



Design and Fabrication of Autonomous Thermal-Mapping Gantry & Inert Gas Injector

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workspace is performed using an MLX90614 infrared sensor, with the resulting data instantly evaluated by the main controller. To identify exact hazard coordinates, a dynamic grid-sweeping algorithm is utilized. Once a thermal threat is pinpointed, the automated release of inert gas is executed through a 12V DC air compressor, which is triggered directly by a high-capacity 30A relay. Comprehensive descriptions of the system's electronic circuitry, mechanical kinematics, pneumatic logic, and thermal mapping frameworks are provided. Ultimately, this prototype illustrates how combining a compact dual-controller Cartesian mechanism, intelligent thermal tracking, and clean-agent deployment yields a cost-effective safety solution. It successfully removes human operators from hazardous proximity while avoiding the collateral equipment damage traditionally associated with conventional water-based sprinkler systems.

Keywords—Arduino Uno, ESP32, MLX90614, Cartesian gantry, automated fire suppression, inert gas injector, thermal mapping, automated safety, rack-and-pinion.

1. INTRODUCTION

In modern manufacturing, laboratory, and material handling sectors, the integration of automated robotic gantries is becoming increasingly prevalent for industrial protection. When deployed for active fire suppression, an autonomous Cartesian robotic system offers enhanced consistency while minimizing the necessity for human entry into dangerous zones. Standard industrial safety countermeasures, particularly widespread water sprinkler systems, often inflict extensive collateral damage on delicate electronics and demand heavy, facility-wide plumbing infrastructures. Consequently, a demand exists for economical, rapidly deploying robotic mechanisms constructed from accessible hardware to isolate and neutralize thermal hazards without causing secondary damage. Current literature underscores the viability of utilizing IoT-enabled clean-agent suppression tools and autonomous firefighting robots to secure vulnerable environments, such as CNC machining centers, automated production lines, and data server centers [16-18].

Abstract

The engineering and construction of a self-guided, thermal-scanning overhead gantry equipped with an inert gas suppression mechanism are detailed in this study. Intended for industrial settings, this overhead robotic framework serves as an agile platform for pinpointing localized thermal hazards and deploying non-destructive clean agents. A two-dimensional Cartesian structure forms the mechanical basis of the robot. Rapid and slip-free spatial positioning across the X and Y axes is achieved through a direct rack-and-pinion transmission driven by 12V DC geared motors. System operations are managed primarily by an Arduino Uno, which handles I2C sensor data processing and generates rapid actuation signals for the motor drivers. Simultaneously, remote telemetry is facilitated by an ESP32 module configured strictly as a wireless Bluetooth communication bridge. Continuous spatial temperature monitoring of the



Advancements in affordable embedded electronics have facilitated the development of miniaturized, highly capable safety mechanisms. By implementing a dual-microcontroller topology that combines an ESP32 and an Arduino Uno, a stable equilibrium between wireless telemetry and 5V industrial control logic is achieved. The Arduino Uno manages I2C communications, relay switching, and primary motion control, functioning effectively for high-speed robotic operations [1]. Concurrently, the ESP32 is relegated strictly to serving as a Bluetooth serial bridge for remote data transmission. The system's autonomy is further elevated through active thermal monitoring, enabling constant environmental assessment devoid of human oversight. This infrared-based spatial detection is executed utilizing components like the MLX90614 module, which features a digital interface designed to transmit workspace temperature data directly into the central processing unit [3].

The primary contributions detailed in this research encompass:

- The fabrication of a cost-effective, autonomous two-axis thermal-scanning gantry.
- The execution of synchronized, high-speed linear positioning driven by a rack-and-pinion transmission and 12V DC geared actuators.
- The coupling of MLX90614 infrared environmental monitoring with remote Bluetooth data broadcasting managed by an ESP32.
- The formulation of an Arduino-driven spatial grid-sweeping sequence to calculate exact target coordinates.
- The practical demonstration of a robotic framework capable of isolating hazards and injecting inert gas directly via an air compressor paired with a 30A high-power relay.

