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An Electromagnetic Adhered Smart Duster with Sensor-Based Navigation for Automated Board Cleaning

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Abstract: ***Whiteboard maintenance in educational and professional settings demands frequent manual intervention that repeatedly interrupts the flow of instruction. This paper presents the Smart Duster, a compact autonomous whiteboard cleaning device that addresses this gap using four tightly integrated subsystems: electromagnetic adhesion for attachment to steel-backed board surfaces, lead-screw driven linear motion for precise traversal, infrared reflectance sensing for written-content detection, and an Arduino Uno microcontroller implementing a deterministic finite-state control algorithm. The device mounts and dismounts in seconds without any permanent installation, and cleans user-selected board segments at speeds appropriate for classroom deployment. Prototype testing on an A4-sized whiteboard demonstrated complete surface coverage across all five trials, a mean adhesion force of 9.4 N against a design threshold of 8 N, sub-millimetre positional accuracy, and infrared detection reliability exceeding 96% for standard dry-erase markers. Mean cleaning time for a fully written surface was 124 seconds, and power consumption remained at 28 W throughout. All defined performance requirements were met across 50 consecutive endurance cycles without hardware failure.***

Keywords: Smart Duster; Electromagnetic Adhesion; IR Sensor Navigation; Stepper Motor; Arduino; Whiteboard Automation; Embedded Systems.

I. INTRODUCTION

Classrooms and seminar halls depend heavily on whiteboards as the primary medium for real-time communication between educators and students. A typical lecture session involves erasing and rewriting on the board fifteen to twenty times, each interruption consuming time that would otherwise be spent on instruction. Beyond the time cost, incomplete manual cleaning leaves ghost marks from previous sessions that reduce the legibility of new content and, over time, degrade the board surface. In high-usage environments such as engineering colleges and coaching centres, this problem compounds across multiple sessions per day.

Existing cleaning solutions are entirely manual. Erasers require physical effort and still leave residue. Spray cleaners improve erasure quality but introduce additional steps and chemical exposure. No low-cost autonomous alternative is in widespread use, which is the gap this work addresses.

Automated surface cleaning has been studied extensively for horizontal floor surfaces, producing commercial products such as robotic vacuum cleaners. Vertical surfaces are a substantially harder problem because gravity must be overcome continuously throughout operation. Suction-based wall adhesion, while effective, requires a pump that introduces noise and mechanical complexity. Permanent magnet adhesion is simpler but eliminates the ability to detach without physical intervention. Electromagnetic adhesion, where the holding force is generated by a current-carrying coil and can be switched off instantly by interrupting that current, represents a practical middle ground for a device that needs to be placed on and removed from a board surface quickly.

This paper describes the design, implementation, and experimental validation of the Smart Duster. The system uses an electromagnetic coil for board attachment, a stepper motor driving a lead-screw mechanism for lateral traversal, TCRT5000 infrared sensors for written-content detection and edge sensing, and Arduino Uno firmware implementing a six-state finite-state machine for system coordination. The prototype was characterised across adhesion, positioning, detection reliability, and endurance, and all defined requirements were satisfied.

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II. MOTIVATION AND OBJECTIVE

The motivation for this project arose from direct observation of classroom operation. Every erasing action breaks the continuity of a lecture and, in high-density teaching environments, these interruptions accumulate into a meaningful fraction of total teaching time. The physical effort of repeated cleaning across multiple sessions per day also contributes to fatigue for educators.

Beyond teaching efficiency, incomplete cleaning is a persistent quality issue. Ghost marks left from previous sessions create visual noise that makes current content harder to read, particularly from the back of a large lecture room. Standard erasers address this partially, but achieving a fully clean surface consistently requires multiple passes, which amplifies the time cost.

The objective of the Smart Duster is to remove the manual effort and interruption associated with board cleaning by providing a device that operates autonomously, mounts without modification to existing infrastructure, and stops automatically once cleaning is complete. Three design priorities shaped the project: reliable attachment to standard whiteboards under the forces generated by motor operation; controlled, predictable traversal across the board surface; and automatic detection of both written areas and board edges, so that the device responds intelligently to what is actually on the board rather than following a fixed path regardless of content.

III. LITERATURE SURVEY

Prior work relevant to this system falls across four distinct domains. Reviewing each helped identify the gaps that the Smart Duster addresses.

