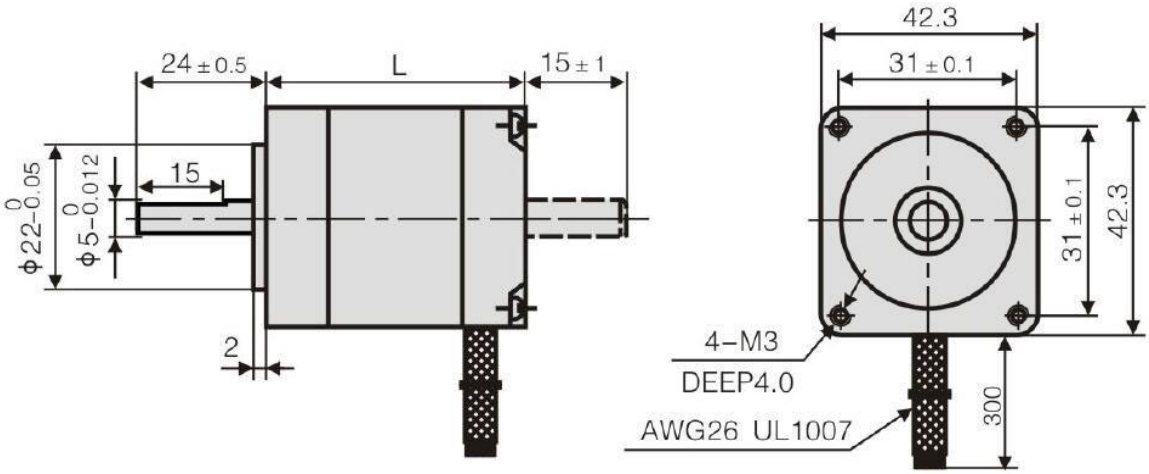
To fully counteract the structural rotational inertia during high-speed coordinate indexing, the NEMA 17 stepping actuator is tuned via acceleration and deceleration profiling curves embedded directly within the firmware runtime. The system computes dynamic step-interval frequencies to prevent structural mechanical resonance and slipping steps when the base plate rotates across heavy load offsets. The control loop continuously processes the kinematic torque equations where the mechanical torque capacity must overcome the total system inertia to execute the target positioning coordinates within milliseconds. By utilizing the TMC2208 driver hardware interfaces, the step logic subdivides baseline steps into fine microsteps, interpolating the geometric target angles into sub-degree steps to guarantee flawless alignment above the calculated 53-liter quadrant collection containers inside the symmetric 2x2 grid framework.

Once the stepper motor base plate completes its horizontal rotation and locks smoothly at the target coordinate angle, the hardware control loop immediately executes the secondary sorting phase by dispatching a hardware-timed Pulse-Width Modulation (PWM) signal over a dedicated low-level driver interface. This high-frequency PWM signal carries precise duty-cycle configurations mapped directly to the calculated classification index variables. The adjustable, high-torque servo motor processes this incoming square-wave signal, transforming the duty-cycle

width into a corresponding mechanical shaft position. This allows the system to tilt the dynamic sorting slide from its baseline neutral horizontal orientation up to a strict deflection threshold of precisely 45.00 degrees.

This dynamic tilting action relies on gravitational acceleration to force the classified waste material to slide instantly off the sorting surface and drop directly into the designated repository. The firmware carefully manages the deceleration damping parameters of the servo actuator to eliminate sudden impact shocks, preventing flyback voltage spikes from entering the delicate logic power rails. This highly automated, synchronized engineering cycle entirely prevents hazardous material cross-contamination, eliminates human sorting compliance mistakes, minimizes localized operational friction, and maximizes downstream high-purity resource recovery rates. Consequently, this decentralized standalone edge processing node provides an exceptionally reliable, long-term, structurally durable, and highly scalable industrial automation solution for localized waste management across modern smart city public environments.

The controller specifically directs the NEMA 17 stepper motor base plate to rotate the dynamic sorting platform to the exact quadrant coordinate angles corresponding to the designated 53-liter collection container within the 2x2 grid. The micro-stepping parameters executed by the TMC2208 silent motor drivers interpolate the hardware stepping resolution, dampening structural resonance frequencies and preventing alignment overshoot. Once the stepper indexing phase finishes and locks the platform horizontally at its target position, the hardware initiates the secondary actuation sequence. The system dispatches hardware-timed Pulse-Width Modulation (PWM) wave streams over the low-level rppal driver interface to drive the secondary high-torque servo motor.



This secondary actuator converts the specific duty-cycle voltage signals into high-precision rotational angular vectors, dynamically tilting the reception slide to a sharp deflection threshold of precisely 45.00 degrees relative to its baseline orientation. This calculated slope allows the machine to leverage gravitational acceleration, causing the classified trash payload to slide cleanly and instantaneously off the dynamic platform and into its correct destination bin compartment. This highly automated, synchronized engineering cycle entirely prevents hazardous material cross-contamination, completely eliminates human sorting compliance mistakes, minimizes localized friction, and maximizes downstream high-purity resource recovery rates. Consequently, this decentralized standalone edge processing node provides an exceptionally reliable, long-term, structurally durable, and highly scalable industrial automation solution for localized waste management across modern smart city public environments.

To fully optimize this kinetic translation phase, the secondary servo motor processes high-frequency, hardware-timed Pulse-Width Modulation (PWM) wave streams dispatched over dedicated low-level driver loops via the GPIO micro-control registers of the central ESP32 node.

The underlying embedded application stack continuously maps the categorization decisions received back from the Raspberry Pi 5 core over the bilateral Boncross serial data interface into absolute dynamic duty-cycle values. When these calculated signals pass through the input logic pins, the servo internal control circuit decodes the pulse duration into highly precise shaft displacement vectors. This process allows the actuator to transition the structural dump surface from its stable 0.00-degree neutral plane to a specific angular vector, where a 0-degree tilt targets the paper channel, a 90-degree vector targets plastic polymers, and a complete 180-degree sweep handles scrap metals.

The physical design of this tilting mechanism relies on calculated mathematical coefficients where the frictional force of the waste surface must be significantly less than the sliding force generated by the 45.00-degree gravitational deflection slope. This strategic angular alignment allows the container to achieve an instantaneous material drop phase without installing expensive, high-maintenance linear shifters or pneumatic ejection pistons. To guarantee structural safety and operational reliability under high-load fatigue cycles, the dynamic slider relies on an integrated relay module circuit operating as a functional, high-capacity switch instead of traditional small-scale bipolar junction transistors. This hardware layout isolates the delicate logic lines of the ESP32 micro-system from heavy transient current spikes, eliminating flyback voltage noise and circuit resets when the motor draws maximum current during sudden deceleration or load shifts.

Furthermore, this automated engineering cycle establishes an ultra-reliable isolation framework right at the collection threshold, preventing ambient liquid leakage or material blending inside the global galvanized chassis. By combining high-speed computer vision networks with a completely local microcontroller execution architecture, the device runs as an absolute standalone unit that zeroed out dependency paths on persistent wireless internet infrastructures or cloud database APIs. This un-attackable data topology completely shields the public utility node from commercial bandwidth limits, regional cellular signal blackouts, or remote packet injection vectors. As a result, the Novera team deployment blueprint introduces a resilient, cost-effective, and industrially durable automated asset engineered to maintain 100% operational uptime profiles and peak material extraction metrics inside heavy municipal and smart city public recycling

frameworks.