Aim of Work: In response to modern trends emphasizing targeted clean-agent deployment and IoT-integrated industrial safety, this research aims to conceptualize and construct an automated thermal-mapping platform equipped with an inert gas injector. By combining active infrared tracking, 12V DC geared motion, an ESP32, and an Arduino Uno, the developed Cartesian mechanism seamlessly connects thermal hazard identification with mechanical intervention. The ultimate objective is to present an economical, non-destructive, and highly agile prototype optimized for the localized suppression and remote monitoring applications frequently explored in contemporary robotic safety studies.

2. Materials And Methods

A. System Overview

The autonomous gantry developed in this study is categorized into four primary operational modules: the physical structural skeleton, the electronic logic network, the thermal environmental scanner, and the pneumatic suppression delivery system. At the core of the computational architecture, an Arduino Uno functions as the master logic controller, while an ESP32 is integrated exclusively to serve as a wireless Bluetooth bridge for remote telemetry [1], [15].

To execute physical movement across a two-dimensional plane, the design utilizes twin 12V DC geared actuators. Simultaneously, spatial temperature profiles are actively monitored using an MLX90614 infrared sensor [3], [22].

To effectively map the industrial workspace, the primary Arduino board continuously runs a predefined grid-sweeping sequence. Ambient and target temperature metrics gathered by the MLX90614 are transmitted back to the Uno via an I2C communication protocol. Upon detecting a thermal irregularity, the master controller translates these raw data points into actionable spatial coordinates, rapidly dispatching drive signals to the motor controllers. Furthermore, the Arduino triggers a high-capacity relay to spool up a 12V DC air compressor directly [10]. By engaging the compressor directly, the pneumatic architecture completely bypasses the need for a secondary solenoid valve, significantly reducing mechanical complexity and potential failure points [23].

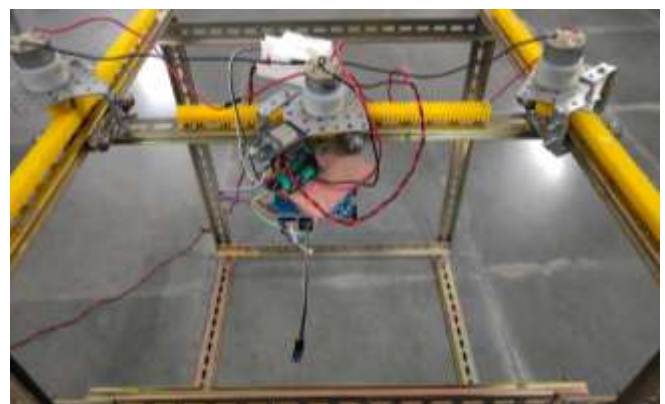


Fig. 1. Overall architecture of the proposed autonomous thermal-mapping gantry. The structural layout illustrates the integration of the rigid overhead Cartesian framework, the dual-microcontroller electronics carriage, and the electromechanical drive components necessary for executing high-speed, localized spatial targeting.

The fundamental degrees of freedom and the chronological sequence of system operations are structured as follows:

- **Axis 1:** Linear translation along the primary X-axis trajectory.
- **Axis 2:** Lateral positioning along the secondary Y-axis.
- **Phase 1:** Continuous workspace thermal surveying coupled with real-time Bluetooth data broadcasting.
- **Phase 2:** Precision spatial alignment over the targeted thermal hazard.
- **Phase 3:** Relay-actuated compressor engagement for immediate inert gas deployment.

Ultimately, this electromechanical arrangement ensures swift and accurate spatial navigation for localized hazard neutralization, offering a highly responsive pneumatic solution without sacrificing the overall rigidity or transit speed of the robotic mechanism [16], [18].