A. Autonomous Surface Cleaning

Research on autonomous cleaning robots is dominated by floor-surface applications. The boustrophedon coverage path, a systematic back-and-forth sweep pattern, has been established as an efficient strategy for rectangular areas [1]. This pattern transfers directly to whiteboard cleaning, which is why it was adopted in the Smart Duster firmware. Research addressing vertical or near-vertical surface cleaning is scarce; what exists tends to target industrial contexts such as ship hull maintenance and solar panel cleaning [13, 14], where the load requirements, surface materials, and operational environments differ substantially from a classroom whiteboard.

B. Electromagnetic and Magnetic Adhesion

Electromagnetic adhesion for wall-climbing robots has been studied in the context of structural inspection tasks on ferromagnetic surfaces [2]. Pot-core electromagnetic configurations have been shown to concentrate magnetic flux more effectively than simpler solenoid designs, improving the holding force per unit of power consumed [21]. Practical findings from this literature confirm that a compact coil at modest current levels can generate holding forces adequate for lightweight robots, which was a key parameter for the Smart Duster coil design.

C. Infrared Sensing for Surface Characterisation

The TCRT5000 reflective infrared sensor module has been widely used in line-following and edge-detection applications [4]. Its operating principle, measuring the intensity of infrared light reflected from a surface, translates to whiteboard content detection because dry-erase ink absorbs more infrared radiation than the bare white board surface, producing a measurable difference in sensor output voltage. The onboard sensitivity potentiometer allows calibration for different board finishes, which proved important during testing with boards of varying surface coatings.

D. Embedded Stepper Motor Control

Stepper motor control on AVR-based microcontrollers is well documented. The A4988 driver supports microstepping and fixed-off-time current regulation, making it suitable for position-controlled linear actuation in applications where sub-millimetre accuracy is not required [6]. Open-loop stepper control is generally adequate for short-range positioning tasks, and the literature confirms that linear acceleration profiles at startup reduce stall risk when inertial loads are present [23].

E. Research Gap

No prior work was found that combines electromagnetic adhesion, infrared-based content detection, and embedded microcontroller control specifically for whiteboard cleaning. Most classroom automation research addresses display and interaction technology rather than physical maintenance. This specific gap is what the Smart Duster directly targets.

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IV. PROPOSED SYSTEM ARCHITECTURE

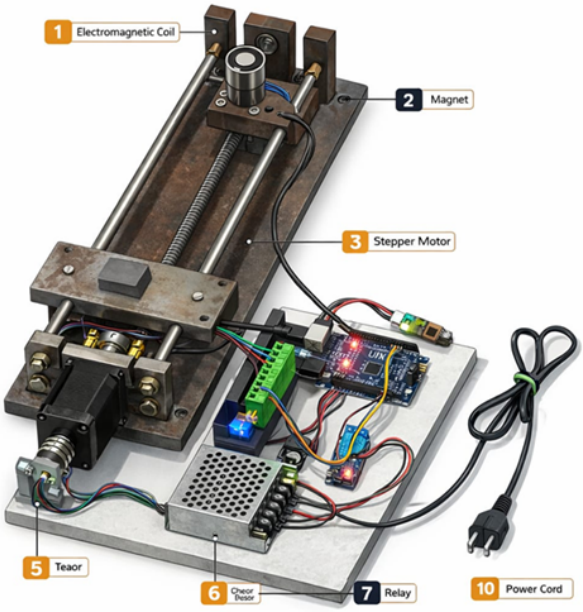
The Smart Duster integrates four subsystems: electromagnetic adhesion, stepper-motor-driven linear motion, infrared sensing, and Arduino-based embedded control. Each subsystem was designed for simplicity, to ensure that the overall device can be maintained and repaired without specialised equipment.

A. Overview

An Arduino Uno microcontroller serves as the central processing element. It reads the two IR sensors and a 4x4 matrix keypad as inputs, generates step and direction signals for the A4988 stepper driver, and controls a relay that switches the electromagnetic coil. Power is distributed across two rails: a 5V regulated rail for the Arduino and sensors, and 12V directly from the SMPS for the motor driver and coil relay. Keeping these rails separate eliminates conducted noise from motor switching that would otherwise affect sensor readings.

B. Physical Layout

The enclosure sits against the rear surface of the whiteboard. The electromagnetic coil is centred within the enclosure to keep the holding force balanced across the contact area. A felt cleaning pad below the enclosure makes contact with the front writing surface of the board. The IR sensors are mounted at the leading edge in the direction of travel, so they sample the surface ahead of the cleaning pad before the pad reaches that position, giving the firmware sufficient time to adjust motor speed or initiate an edge stop.