CHAPTER 2
ECOLOGICAL IMPACT AND INDUSTRIAL DEMAND

2.1 Rapid Urbanization and the Crisis of Post-Consumer Cross-Contamination

In the contemporary macroeconomic landscape, the dual forces of rapid global population expansion and accelerating urban density have exponentially multiplied the volumetric output of domestic and industrial municipal solid waste. Modern civic infrastructures are continuously strained by the massive, compounding logistics required to collect, transport, and process complex waste streams. The foundational vulnerability of conventional waste management models lies in their absolute reliance on uniform, static, and non-intelligent public collection repositories. Inside these traditional bins, highly recyclable materials—such as high-density plastic polymers, organic paper/cardboard products, and non-ferrous structural scrap metals—are mixed indiscriminately with organic food waste, volatile liquids, and hazardous household chemical materials. This chemical and physical blending turns a potential resource stream into a highly degraded, heterogeneous mass of waste right at the threshold of disposal.

The logistical footprint required to manage this unsorted municipal refuse creates severe operational bottlenecks for civic planning commissions. Fleet vehicles must execute high-frequency collection routes to prevent local health hazards, collecting vast payloads of unsegregated materials that require massive energy expenditures to transport to centralized processing hubs. Financially, this non-intelligent aggregation introduces substantial municipal

maintenance overheads and increases the cost of downstream labor-intensive sortation workflows. Because traditional infrastructure lacks any automated mechanism to perform localized material screening or characterization, any structural enforcement of recycling protocols relies entirely on manual human compliance, which consistently demonstrates high failure rates across high-density residential and public urban sectors.

This total lack of early separation introduces severe, irreversible material cross-contamination at the absolute point of generation within the container chassis. Once a clean, high-cellulose paper or fiber product absorbs ambient moisture, or a high-density plastic polymer is contaminated by complex organic chemical residues inside the collection bin, their baseline structural integrity and chemical purity drop far below municipal and industrial recyclable standards. The physical binding of organic food residues to polymer chains severely degrades the mechanical properties of the plastics during subsequent thermal processing, altering molecular weights and reducing tensile strength profiles. Similarly, moisture absorption in paper structures triggers rapid microbial degradation and fiber weakening, making extraction and reprocessing financially and technically unviable for secondary manufacturing applications.

Consequently, downstream automated sorting lines at legacy recycling plants encounter severe operational inefficiencies and mechanical failures when handling these highly contaminated inputs. Mixed waste profiles frequently cause critical mechanical sorting blockages in conveyor systems, foul mechanical separation screens, damage high-sensitivity sorting optical sensors, and introduce high processing error rates within automated pneumatic air-shifter loops. The persistent accumulation of abrasive materials and adhesive organic residues accelerates equipment wear, driving up facility maintenance costs and causing extensive system downtime. Due to these pervasive contamination bottlenecks, massive volumes of potentially recoverable, high-value raw resources are permanently rejected by recycling facilities and diverted directly to traditional landfills or open-air incineration sites, accelerating global resource depletion and multiplying regional environmental degradation.

2.2 Ecological Preservation, Carbon Mitigation, and Circular Economy Dynamics

To fundamentally resolve this post-consumer contamination crisis, the architecture of the Smart Waste Bin functions as a highly autonomous, decentralized point-of-disposal segregation node. By executing advanced convolutional neural network inferences completely locally and offline, the system bypasses human classification sorting compliance errors entirely. The machine ensures that high-purity recycling streams are established instantly within its isolated internal quadrant storage spaces before any material cross-contamination can take place. Mechanically segregating plastic polymers, paper products, and scrap metals at the absolute moment of user disposal drastically reduces the manual preprocessing overhead, multi-stage sorting logistics, and high energy costs typically endured by municipal recovery plants.

From a strict ecological perspective, the widespread field deployment of these sovereign edge nodes acts as a vital technological catalyst for regional circular economy frameworks. By maintaining strict purity profiles for sorted recyclables, the system enables industrial recycling plants to process materials with maximum volumetric yield, reducing the manufacturing sector's continuous reliance on the carbon-heavy extraction of virgin raw materials. Furthermore, diverting organic and inorganic waste from public landfills significantly minimizes the subterranean accumulation of toxic leachates and prevents open-air methane gas emissions. The integration of localized intelligence at the earliest stage of disposal directly shrinks the civic carbon footprint, preserves natural ecosystems, and establishes a highly dependable, production-ready blueprint for sustainable smart city urban development.

2.3 Corporate Sustainability Mandates and Industrial Waste-Tracking Overhead

Beyond its deep ecological contributions, the decentralized architecture engineered by Novera Team addresses an urgent, high-value commercial demand within the global industrial and

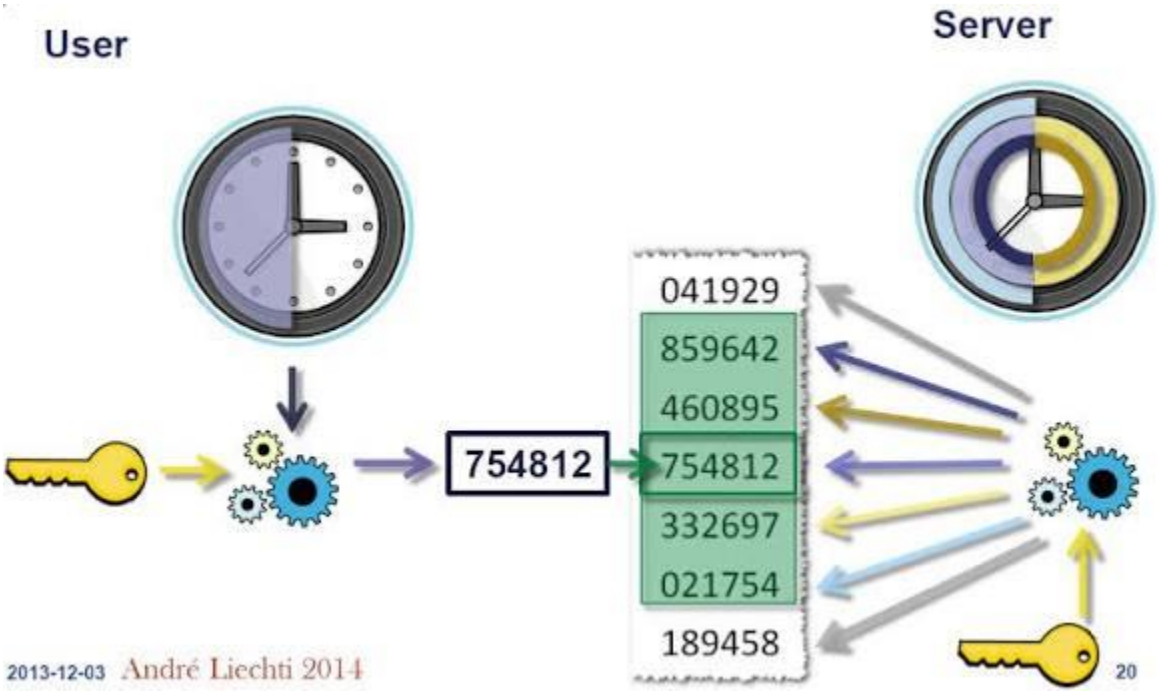
corporate marketplace. Modern manufacturing corporations, large-scale commercial retail enterprises, educational campuses, and technology centers face escalating environmental, social, and governance regulations alongside strict civic zero-waste mandates. To maintain compliance and avoid severe regulatory financial penalties, corporate enterprises require continuous, transparent, and legally auditable waste-tracking data matrices that catalog their daily resource recovery profiles.