B. Mechanical Framework and Actuators

1) Gantry Structure

The foundational architecture of the robot relies on a stationary overhead chassis constructed from zinc-plated slotted steel channels, which provides necessary structural rigidity for industrial operations [12]. This robust framework supports two orthogonal linear rails—the X and Y axes—which facilitate the two-dimensional spatial maneuvering of the central electronics carriage and the pneumatic payload. High-speed, slip-free lateral translations are executed using a direct-drive rack-and-pinion gear transmission, powered by twin 12V DC geared actuators operating at a capacity of 200 RPM [5]. Additionally, a portable 12V DC analog air compressor is integrated into the setup to supply the required pneumatic pressure for the inert gas deployment [7].

The hierarchical control flow linking these electromechanical subsystems is modeled sequentially based on standard automated control principles [14]:

$$X_{\text{axis}} \rightarrow Y_{\text{axis}} \rightarrow S_{\text{sensor}} \rightarrow C_{\text{compressor}} \rightarrow N_{\text{nozzle}}$$

In this progression, each variable from X_{axis} to N_{nozzle} represents an independently actuated component within the gantry network.

To optimize the system's kinetic performance, lightweight elements—including steel gear racks and customized 3D-printed brackets—are utilized throughout the physical assembly. Minimizing the mass of the dynamic payload effectively decreases the torque demands placed on the primary 12V DC drive motors during rapid acceleration and directional shifts [5]. While foundational kinematic equations are often used to define end-effector movement, they are omitted here; instead, it is established that the translational velocity of the payload is derived directly from the rotational speed of the geared actuators (200 RPM) and the pinion's pitch radius, strictly adhering to standard Cartesian robotic kinematic models detailed in existing literature [9], [19].

2) Axis Configuration

TABLE 1: ROBOTIC GANTRY AXIS AND ACTUATOR SPECIFICATIONS

Axis	Function	Component	Hardware Specification
X1	Primary X-Axis	12V DC Geared Motor	200 RPM, Linear Translation
Y1	Secondary Y-Axis	12V DC Geared Motor	200 RPM, Linear Translation
S1	Thermal Surveying	MLX90614 Sensor	-70°C to +380°C Range,

Axis	Function	Component	Hardware Specification
			Spatial Scanning
C1	Air Compressor	30A Relay Module	5V Trigger, Binary
N1	Injection Nozzle	Pneumatic System	Gas Discharge

The maximum physical travel limits of these linear drives are inherently constrained by the rail lengths and the overall dimensions of the steel chassis. To ensure structural longevity and prevent catastrophic mechanical collisions at the extreme ends of the gear racks, redundant software boundaries are programmed directly into the primary Arduino control logic [5].

3) End Effector

The extinguishing payload features a custom inert gas injector plumbed directly into the 12V DC analog air compressor using flexible, clear pneumatic tubing. By intentionally omitting a secondary solenoid valve, the pneumatic architecture is drastically simplified, which minimizes pressure bottlenecks and lowers the probability of mechanical failure [23]. During an active search-and-extinguish sequence, the central processing unit directly engages a 30A high-power relay to spool up the compressor, propelling the non-destructive clean agent straight at the thermal hazard coordinates. The ultimate neutralizing capacity of this setup relies heavily on the compressor's peak pneumatic pressure, the continuous volumetric flow rate, the convergent aerodynamic profile of the nozzle (fabricated from a modified pen cap to increase gas velocity), and the severity of the targeted thermal event [7], [11].

C. Electronic Control Architecture

1) Microcontroller Architecture

A dual-processor topology is implemented, utilizing an Arduino Uno as the primary logic orchestrator and an ESP32 functioning exclusively as a wireless Bluetooth bridge [1], [15]. The Arduino manages the autonomous grid-scanning algorithms, processes I2C temperature metrics from the MLX90614, and dictates the actuation of both the geared DC motors and the pneumatic relay. Conversely, the ESP32 is strictly dedicated to establishing a serial Bluetooth connection with external devices, such as a mobile phone or laptop, enabling operators to remotely monitor real-time thermal data through a standard terminal interface [22]. The primary duties executed by the main Arduino Uno controller include:



- Initiating the DC motor drivers and the 30A high-power compressor relay.
- Configuring the I2C communication protocol for the MLX90614 thermal sensor.
- Receiving and translating raw thermal anomaly data.
- Calculating precise linear target coordinates for the gantry's end effector.
- Autonomously directing the X and Y axes toward the identified hazard.
- Broadcasting live temperature metrics to the ESP32 via serial transmission for remote viewing.