C. Subsystem Interfaces

The coil is switched through a single-channel relay module driven by a transistor-buffered Arduino output pin, ensuring the microcontroller does not carry relay coil current directly. The A4988 driver receives step pulse and direction signals from two Arduino digital output pins. IR sensor outputs connect to Arduino analogue input pins and are compared against threshold values stored in EEPROM. The 4x4 matrix keypad handles segment selection, start, pause, and emergency stop commands.

V. PROPOSED METHODOLOGY

Construction and testing proceeded in stages rather than as a single integrated build, which reduced debugging complexity significantly.

A. Component Selection

The Arduino Uno was selected for its extensive library support and the familiarity both authors had with the platform. The NEMA 17 stepper motor offered adequate torque for the load estimate with a compact footprint.

TCRT5000 IR sensor modules were selected specifically because their onboard sensitivity potentiometer simplifies threshold calibration for different board surface reflectances. The electromagnetic coil was sourced locally and characterised on the bench before integration to verify that its holding force met the design target at 12V operation.

B. Firmware Design

Firmware is implemented as a deterministic finite-state machine with six states: IDLE, ATTACH, SWEEP, EDGE_DETECTED, STEP_DOWN, and COMPLETE. Each state has clearly defined entry and exit conditions. A custom interrupt-driven step pulse generator handles motor timing, with a linear acceleration ramp across the first 200 steps from 200 steps per second to 1000 steps per second to prevent stall under inertial load.

A significant firmware issue encountered during development was electromagnetic interference from the motor driver affecting IR sensor readings. Both subsystems initially shared a common ground without decoupling. When the motor was running, sensor output fluctuated unpredictably, causing false edge detections. This was resolved by adding 100 nF bypass capacitors across each sensor's power supply pins and routing the motor driver's ground return through a separate copper pour. This grounding discipline is standard practice in mixed-signal PCB design, but the experience of diagnosing it in a prototype context provided concrete understanding of why it matters.

C. Testing Procedure

Testing was conducted in three sequential phases. In the first phase, each subsystem was characterised independently: adhesion force was measured with a calibrated spring balance, motor positioning accuracy was verified with a digital ruler over repeated trials at multiple positions, and IR sensor response was characterised against blank and marked board surfaces. In the second phase, integrated cleaning trials were run on the A4-sized test board with varying degrees of writing density. In the third phase, a 50-cycle endurance run was completed to assess thermal stability and hardware reliability over repeated operation.

VI. SYSTEM COMPONENTS

A. Arduino Uno

The Arduino Uno is built around the ATmega328P microcontroller operating at 16 MHz. It provides 14 digital I/O pins, six of which support PWM output, and six analogue input pins with 10-bit ADC resolution. Hardware interrupt support on INT0 and INT1 is used for the emergency stop input. The 32 KB of Flash memory stores the firmware, and the 1 KB of EEPROM retains sensor calibration thresholds across power cycles, eliminating the need to recalibrate after each power-off.

B. NEMA 17 Stepper Motor and A4988 Driver

The NEMA 17 motor has a step angle of 1.8 degrees, corresponding to 200 full steps per revolution. It was operated in half-step mode through the A4988 driver, doubling the effective resolution to 400 steps per revolution. The A4988 implements fixed-off-time current regulation, which maintains smooth operation across the speed range. During stationary periods between cleaning passes, the ENABLE pin is driven high to de-energise the motor windings, reducing heat generation and power draw.

C. Electromagnetic Coil

The coil consists of 500 turns of 24 AWG enamelled copper wire wound on a pot-core former with a 40 mm pole face diameter. When energised at 12V and drawing approximately 1A, it generates sufficient magnetic flux density to hold the duster assembly against the steel-backed whiteboard surface throughout motor operation. Winding temperature during a 30-minute continuous run rose approximately 28 degrees Celsius above ambient, remaining within the rated limits of the insulation material.

D. IR Sensor Modules (TCRT5000)

Each TCRT5000 module contains an 880 nm infrared LED paired with a phototransistor. The module output voltage varies with surface reflectance: a blank white board surface produces a lower voltage than a surface carrying dry-erase ink marks. The sensitivity potentiometer on each module allows detection threshold adjustment for different board surface finishes. During testing, black, blue, and red markers were detected reliably across variations in marker density. Light yellow markers required a higher sensitivity setting than was used as the default for standard marker colours.