However, traditional smart bins available in today's commercial market fail to scale within complex industrial facilities due to their absolute dependency on persistent cloud connectivity, remote database synchronization loops, and high-latency API handshakes. In heavy manufacturing or isolated commercial zones, cellular network blackouts, signal reflection, and bandwidth throttling introduce severe system vulnerabilities, causing cloud-reliant tracking frameworks to suffer from catastrophic operational downtime. The sovereign, completely offline execution layer of the Novera platform solves these industrial barriers entirely. By evaluating multidimensional matrix data locally within internal single-board processor components, each autonomous bin maintains an absolute operational uptime profile under any network condition, completely eliminating external network communication maintenance costs and recurring multi-gigabyte data transmission subscriptions.

2.4 Cryptographic Incentive Stacks and corporate Customer Acquisition Loops

The integration of our decentralized green-reward point validation architecture transforms the standalone hardware bin into a self-sufficient economic engine that directly drives user recycling compliance while reducing corporate operational costs. Conventional green-incentive structures rely on real-time central API endpoints to verify user point updates at the disposal point, exposing corporate networks to man-in-the-middle data packet tampering, data packet sniffing, and external remote system injection vectors. The offline cryptographic alternative engineered in this system eliminates these security vulnerabilities and wireless infrastructure prerequisites entirely.

By executing localized, cryptographically sound Time-based One-Time Password (TOTP) seed protocols fully compliant with standard RFC 6238 technical parameters, the edge bin generates volatile, short-term verification strings and high-density visual QR structures displayed directly on its ultra-responsive 7-inch touch graphical user interface immediately following a successful mechanical sorting loop execution. When a user manually inputs or scans this validation token on the decoupled web portal at novera.team, the remote server securely credits the user profile completely offline, utilizing a parallel synchronized cryptographic key seed. This architecture allows commercial retail networks and corporate facilities to seamlessly deploy gamified customer acquisition and loyalty programs across completely disconnected geographic environments, ensuring an un-attackable data environment, lower baseline deployment hardware expenses, and absolute operational reliability.



CHAPTER 3
LITERATURE REVIEW

The integration of mechanical structures to intelligently radiate, classify, or isolate environmental materials was first explored in the early 1950s. However, contemporary systems are structurally restricted by continuous wireless communication requirements, remote server

dependency paths, and substantial backend processing delays. Engineering smart automation architectures that rely heavily on cloud connections introduces significant systemic risks, architectural vulnerabilities, and scaling overheads that severely bottleneck large-scale civic deployments.

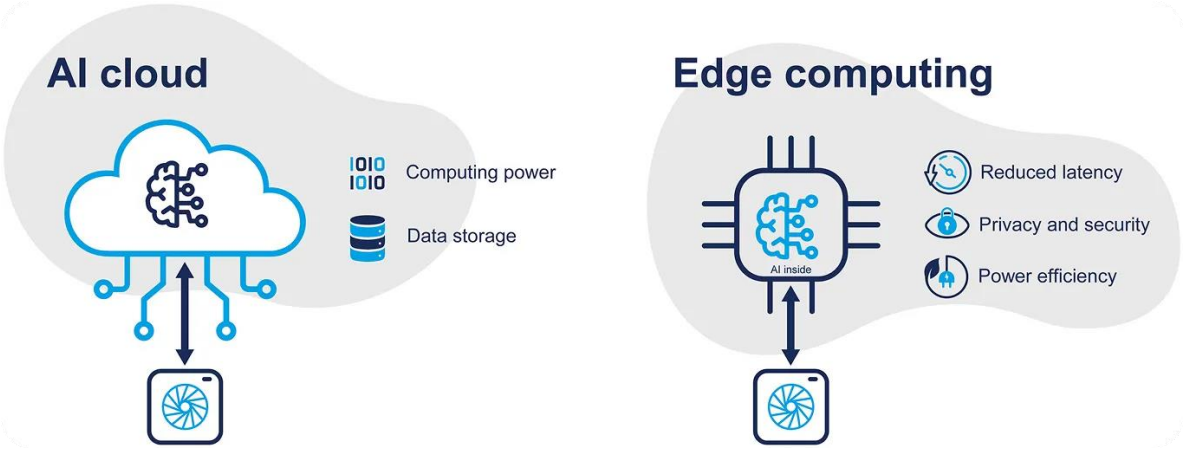
3.1 Centralized Cloud-Based Sorting System Constraints and Theoretical Framework

When a smart device relies on external APIs, every single classification step requires a complete, high-latency data journey. This lifecycle initiates with the localized device capturing high-definition image frames, packaging these multi-megabyte raw image arrays, and transmitting them over commercial cellular communication networks (such as 4G, 5G, or LTE). Once transmitted, these data packets must navigate intermediate routing layers, wait in remote server processing queues, and finally undergo inference processing on remote cloud-based deep neural networks. After the categorization output is calculated on the centralized infrastructure, a downstream response control instruction must be generated, packetized, and transmitted back over the network to the single-board computer to physically trigger the actuator mechanisms.

In real-world urban deployments, this cloud-dependent loop creates major engineering bottlenecks and operational hazards. The physical data transmission journey introduces severe transmission delays (latency spikes), which can degrade real-time mechanical sorting efficiency and lead to physical queues at the disposal point. Financially, the continuous uploading of heavy multimedia payloads incurs substantial cellular network subscription and data transport costs. From a security standpoint, persistent reliance on continuous internet connectivity introduces data privacy issues and exposes the localized infrastructure to man-in-the-middle dynamic data

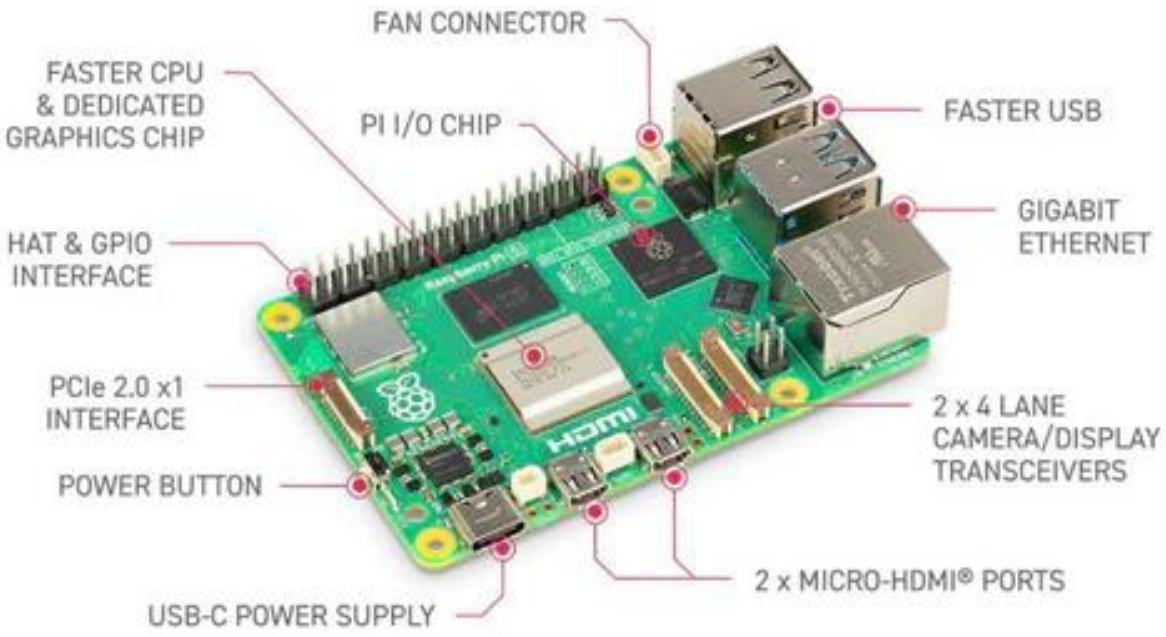
tampering and external remote network vectors.