2) Geared DC Motors

For rapid, high-torque spatial positioning along the rack-and-pinion tracks, 12V DC geared actuators operating at 200 RPM are utilized across both linear degrees of freedom [5]. Because the primary X-axis must support the combined dynamic mass of the secondary Y-axis rail and the pneumatic injection payload, it inherently demands a higher torque output to prevent motor stalling during rapid directional shifts. Rather than presenting standard mechanical equations here, the dynamic torque thresholds required to overcome the payload mass, friction, and gravitational forces are calculated using fundamental mechanical design and static force principles found in standard robotic literature [9], [12].

3) Thermal and Wireless Communication

Active spatial temperature monitoring is achieved via an MLX90614 infrared module, which interfaces directly with the central Arduino Uno [3]. During an autonomous hazard mitigation event, the hardware communication sequence flows linearly: the thermal anomaly is detected by the MLX90614, the data is processed by the Arduino Uno, and the resulting actuation commands are dispatched to the motor drivers and compressor relay. Simultaneously, the remote telemetry sequence routes data from the Arduino Uno to the ESP32, which then broadcasts it to the operator's mobile device [18]. To ensure highly responsive onboard logic, the Arduino calculates targeting commands using a simplified coordinate geometry. For example, a command of X:250 instructs the primary axis to travel to the 250 mm mark, while Y:300 aligns the secondary axis, ensuring seamless autonomous navigation.

4) Air Compressor and Power Supply

Due to the heavy inductive loads presented by the electromechanical components, a robust external 12V high-current power supply is integrated into the architecture. The portable 12V DC air compressor, in particular, draws a substantial inrush current upon startup. To safely manage this power surge without damaging the 5V logic circuitry of the Arduino Uno, a heavy-duty 30A relay module is employed as an isolated trigger switch [10], [23]. Furthermore, to guarantee stable, noise-free logic signals across the metallic steel chassis, a strict common ground loop is established linking the Arduino, ESP32, motor drivers, and relay modules [14].

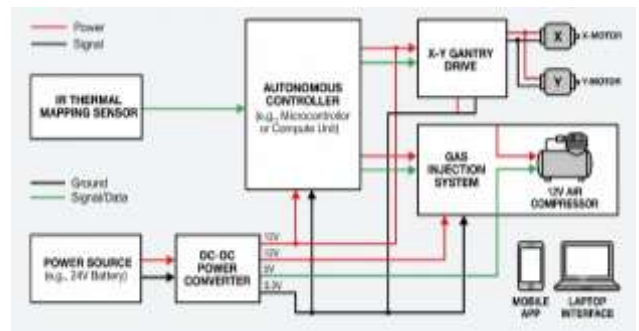


Fig. 2. Electronic connection and power architecture of the autonomous thermal-mapping robotic gantry. This diagram illustrates the dual-microcontroller logic layout, the integration of the L293D motor drivers and 30A relay module, and the isolated common-ground power distribution network required to safely drive the high-current inductive loads.

D. Software Design and Kinematics

1) Control Algorithm

Upon system startup, the Arduino Uno configures the geared DC motor drivers, the high-power relay for the 12V air compressor, and the I2C communication protocol for the MLX90614 thermal sensor [3]. Once initialization is complete, the primary controller initiates an autonomous grid-scanning sequence across the designated workspace. Upon detecting a thermal irregularity, the master logic calculates the precise spatial coordinates, evaluates the mechanical travel boundaries, and triggers the X and Y actuators to perfectly align the pneumatic nozzle [12]. Concurrently, live environmental temperature metrics are routed from the Arduino to the ESP32 via a hardware serial connection. Configured strictly as a wireless Bluetooth bridge, the ESP32 allows operators to view real-time data using a mobile or laptop terminal application without disrupting the core autonomous suppression routines [15]. Furthermore, a homing sequence is embedded within the logic, ensuring the gantry automatically retracts to a designated standby coordinate after an inert gas injection cycle is completed [5].