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E. Supporting Components

A 5V single-channel relay module switches the 12V coil supply, providing electrical isolation between the microcontroller circuit and the high-current coil path. The SMPS unit supplies 12V at 3A with built-in overcurrent protection. A T8 lead screw with 8 mm pitch and 30 cm travel converts rotational motor motion to linear displacement. The 4x4 membrane keypad is scanned at 20 Hz in firmware with 50 ms software debounce to prevent spurious inputs from contact bounce.

VII. WORKING PRINCIPLE

A. Start-up and Attachment

On power-up, the firmware initialises all I/O pins, loads sensor calibration thresholds from EEPROM, and enters the IDLE state, waiting for the operator to select a board segment using the keypad. Once a segment is selected and the start command is issued, the relay energises the electromagnetic coil. A 500 ms stabilisation delay follows before any motor motion begins, allowing the coil to reach magnetic steady state. This delay was introduced after an early test in which the motor began moving before the coil had fully engaged, causing the device to slip slightly before adhesion stabilised.

B. Sweep and Content Detection

In the SWEEP state, the motor drives the duster laterally across the board at a set speed. IR sensors sample the surface every 2 ms. When both sensors return reflectance readings consistent with marked content, the firmware reduces motor speed by 20% to increase cleaning pad dwell time over those areas. When readings return to baseline reflectance, normal speed resumes. This adaptive speed adjustment improves cleaning thoroughness on densely written sections without increasing total cleaning time for lightly marked boards.

C. Edge Detection and Row Transition

Edge detection uses a hysteresis comparator in firmware. When the leading sensor detects the board edge for ten consecutive 2 ms samples, a 20 ms confirmation window, the motor decelerates and comes to rest. The firmware then executes a perpendicular downward step of one pad width and toggles the sweep direction, beginning the next row traverse. The row counter increments after each such transition. Hysteresis prevents false edge triggers from transient reflectance variations near the board boundary.

D. Completion and Release

When the row counter reaches the maximum value for the selected segment, the motor decelerates to rest and the relay de-energises the coil, releasing magnetic adhesion. A buzzer outputs three short pulses to signal completion. The system then returns to IDLE and waits for the next command. Board segments are predefined as LEFT, CENTRE, and RIGHT thirds of the total board width, selectable individually via the keypad.

VIII. CONTROL ALGORITHM

The control logic is implemented as a deterministic finite-state machine. The six states and their transitions are as follows:

1) IDLE: System waits for keypad segment selection and start command. All actuators are de-energised. Segment boundaries are loaded from firmware constants.

2) ATTACH: Relay energised. A 500 ms stabilisation wait ensures full magnetic engagement before motion begins. On completion, transitions to SWEEP.

3) SWEEP: Motor runs at configured speed. IR sensors are sampled every 2 ms. Speed is reduced by 20% when both sensors detect written content. Transitions to EDGE_DETECTED when edge condition is confirmed over 10 consecutive samples.