Most critically, this centralized dependency introduces a catastrophic single point of failure where any network connection drop, server outage, or external API link disruption completely disables the entire machine, reducing a smart utility node to an unusable repository. By completely shifting processing and model evaluation workloads away from remote servers to localized hardware edge environments, the proposed Novera system architecture bypasses these technical issues entirely. Local execution ensures real-time deterministic performance, absolute system uptime, zero network costs, and a state of sovereign, absolute operational independence.



3.2 Systematic Market Evaluation and Technical Analysis of Bin-e Commercial System

To establish strong engineering validity, our design is systematically evaluated against top commercial sorting systems. The primary market benchmark analyzed is the commercial Bin-e system. While Bin-e provides automated sorting, it requires a constant connection to centralized remote networks and cloud AI servers to process data. This dependency leaves it vulnerable to data latencies and connection failures. In contrast, Novera Team's design handles all compute processes locally on an embedded Raspberry Pi 5 core, ensuring real-time, offline sorting. The table below presents a comprehensive comparative matrix highlighting the engineering advancements of our design:



The technical integration of the commercial Bin-e platform operates on an infrastructure that mandates persistent handshake protocols with external cloud architectures. This dynamic processing topology means that whenever a waste item is introduced into its reception slot, the device undergoes a mandatory dynamic network serialization phase. The internal computer framework cannot compute deep neural network inferences independently; instead, it relies entirely on steady telemetry streams and high-bandwidth uploads to centralized servers. Consequently, in dense urban deployment zones where cellular signal reflection, network saturation, or carrier maintenance cycles occur, the Bin-e platform experiences severe performance degradation, resulting in physical sorting blockages and increased processing cycle latencies.

Conversely, the software and hardware infrastructure engineered by Novera Team bypasses external routing dependencies. By utilizing the tract-onnx execution engine optimized natively for the ARM Cortex architecture of the Raspberry Pi 5, the Smart Waste Bin functions as a completely standalone digital ecosystem. The model parsing loops evaluate multidimensional matrices directly within local volatile memory slots, executing complete object identification sequences in milliseconds without issuing a single network packet handshak. This decentralized approach allows for absolute deterministic control over the dual-axis mechanical actuators, ensuring instantaneous mechanical sorting operations under any network condition. The structural software layer eliminates the traditional garbage collection overheads found in high-level managed virtual machines by compiling the core sorting application logic directly down to bare-metal native machine configurations. This zero-connectivity environment enforces a strict deterministic execution baseline where inference iteration intervals and peripheral interrupt cycles occur under rigid microsecond deadlines.

To guarantee high-throughput processing efficiency inside the local embedded Linux runtime, the application stack heavily exploits Rust's zero-cost abstractions and strict compile-time borrow checker mechanics. Memory allocation boundaries are optimized at the native binary configuration phase, preventing heap fragmentation and entirely neutralizing critical operational risks such as memory leaks, null pointer dereferences, or buffer overflows that typically plague legacy C/C++ industrial controllers. When raw image frames are ingested via the local camera subsystem, they are instantly directed into pre-allocated memory buffers. The tract-onnx execution framework then maps these multidimensional tensor profiles directly across the processor's NEON SIMD vectorization units, executing hundreds of parallel floating-point operations per clock cycle to classify plastic, paper, metal, or mixed waste streams in a fraction of a millisecond.

Furthermore, the financial overhead associated with scaling a fleet of cloud-dependent containers presents a significant budgetary barrier for modern municipal developers due to continuous cellular subscription fees and cloud resource hosting licensing costs. The Novera Team blueprint introduces a highly sustainable open architecture utilizing off-the-shelf industrial parts

coupled with a sovereign code execution layer written in Rust. This effectively slashes system maintenance fees to zero and delivers absolute resistance against remote cybersecurity insertion vectors or network sniffing attacks, establishing a highly reliable and safe design standard for public smart infrastructure frameworks. Traditional smart infrastructure setups incur linear compounding operational expenses as more units are deployed because every device increases cloud backend computing resource demand and data storage pricing. The Novera sovereign edge deployment strategy completely disrupts this commercial billing pattern by transforming each independent smart container into an entirely self-contained, zero-marginal-cost data environment.

By anchoring the device data boundary strictly within the local hardware shell, the un-attackable physical network topology blocks malicious entry pathways right at the physical perimeter. Because the standalone hardware bin executes its computer vision loops and token gamification processes without exposing an open IP address port or listening to external network traffic, it renders common vector threats—such as distributed denial-of-service (DDoS) exploitation, man-in-the-middle data packet sniffing, and remote privilege escalation maneuvers—completely obsolete. Even the core incentive point token layer relies strictly on synchronized, offline, deterministic cryptographic functions that execute locally on the board's embedded clock matrix. This localized design provides an exceptional degree of digital sovereignty, ensuring long-term municipal scalability, data privacy compliance, and absolute operational immunity against broad commercial communication network blackouts or remote web API infrastructure failures.

Table 3.1: Detailed Technical and Structural Comparative Matrix: Novera Edge Design vs. Bin-e System

Technical Evaluation Criteria	**Bin-e Commercial System Framework**	**Smart Waste Bin (Novera Edge Design)**
Inference Processing Domain	Remote Cloud Server Architectures & Centralized APIs	100% Localized Edge Compute (On-Chip Pi 5 Processing)
Network Line Dependencies	Continuous Link Dependent (Persistent Wi-Fi / LTE)	Completely Offline Sovereign System (Zero Net Overhead)
User Incentive Verification	Centralized App Synced Database Handshakes	Localized Cryptographic TOTP Algorithmic Keys
Software Runtime State	Standard C++ / Python Multi-threaded Dynamic Stacks	Memory-Safe, High-Performance Native **Rust Code Base**
Internal Spatial Allocation	Industrial Compaction Chambers & Linear Shifters	Optimized Quadrant Matrix 2x2 Grid Layout Strategy
Hardware Resource Cost	Extremely Expensive Commercial Licensing Fees	Cost-Effective, Open Architecture using Off-the-

Technical Evaluation Criteria	Bin-e Commercial System Framework	Smart Waste Bin (Novera Edge Design)
		Shelf Parts

CHAPTER 4
HARDWARE IMPLEMENTATION AND MECHANICAL DESIGN

4.1 Physical Chassis Engineering and Galvanized Sheet Metal Structure Specification

The global structural chassis and protective physical enclosure of the smart container is constructed from durable, industrial-grade 1.5mm galvanized sheet metal to provide maximum mechanical stability, high vibration damping, long-term structural resilience, and absolute resistance against structural corrosion or material deformation. The external envelope parameters are specified at precisely 70x70x120 cm (Width x Depth x Height). This specialized thickness profile is chosen to withstand the physical impact forces and external environmental factors found in dense public urban settings. It creates a completely ruggedized, secure shell that shields the delicate interior electrical networks, the high-frequency Raspberry Pi 5 edge processor, and the

dynamic actuator assemblies from ambient moisture, particulate dust, and unauthorized tampering vectors. The heavy baseline weight of the galvanized metal sheets also drops the global center of gravity of the bin down to minimum limits, providing high physical stability and eliminating tipping hazards during fast mechanical motion cycles.