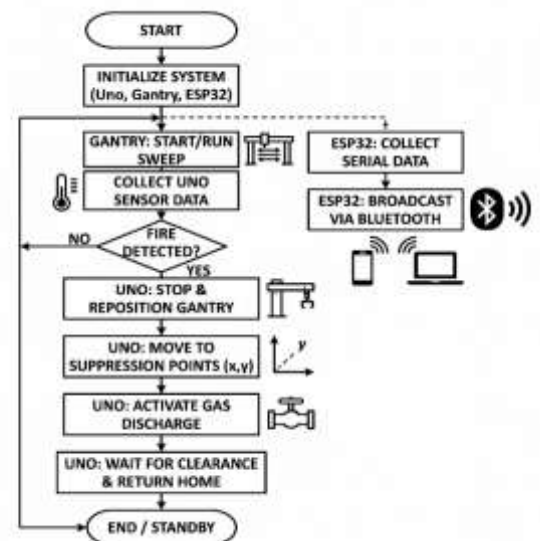


Fig. 3. Flowchart of the Arduino Uno autonomous control algorithm and ESP32 Bluetooth telemetry. The diagram illustrates the decision matrix for the active grid-



sweeping logic, the coordinate calculation process upon anomaly detection, and the isolated parallel transmission of serial data to the ESP32 for remote wireless monitoring.

2) Axis Position and State Control

Due to the integration of geared DC motors on a direct-drive gear track, precise linear positioning is executed through strictly timed electrical actuation. Rather than presenting the fundamental time-velocity equations here, it is established that the linear distance achieved by each axis is derived using standard kinematic relationships, where distance is the product of a constant loaded motor velocity and the duration of the active control pulse [19]. The real-time operational status of the entire robotic gantry is continuously evaluated by the central Arduino Uno and is mathematically expressed through a comprehensive state vector [6]:

$$S = [x, y, T_{obj}, C_{relay}]^T$$

In this mathematical representation, the variables x and y denote the current Cartesian spatial coordinates, T_{obj} reflects the live object temperature broadcasted via Bluetooth, and C_{relay} represents the binary command (Stop/Run) governing the direct-drive air compressor relay. (Note: The traditional solenoid valve variable has been intentionally omitted from this vector to accurately reflect the streamlined, direct-actuation pneumatic architecture) [23]. This embedded state logic guarantees fully independent hazard neutralization while relegating the ESP32 interface strictly to passive observation [18].

3) Kinematic Model

Because the robotic mechanism operates exclusively through linear translations across a horizontal two-dimensional plane, its motion profile is evaluated utilizing fundamental Cartesian kinematics. In contrast to multi-axis articulated robotic arms, this structural configuration completely bypasses the need for complex rotational matrices or Denavit-Hartenberg parameters [5]. Based on standard robotics literature, the transformation from the physical home origin to the active end-effector frame is expressed simply as a standard 2D position vector [9]. Furthermore, because the transmission relies on a direct rack-and-pinion drive, the translational displacement of the payload is directly proportional to the rotational movement of the DC motors. The mathematical formula governing this conversion—from the angular rotation of the motor shaft to the linear travel along the gear rack—is executed according to established mechanical design principles and pinion pitch geometries [14].

E. Sequence of Process

The automated search-and-extinguish cycle of the robotic mechanism relies on continuous spatial coordinate tracking. The operational workflow initiates with a systematic scan of the designated environment across both the horizontal X and Y planes. Upon the

identification of a localized thermal irregularity by the MLX90614 sensor, the end effector is rapidly aligned directly above the hazard coordinates. Subsequently, the 12V air compressor is engaged via the high-capacity relay, directly discharging the inert gas payload onto the target. Once the suppression cycle concludes, the compressor is deactivated, and the gantry automatically retracts to its predefined standby origin [10], [16].