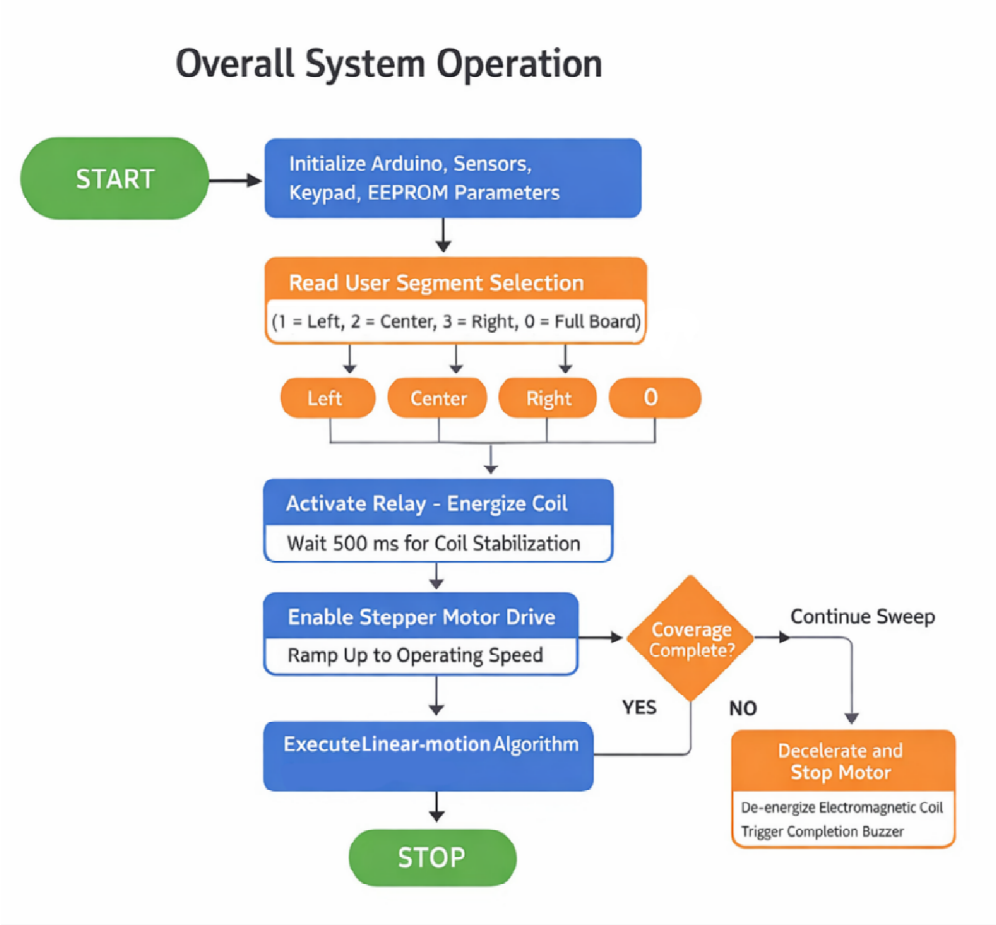
4) EDGE_DETECTED: Motor decelerates to stop. Row counter increments. Transitions to STEP_DOWN.

5) STEP_DOWN: Motor executes one pad-width perpendicular movement. Sweep direction flag is toggled. Transitions to SWEEP if row count is below the segment maximum; otherwise transitions to COMPLETE.

6) COMPLETE: Motor decelerates to rest. Relay de-energises. Buzzer outputs three-pulse completion signal. System transitions to IDLE.

Segment boundaries are calculated from the total board-width step count divided into thirds. The acceleration profile at motor start is a linear ramp over 200 steps from 200 steps/s to 1000 steps/s, implemented by varying the timer interrupt period at each step.

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IX. HARDWARE AND SOFTWARE REQUIREMENTS

A. *Hardware Components*

Component	Specification	Qty	Purpose
Arduino Uno R3	ATmega328P, 16 MHz	1	Central controller and FSM execution
NEMA 17 Stepper	1.8 deg/step, 44 N.cm	1	Lead-screw driven linear motion
A4988 Driver	2 A max, microstepping	1	Motor current regulation and microstepping
Electromagnetic Coil	12 V, 1 A, 500 turns, 40 mm pole	1	Magnetic adhesion to steel-backed board
IR Sensor (TCRT5000)	5 V, 880 nm, adjustable sensitivity	2	Edge and ink-presence detection
Relay Module	5 V trigger, 10 A contact rating	1	Coil supply switching with isolation
SMPS Power Supply	12 V / 3 A, overcurrent protected	1	System power source
T8 Lead Screw	8 mm pitch, 30 cm travel	1	Rotary-to-linear motion conversion
4x4 Matrix Keypad	Membrane type, 20 Hz scan rate	1	Segment selection and system commands

B. *Software Environment*

Firmware was written in the Arduino IDE (version 1.8.19). Three external libraries were used: the Keypad library by Mark Stanley and Alexander Brevig for matrix keypad scanning, the AccelStepper library by Mike McCauley for acceleration-profile motor control, and the standard Arduino EEPROM library for persistent threshold storage.

Serial output at 9600 baud was used extensively during development for real-time state and sensor value logging through the Arduino USB connection.

X. EXPERIMENTAL RESULTS

A. *Adhesion Force*

Adhesion force was measured using a calibrated spring balance. Five pull-off tests were performed, recording the force at which the energised device detached from the board surface. Mean detachment force was 9.4 N with a standard deviation of 0.3 N, exceeding the design target of 8 N minimum. During all motor operation tests, the device remained attached to the board surface without slipping, confirming that the adhesion margin is adequate for the mechanical loads generated by the stepper motor and lead screw during normal operation.