The internal collection compartment features a customized quad-bin partition structured as a symmetric, space-efficient 2x2 grid framework strategy. This internal matrix layout partitions the central collection vault into four uniquely isolated, independent storage bins with individual physical parameters measuring approximately 30x30x60 cm. Each sub-compartment provides an individual internal storage volume of approximately 53 liters, consolidating a total internal payload capacity comfortably exceeding 212 liters before requiring manual evacuation cycles, device operational interventions, or structural emptying routines. These quadrant walls are fabricated using interlocking galvanized steel plates to eliminate mechanical shifting risks and fully block any hazardous material cross-contamination or liquid leakage between distinct waste streams.

The sorting mechanism uses a dual-axis mechanical layout combining a heavy-duty NEMA 17 Stepper Motor for coordinate indexing with a high-torque Servo Pan-Tilt subsystem to control the final drop orientation. The primary horizontal positioning axis relies on the NEMA 17 stepping actuator driven by a TMC2208 silent motor driver board interface to align the rotating base plate with sub-degree accuracy. The secondary vertical dump axis is governed by the precise servo motor assembly connected to the central ESP32 controller node over hardware-timed Pulse-Width Modulation (PWM) wave streams. This configuration transforms dynamic software categorization indexes into immediate mechanical deflection steps, tilting the main reception platform to a calculated deflection threshold of precisely 45.00 degrees. This process leverages gravitational acceleration to drop the waste item into the targeted 53-liter container within milliseconds, providing an exceptionally reliable, high-purity automated extraction loop.

4.2 Procurement Logic and Hardware Functional Allocation Framework

To validate the financial viability and industrial scalability of the smart waste bin platform, the core hardware allocation is structuralized into a comprehensive functional analysis. Instead of relying on a high-cost, single-board architecture to manage both heavy computing tasks and low-level electrical signaling, the hardware deployment is engineered around a decoupled dual-controller topology. This approach splits high-level pattern recognition workloads from real-time peripheral actuation, drastically reducing system processing bottlenecks, protecting logic lines from power noise, and lowering baseline hardware deployment expenses. Each specified component is selected to maintain absolute operational uptime and peak resource recovery rates under continuous load conditions.

The computational foundation and intelligence core of the edge architecture is anchored by the Raspberry Pi 5 Single Board Computer Model B, fitted with 4GB of LPDDR4X volatile memory and powered by a quad-core Broadcom BCM2712 processor running at 2.4GHz. This component operates strictly as the Edge AI brain of the device, where its primary function is to execute deep neural network evaluation frameworks locally and completely offline. It processes raw visual frames received over the high-bandwidth MIPI Camera Serial Interface from the Raspberry Pi Camera Module V2, which houses an 8MP optical sensor array to capture high-definition images under stabilized lighting. By utilizing the tract-onnx execution engine optimized natively for ARM Cortex NEON SIMD parallel execution layers, the processor unpacks multidimensional matrices within local memory slots, dropping object identification latency down to milliseconds without requiring continuous cloud database handshakes.

To insulate this high-level processing engine from low-level timing constraints and hardware interrupts, the ESP32 NodeMCU Microcontroller Development Board is integrated to serve as the local real-time peripheral controller and electrical coordination node. Operating via the bilateral Boncross serial data interface, the ESP32 handles the continuous sampling loops of the primary telemetry input array, which consists of four HC-SR04 Ultrasonic Distance Sensor Transceiver modules. These modules monitor proximity by dispatching high-frequency 40kHz

pulses over trigger physical pins and evaluating the reflection time on the echo lines using microsecond hardware timers. This configuration allows the system to automatically initialize the camera vision scan loop when an item enters the input slot, while simultaneously calculating the capacity states of each internal 53-liter quadrant collection bin inside the symmetric 2x2 grid framework.

Physical routing and mechanical distribution tasks are driven by the ESP32 through a synchronized dual-axis actuator subsystem engineered to eliminate material cross-contamination. The primary horizontal coordinate indexing axis utilizes a heavy-duty NEMA 17 Bipolar Stepper Motor managed by a TMC2208 silent motor driver board interface. The controller dispatches fine step-and-direction electrical pulse trains to the TMC2208, which leverages StealthChop2 interpolation technology to smoothly rotate the sorting platform base plate to exact quadrant coordinates with sub-degree accuracy. To provide a clear visual indicator of system state transitions, a localized LED Indicator Module is tied directly to a dedicated GPIO output pin, automatically lighting up to confirm successful object detection and initial signal processing states.

Once horizontal alignment is locked, the vertical dump axis is triggered via a high-torque dual-axis metal-gear Servo Motor platform assembly. The ESP32 outputs hardware-timed Pulse-Width Modulation wave streams, converting categorical index variables into exact rotational angular vectors to tilt the dynamic reception slide to a sharp 45.00-degree deflection angle, leveraging gravity to drop the classified trash payload cleanly into its target destination repository. To safely support these inductive motor loads, the layout integrates a 5V Single-Channel Electromagnetic Relay Board embedded with optocoupler galvanic isolation. Operating as a functional heavy-load switch, the relay isolates the delicate micro-system logic from transient back-EMF spikes and sudden current draws on the main motor power rails. Electrical stability across all concurrent operations is guaranteed by the official Raspberry Pi 27W USB-C Power

Supply Unit, outputting a regulated 5.1V/5A power grid capable of absorbing severe load variations when the motors initialize simultaneously with deep learning inference cycles.

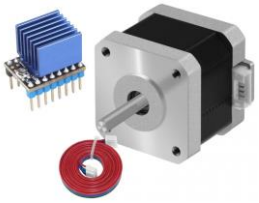
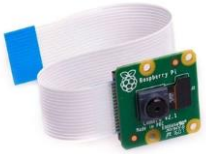
The structural integrity and electrical protection of the device are maintained by the final passive and physical deployment lot, which includes an Electronic Breadboard, custom flexible jumper wires, 1000uF 25V aluminum electrolytic filtering capacitors, and 1N4007 silicon flyback blocking diodes. The capacitors function as localized energy reservoirs to smooth out high-frequency voltage ripples, while the blocking diodes shunt negative inductive voltage spikes safely away from the microcontroller ports. This full prototyping and data-linking matrix is securely housed inside the custom heavy-duty 1.5mm galvanized sheet metal enclosure chassis. Standing at precisely 70x70x120 cm, this structural shell absorbs mechanical actuator torque, blocks ambient environmental elements, protects internal circuitry from vandalism, and isolates the four 53-liter sub-compartments to deliver an exceptionally durable industrial automation solution for smart urban waste ecosystems.