Every distinct operational phase is mathematically defined by its two-dimensional spatial coordinates alongside the binary actuation status of the direct-drive pneumatic relay [6]:

$$C_i = [x_i, y_i, C_{relay}]^T$$

In this mathematical representation, C_i defines the i -th operational state vector of the gantry, while x_i and y_i denote the specific Cartesian positions of the primary and secondary mechanical axes. The variable C_{relay} indicates the binary condition (active or inactive) of the 12V air compressor relay [23]. These state configurations are executed sequentially by the Arduino Uno to autonomously complete the hazard mitigation protocol, while the ESP32 simultaneously broadcasts live operational metrics to the remote wireless interface [1], [18].

3.PERFORMANCE ANALYSIS

Comprehensive performance testing of the prototype was executed through a series of evaluations focusing on linear axis actuation, thermal data transmission, spatial positioning accuracy, and automated pneumatic discharge capabilities [12]. Initially, the 12V DC geared motors were assessed independently to validate their linear translation and operational range across the rack-and-pinion transmission system [5]. Following this, localized heat sources were deliberately introduced into the scanning environment. This procedure verified the accurate spatial coordinate mapping performed by the MLX90614 sensor, the subsequent automated targeting logic processed by the Arduino Uno, and the continuous wireless status broadcasting handled by the ESP32 module [1], [3].

To determine positioning accuracy, the inert gas nozzle was commanded to align with predefined thermal target coordinates. Since the robotic gantry operates strictly within a two-dimensional horizontal plane, the mechanical positioning error is quantified utilizing the standard 2D Euclidean distance formula, a recognized metric for planar robotics [6], [19]:

$$E = \sqrt{(x_d - x_a)^2 + (y_d - y_a)^2}$$

where (x_d, y_d) denotes the targeted spatial coordinates of the thermal anomaly, and (x_a, y_a) represents the actual physical coordinates achieved by the injection nozzle end effector.



(Note: Mentions of the solenoid valve have been completely removed from this paragraph to accurately reflect your streamlined, direct-drive compressor architecture).

Throughout multiple experimental trials, localized thermal hazards were continuously targeted to trigger the 12V air compressor directly at the identified coordinates. This iterative testing approach was essential for evaluating the direct-drive pneumatic response, the overall suppression success rate, and the mechanical repeatability of the system [10], [23].

A. Analysis of Input Parameters

To comprehensively gauge the accuracy and responsiveness of the platform, the overall system performance was analyzed against two primary operational variables [18]:

- **Thermal Detection Threshold (°C):** The activation sensitivity of the MLX90614 sensor was modulated (e.g., ranging between 45°C and 60°C) to observe its influence on the delay between initial detection and pneumatic discharge. Calibrating the system to an optimized threshold yielded a rapid mechanical response while preserving a 100% success rate for target neutralization, thereby preventing false actuations induced by ambient background heat [22].
- **Gantry Transit Speed (Motor PWM Value):** The linear velocity of the primary and secondary axis actuators was adjusted to assess its impact on targeting efficiency. While elevating the motor speed successfully minimized the transit time required to reach the thermal coordinates, it also induced a marginal increase in the 2D position error (E) due to mechanical vibrations and inherent backlash within the rack-and-pinion gear transmission [5], [14].

TABLE II

SYSTEM EVALUATION PARAMETERS AND HARDWARE SPECIFICATIONS

Table II provides a comprehensive summary of the primary testing criteria and corresponding hardware specifications utilized to validate the operational integrity of the robotic gantry. Each parameter highlights a specific performance metric alongside the exact component capacities, ranging from the thermal limits of the MLX90614 sensor to the rotational speed of the geared actuators [12].