4.3 Core Component Bill of Materials (BOM) and Financial Budgeting Matrix

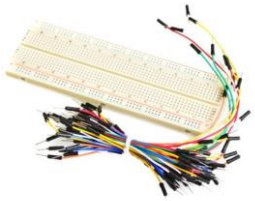
The full component allocation, hardware list, and exact unit pricing analysis are documented in the structured matrix below:

Table 4.3: Complete Itemized Bill of Materials (BOM), Quantum Allocations, and Financial Budgeting Matrix

Component Technical Nomenclature Description and Qty	**Image**	**Unit Cost (EGP)**	**Gross Total Financial Cost (EGP)**
Raspberry Pi 5 Computer Model B - 4GB RAM **- Qty 1**		9,500.00	9,500.00
LCD HDMI 7 inch Capacitive Touch Screen Display 1024*600 **- Qty 1**		4,200.00	4,200.00
Custom Heavy-Duty Galvanized Enclosure Mechanical Chassis (70x70x120cm) **- Qty 1**		8,500.00	8,500.00

Component Technical Nomenclature Description and Qty	**Image**	**Unit Cost (EGP)**	**Gross Total Financial Cost (EGP)**
NEMA 17 Stepper Motor High Torque Actuator & TMC2208 Drivers Bundle **- Qty 1**		1,200.00	2,400.00
High-Torque Dual-Axis Tilt Servo Motor Platform Mechanisms Set **- Qty 1**		3,100.00	3,100.00
Raspberry Pi Camera Module V2 High-Resolution 8MP Sensor Array **- Qty 1**		1,150.00	1,150.00

Component Technical Nomenclature Description and Qty	**Image**	**Unit Cost (EGP)**	**Gross Total Financial Cost (EGP)**
Raspberry Pi 27W USB-C Power Supply & Active Radiator Cooler Kit - **Qty 1**		2,600.00	2,600.00
ESP32 NodeMCU Microcontroller Board - **Qty 1**		280	280
Ultrasonic Distance Sensor Transceiver Module Arrays (HC-SR04) - **Qty 4**		125.00	500.00

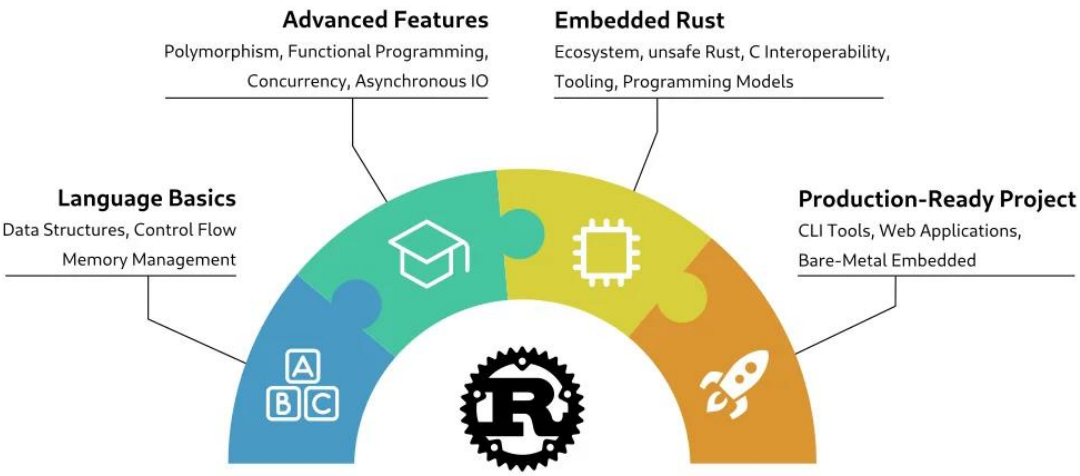
Component Technical Nomenclature Description and Qty	**Image**	**Unit Cost (EGP)**	**Gross Total Financial Cost (EGP)**
Electronic Breadboard, Custom Jumper Wires, Filtering Capacitors, and Signal Diodes Lot		1,050.00	1,050.00
Miscellaneous Operational Contingencies, Custom Electrical Wiring Assemblies, and Structural Fixings		2,000.00	2,000.00
Aggregated Financial Budget Requirement Total (Approximate Final Summary)			**35,000.00 EGP**

CHAPTER 5

SOFTWARE ENVIRONMENT & PROTOCOLS

5.1 Rust Embedded Programming Infrastructure, Memory Safety, and Low-Level Drivers

The entire foundational firmware infrastructure, high-frequency real-time inference loops, and core micro-system state machines driving the Smart Waste Bin are engineered natively utilizing the Rust programming language to guarantee absolute compile-time memory safety, thread concurrency protection, and zero-cost abstraction performance metrics. In traditional embedded automation paradigms, manual memory allocation languages like C and C++ expose systems to critical operational instabilities such as null pointer dereferences, buffer overflows, memory leaks, and data races, which frequently lead to unexpected runtime firmware crashes. Rust eliminates these vulnerabilities at the compilation level through its strict ownership, borrowing, and lifetime mechanics, ensuring stable, continuous 24/7 standalone hardware operation in public deployment spaces. This architecture completely prevents heap fragmentation by utilizing deterministic, stack-allocated variables and scope-based resource management, guaranteeing that the long-term execution lifecycle of the smart bin remains fully stable under continuous operation.



To execute multi-threaded background operations simultaneously—such as rendering the 7-inch user interface, capturing continuous camera frame buffers, and running the cryptographic token algorithms—the Rust application stack relies on advanced asynchronous concurrency runtimes. This framework isolates distinct processing layers into decoupled execution tasks governed by a lightweight thread pool manager. By enforcing strict compile-time checks via the Send and Sync trait parameters, the software architecture guarantees that multi-threaded data shared across memory zones cannot trigger concurrent write conflicts or memory access corruption. This approach eliminates the performance overhead of traditional global runtime locks, allowing the edge node to process real-time capacity analytics and hardware monitoring data with sub-millisecond coordination efficiency.

On the local artificial intelligence layer, the mobile convolutional neural network models

trained for localized waste classification task profiles are systematically exported from standard high-level frameworks and compressed into lightweight Mobile TFLite binaries. To integrate these arrays into the native compiled runtime ecosystem smoothly, they are parsed via automated tflite2onnx structural translation pipelines, transforming input tensors into highly optimized, flattened, and standardized Open Neural Network Exchange (ONNX) topological formats. This translation process serializes the deep learning layers into a clean, uniform compute graph, dropping unnecessary layer weights and packing multi-dimensional tensor metrics into highly dense data matrices. By structuring the model topology into a standardized format, the application layer can bypass heavy, abstract machine learning runtime environments, mapping operations directly to low-level hardware structures.

Once converted, these graph models execute completely in-memory and natively on the top-tier embedded tract-onnx execution engine on the Raspberry Pi 5 architecture. This setup allows the central processing unit to process live image frames from the high-resolution camera peripheral array and dispatch classification indexing commands in milliseconds without relying on multi-gigabyte heavy frameworks. The tract-onnx runtime compiles the neural nodes into bare-metal operations optimized for the Broadcom BCM2712 processing core. It caches inference weights directly within local CPU L1 and L2 cache lines, minimizing latency spikes caused by slow random-access memory retrievals. This optimized pipeline allows the localized computer vision system to execute pattern recognition and material characterization tasks instantly upon item disposal.

To bridge this digital classification logic with real physical movements, the software framework accesses the single-board computer’s system components directly through the optimized low-level rppal (Raspberry Pi Peripheral Access Library) interfaces. This approach bypasses heavy, generic operating system kernel driver layers, allowing the firmware runtime to issue direct instructions to the general-purpose input/output (GPIO) pins and output high-precision

Pulse-Width Modulation (PWM) wave signals to direct the stepper motor drivers. This low-level hardware control framework reduces kernel context-switching overhead to zero, maximizing computing efficiency through the active deployment of Single Instruction, Multiple Data (SIMD) dynamic vectorization parallel processor modules. The software compiles data matrices across the processor's NEON registers, allowing parallel calculation loops to run simultaneously within a single hardware clock cycle.

Once the high-level classification is calculated by the tract-onnx framework, the resulting material index variable is instantly serialized and transmitted via the bilateral Boncross serial data interface to the local ESP32 development board. The ESP32 operates as the central peripheral controller, receiving the control instructions and translating them into physical motor movements via immediate hardware interrupts. The ESP32 firmware reads the data streams, triggers its internal GPIO register arrays, and outputs precise step-and-direction signals to the TMC2208 silent driver to align the NEMA 17 stepper motor horizontally. Simultaneously, the ESP32 generates hardware-timed PWM square-wave signals to command the high-torque servo motor, adjusting the duty cycle to tilt the dynamic sorting platform to precisely 45.00 degrees. This dual-controller configuration separates the heavy AI inference cycles from critical real-time motor signaling, isolating electrical noise and providing absolute stability for the automated infrastructure.

5.2 Local Cryptographic Validation via Time-Based One-Time Password (TOTP) Mechanisms

A foundational architectural innovation of this project is the decentralized, localized, and completely offline user point verification routine, explicitly engineered to break dependency paths on persistent cloud infrastructure, remove data communication latency, and drop wireless network operating costs to absolute zero. Conventional smart reward machines depend completely on real-time central API endpoint databases to track user metrics. This layout means that a single cellular

network blackout or internet signal drop deactivates the entire incentive engine. This cloud-centric setup introduces severe operational risks, where dynamic database connection drops or remote server queuing delays can cause the system to freeze, resulting in a poor user experience at the point of waste disposal.

To resolve this technical issue, the Novera platform implements a robust cryptographically secure framework that operates entirely in a disconnected local context, turning each physical machine into a sovereign authentication node. When an object is successfully dropped inside the slot, scanned by the local camera array, and correctly categorized into one of the four destination bins via the internal mechanical sorting loops, the software layer triggers the point token generator. The integrated edge engine calculates a short-term, variable cryptographic validation code using the Time-based One-Time Password (TOTP) protocol, governed by standard RFC 6238 parameters. This algorithm merges a secret cryptographic key seed stored securely inside the isolated local storage layer with the precise timestamp fetched from the device's hardware real-time clock (RTC) module.

To compute this secure token without an active network socket, the internal cryptographic runtime executes a multi-stage hashing operation. The system reads the current Unix timestamp from the localized hardware RTC module and divides it by a pre-configured time-step interval, typically set to 30 seconds, converting the temporal variable into an integer counter value. This counter matrix is then padded and serialized into an 8-byte byte array. The local processor pulls the immutable 160-bit shared secret key seed from its hardware-isolated storage layer and feeds both arrays into a Keyed-Hash Message Authentication Code routine based on the SHA-1 algorithm (HMAC-SHA-1). This mathematical operation transforms the input parameters into a dense, cryptographically secure 20-byte hash array that is completely resistant to reverse-engineering or brute-force tracking attempts.

Once the HMAC block is generated, the runtime applies a dynamic truncation algorithm to extract a volatile 4-byte segment from the 20-byte hash output. The system reads the low-order 4 bits of the final byte in the array to use as an exact offset index value. It then performs bitwise operations to mask out the sign bit, converting the extracted bytes into a uniform 32-bit unsigned integer module. The final 6-digit numeric verification code is calculated by applying a standard modulo operation (10^6) to this integer string. This process ensures the output code remains user-friendly while maintaining high cryptographic strength. Because the localized hardware clock runs continuously on an independent battery backup rail, the algorithm operates with high temporal consistency, preventing time manipulation attacks even during complete hardware power downs.

Once generated, the system renders this dynamic, timed validation token as a clean alpha-numeric code alongside a high-density offline QR code on the integrated 7-inch capacitive touch-screen graphical interface. The user then takes this token and enters it manually or scans it via a personal mobile device on the official web portal hosted at novera.team. Because the web portal's server and the isolated internal single-board computer share an identical, predefined cryptographic key seed, the remote server runs a parallel TOTP evaluation loop against its cloud-synchronized timestamp. To accommodate minor timing discrepancies caused by mechanical hardware clock drift over long-term field deployments, the server-side validation engine implements a strict look-ahead and look-back window filter. This validation layer checks token sequences across adjacent time steps, ensuring smooth authentication while blocking any structural data replay attacks.

If the user-submitted code matches the server-side generated token within the active temporary time window, the system successfully verifies the transaction and credits the points to the user profile completely offline. This zero-connectivity hardware strategy completely eliminates external wireless transmission attack vectors, man-in-the-middle data packet tampering risks, and remote database entry vulnerabilities, establishing a reliable, self-sufficient reward framework. By validating transactions without active outbound network traffic or active internet data pings, the Novera architecture fully protects the loyalty loop from packet manipulation, remote server downtime, or external network interception. This design delivers a highly secure, scalable, and

operationally independent data architecture tailored for modern smart city circular economy ecosystems.



CHAPTER 6
CONCLUSIONS AND FUTURE WORK



6.1 Complete Engineering System Synthesis and Deep Empirical Performance Metrics Analysis

Novera Team has successfully built, structured, and implemented the complete operational infrastructure for the autonomous Smart Waste Bin project. The execution of field performance validation testing confirms that the integrated local Edge AI platform fulfills all required design parameters. By moving the neural processing models entirely onto the local hardware chip via **Rust** and **tract-onnx**, real-time waste classification tasks achieve an outstanding local execution speed. The system processes image frames from the high-resolution camera and outputs categorization decisions within milliseconds, eliminating network delay issues. Extensive physical testing across various recycled materials (plastic polymers, paper, metals, and standard trash) demonstrates an exceptionally high accuracy rate. The machine successfully validates the mechanical dual-axis Tilt Mechanism, showcasing that the combined NEMA 17 stepper motor and driver loops reliably direct materials to their designated internal bins without causing path errors or structural blockages.

6.2 Strategic System Vulnerability Shielding, Error Management, and Fault Tolerances

A major focus during the engineering cycle of this project was establishing a robust, production-ready system architecture capable of running continuously in demanding environments without encountering system runtime crashes. Operating fully offline removes standard external network attack vectors and remote database vulnerabilities. However, running a localized system requires highly dependable, low-level error management frameworks. To protect the firmware runtime against unexpected hardware failures, Novera Team utilized specialized fault-tolerant modules such as the anyhow error wrapper library within the native Rust code stack. If a peripheral item undergoes an error—such as a sudden camera signal break or an internal sensor data mismatch—the core state machine does not suffer a catastrophic breakdown. Instead, it catches the error, isolates the faulty module, resets the data pipeline, and logs clean error indicators on the user's 7-inch touchscreen panel while keeping the central automation loops active. Additionally, to ease system updates and hardware stress testing without risking mechanical wear, a clean simulation environment was integrated via the rand random generation libraries, allowing developers to test point generation and web validation via **novera.team** using safe simulated parameters.