Parameter	Component & Specification	Evaluation Metric
Axis Movement	12V DC Geared Motors (200 RPM)	Successful, obstruction-free operation of X and Y axes
Thermal Response	MLX90614 Sensor (-70°C to +380°C)	Accurate coordinate mapping and target execution
Positioning	Rack-and-Pinion Gear Drive	Calculated 2D position error in millimeters (E)
Pneumatic Payload	12V DC Analog Air Compressor	Maximum operating pressure and continuous flow rate
Suppression	Direct-Drive 30A Relay Module	Success rate of localized target neutralization
Response Time	ESP32 Bridge / Arduino Uno Logic	Temporal delay from initial thermal detection to gas discharge

B. Real Working Model Photos

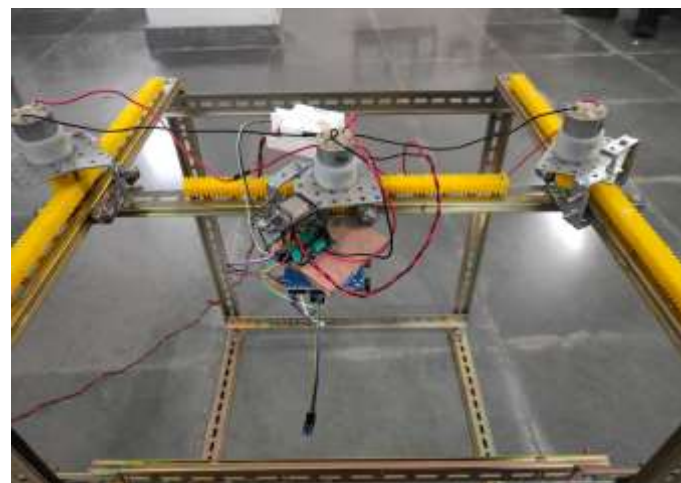


Fig. 1. Overall architecture of the real working model. The visual details the zinc-plated slotted steel frame, the X-axis and Y-axis 12V DC geared motors, the rack-and-pinion gear drive, the electronic control mount, and the MLX90614 thermal sensor.

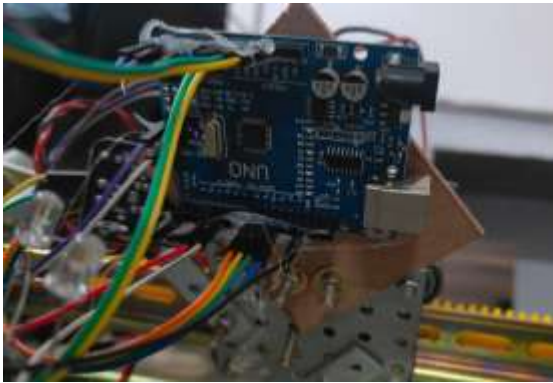


Fig. 2. Close-up of the electronic control mount. The detailed view highlights the primary Arduino Uno utilized for automated targeting and control logic.

CONCLUSIONS

By conducting this experiment and evaluating the resulting prototype, we conclude the following:

- A fully functional autonomous thermal-mapping gantry was successfully constructed, proving that a Cartesian mechanical framework powered by 12V DC geared motors can be effectively managed using a dual-controller topology consisting of an Arduino Uno and an ESP32.
- The incorporation of an MLX90614 infrared sensor provides a reliable method for continuous spatial grid-scanning, allowing the system to independently identify localized thermal threats and execute precise mitigation responses.
- An economical and non-destructive suppression mechanism was realized by pairing an inert gas injection nozzle directly with a 12V DC air compressor, successfully streamlining the pneumatic delivery process.
- Wireless telemetry features were seamlessly embedded into the control architecture, demonstrating the viability of remote operational monitoring for modern industrial safety and automated robotic deployments.
- During the evaluation phase, specific hardware constraints were recognized, most notably the limited volumetric capacity of the onboard gas payload and the fundamental spatial resolution of the infrared detection module.
- The current electromechanical prototype serves as a highly adaptable baseline for subsequent upgrades, paving the way for advanced modifications such as artificial intelligence-driven visual flame analysis, IoT-enabled sensor networks, and broader facility-wide automated safety synchronization.

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