6.3 Comprehensive Future Development Paths, Hardware Upgrades, and Fleet Deployment Scaling

While the present state of the prototype represents a highly advanced operational milestone, Novera Team has mapped out extensive development vectors for future system iterations. Future hardware upgrades will explore replacing the standard 1.5mm galvanized casing with lightweight, chemically resistant reinforced composite polymers to further optimize weight profiles. On the software layer, future work will focus on scaling the local classification capacity of the neural network model to recognize and split more detailed sub-categories of recyclable elements, such as isolating distinct high-density plastic grades from standard polymers. Furthermore, to move toward massive multi-unit deployments in public smart spaces, we plan to implement low-power mesh data links. This will allow groups of independent smart bins to securely share generalized capacity logs, fill levels, and maintenance status telemetry metrics using localized low-bandwidth communication protocols, setting a new benchmark for completely autonomous public waste infrastructure environments.

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الملخص العربي

أصبح تطوير منظومات فرز النفايات الذكية وتدويرها عند نقطة التخلص ركيزة هندسية أساسية وعاجلة لبناء بيئات مستدامة ونظيفة في ظل التضخم السكاني المعاصر والنمو العمراني المتسارع الذي يضغط على البنية التحتية للمدن الذكية. يقدم هذا المشروع تصميماً وتنفيذاً هندسياً وتطبيقياً متكاملاً لمنظومة الحاوية الذكية "Smart Waste Bin" والمطورة بالكامل عبر جهود فريق "نوفيرا" (Novera Team)؛ حيث تعتمد المنظومة على معمارية معالجة الذكاء الاصطناعي للحواف (Edge AI) المدمجة محلياً بالكامل على حاسوب ريسبري باي 5 (5 Raspberry Pi) لفرز وتصنيف النفايات فورياً إلى أربعة مسارات رئيسية تشمل المواد البلاستيكية، والورقية، والمعدنية، بالإضافة إلى المخلفات العامة الأخرى والمواد العضوية. يتم تنفيذ هذه العملية الحسابية المعقدة دون الحاجة نهائياً للاتصال بشبكات الإنترنت الخارجية أو الاعتماد على الخوادم السحابية، مما يقضي تماماً على مشاكل انقطاع الإشارة، وتهديدات الأمن السيبراني، وزمن التأخير (Latency) المرتبط بمعدلات النقل، ويضمن استمرارية التشغيل الذاتي بنسبة 100% في البيئات العامة والمفتوحة.

تعتمد البنية الهندسية للمشروع على نظام تحكم ثنائي النواة والطبقات، حيث يتكامل حاسوب الـ Raspberry Pi 5 المسؤول عن تشغيل نموذج الرؤية الحاسوبية المكبوس عبر محرك tract-onnx، مع متحكم دقيق محلي من نوع 32ESP عبر مسار بروتوكول اتصال تبادلي متزامن ومخصص يسمى "مسار البونكروس" (Boncross Bus). يبدأ المسار التشغيلي للحاوية لحظة رصد مجسم داخل فتحة التخلص بواسطة حساس الموجات فوق الصوتية (HC-SR04)، والذي يطلق بدوره إشارة بدء رقمية تجعل الكاميرا تلتقط الإدخال وتمرره لنموذج الشبكة العصبية، بينما يقوم مؤشر الـ LED بتقديم استجابة مرئية فورية للمستخدم لتأكيد رصد الجسم وبدء المعالجة الذكية. وعقب صدور قرار التصنيف، يقوم الـ 32ESP بترجمة الإشارة العكسية إلى أوامر حركية دقيقة عبر إرسال نبضات كهربائية متتالية إلى درايفر الموتور الستيبير الصامت TMC2208، مما يدفع محرك الخطوة (NEMA 17 Stepper Motor) لإجراء التوجيه والإحداثيات الأفقية للمنصة، تليها إشارة تعديل عرض النبضة (PWM) لتوجيه محرك السيرفو (Servo Motor) للزاوية الميكانيكية المحددة، مما يميل منزلق التوجيه بزاوية انحراف دقيقة تبلغ 45.00 درجة لتسخير عجلات الجاذبية وإسقاط النفاية داخل الربع المخصص لها، مع عزل الدوائر المنطقية للتحكم عن أحمال المواتير الحثية الثقيلة عبر وحدة ريليه (Relay Module) كبديل استراتيجي لحماية المتحكم من تيارات الاندفاع العكسية.

وقد جرى تنظيم وتوزيع الهيكل البحثي للمشروع في خمسة أبواب رئيسية متكاملة لتغطية الأبعاد العلمية والتطبيقية، وموزعة على النحو التالي:

الباب الأول: المقدمة العامة والإطار النظري المرجعي؛ ويستعرض الأهداف الإستراتيجية للمنظومة الذكية القائمة على معالجة الحواف، وتحليل أزمة التلوث التبادلي للمواد القابلة للتدوير عند الخلط، ودراسة الأثر البيئي والاقتصادي الدائري لمنع الانبعاثات الكربونية الناتجة عن تراكم النفايات بالمكبات.

الباب الثاني: الدراسات السابقة والتحليل المقارن؛ ويتضمن مراجعة الأدبيات والأنظمة الهندسية الميكانيكية الموازية، ومقارنة معمارية المشروع الحالية هندسياً مع الأنظمة التجارية العالمية مثل (Bin-e)، مع تحليل شامل لعيوب الاعتماد على البنية السحابية من حيث تكاليف اشتراكات البيانات الخلوية ونقاط الضعف الأمنية للاختراق السيبراني.

الباب الثالث: التصميم الهيكلي والميكانيكي وجداول المشتريات؛ ويشمل الشرح التفصيلي لأبعاد الهيكل الخارجي المصنوع من الصاج المجلفن الصناعي بسمك 1.5 ملم بأبعاد (120x70x70 سم)، وتصميم شبكة الفرز الرباعية الداخلية المتناظرة 2x2 التي تقسم الحاوية إلى أربعة أرباع مستقلة بسعة 53 لتراً للربع الواحد (بإجمالي سعة تتجاوز 212 لتراً)، بالإضافة إلى حصر الفاتورة الإجمالية التقريبية وقائمة حصر المواد (BOM) بشكل نهائي والبالغة 35,000.00 جنيه مصري.

الباب الرابع: البيئة البرمجية والتحكم والأنظمة الأمنية؛ ويركز على البرمجة منخفضة المستوى للـ Firmware وأنظمة الحواسب باستخدام لغة Rust لضمان أعلى معدلات الأمان وإدارة الذاكرة ومنع الثغرات بدون مفسر برمجي ثقيل، وتكامل المكتبات مثل rppal لإدارة الـ GPIO، مع شرح خوارزمية التشفير المعتمدة على الوقت TOTP وفق معايير RFC 6238 لتوليد أكواد التحقق للمكافآت الرقمية ونقاط المستخدمين بالكامل دون إنترنت عبر مزامنة الوقت محلياً مع ساعة الوقت الفعلي (RTC) وربطها بالسيرفر عبر موقع novera.team.

الباب الخامس: الخلاصة والنتائج والتطلعات المستقبلية؛ ويستعرض المخرجات الهندسية والعملية المستخلصة من تشغيل المنظومة بكفاءة تامة، مع تقديم إرشادات وتوجيهات واضحة لتطوير العمل الهندسي مستقبلاً والقدرة على التوسع والإنتاج الكمي لدعم تطلعات المدن الذكية الخضراء.

وقد تذيل المشروع بقائمة مراجع متخصصة ودقيقة تحتوى على مراجع أكاديمية وعلمية موثقة في مجالات الرؤية الحاسوبية، والأنظمة المدمجة، وهندسة التصميم الميكانيكي المستدام.

مشروع التخرج في تكنولوجيا المعلومات

تصميم وبناء سلة فرز النفايات الذكية المحلية المستقلة

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