B. *Positional Accuracy*

Linear displacement accuracy was evaluated at three positions across the board width with twenty trials at each position, using a digital ruler as the measurement reference. Mean positioning error across all sixty trials was 0.12 mm, with a maximum observed error of 0.34 mm. For a cleaning application where the practical tolerance is several millimetres, open-loop stepper motor control proved more than adequate.

C. *Infrared Detection Reliability*

Detection reliability was assessed by presenting the sensors with 100 surface segments under five conditions: blank board, black marker, blue marker, red marker, and light yellow marker. Black, blue, and red markers were correctly detected in over 96% of tests. Light yellow markers produced the lowest reliability at 94.2%, requiring the sensitivity potentiometer to be adjusted to a higher setting than was used for the standard marker detection threshold. This limitation would be addressed in a future design by incorporating threshold auto-calibration during the setup routine.

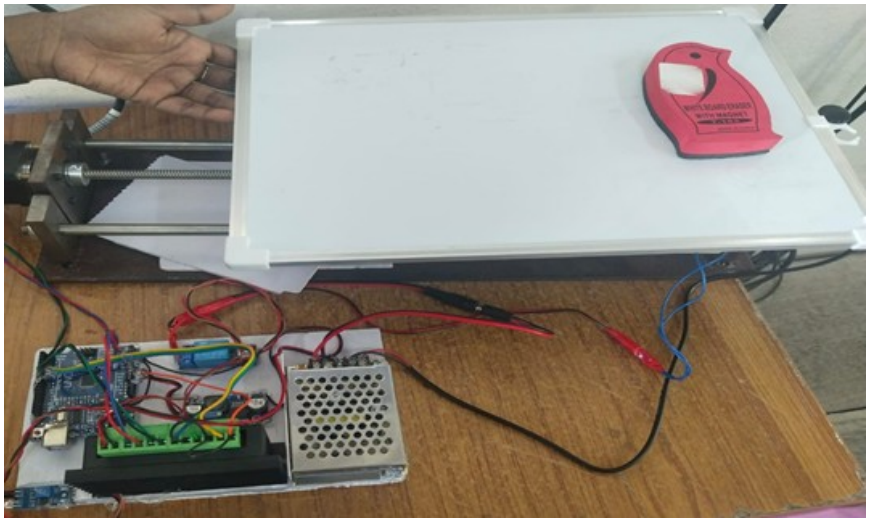
D. *Full Cleaning Trials and Endurance*

Five complete cleaning passes were run across the A4-sized test board with writing density ranging from sparse to fully covered. Cleaning times ranged from 110 to 142 seconds, with a mean of 124 seconds. All five trials achieved complete erasure with no visible ghost marks remaining after the cleaning pass. A 50-cycle endurance run showed no hardware failures. Coil temperature stabilised at 52 degrees Celsius and the motor driver at 61 degrees Celsius, both within their respective rated operating ranges.

Table I: Performance Evaluation Summary

Metric	Requirement	Measured	Status
Cleaning Time (45 cm board)	≤ 180 s	124 s (mean)	PASS
Adhesion Force	≥ 8.0 N	9.4 N (mean, SD 0.3 N)	PASS
Positional Accuracy	≤ 1.0 mm error	0.12 mm mean, 0.34 mm max	PASS
Surface Coverage	100%	100% (5 of 5 trials)	PASS
IR Detection Reliability	≥ 90%	96.8% (standard markers)	PASS
Coil Temperature Rise	≤ 80°C above ambient	+28°C after 30 min	PASS
Endurance (cycles)	≥ 50 without failure	50 (no failure)	PASS
Power Consumption	≤ 36 W	28 W	PASS

Energy consumption per cleaning cycle is approximately 0.97 Wh, which is negligible relative to a classroom's total electrical load. The principal compatibility constraint identified is the requirement for a ferromagnetic board backing; boards constructed from aluminium, wood, or glass without a steel substrate are not compatible with the electromagnetic adhesion approach.



XI. ADVANTAGES AND LIMITATIONS

A. *Advantages*

1) The device requires no permanent mounting, adhesive, or structural modification to the classroom. It can be placed on or removed from any compatible board within a few seconds.

2) Electromagnetic attachment generates a strong, controllable holding force that can be released instantly by de-energising the coil relay.

3) Segment-selective operation means the device only traverses the area of the board that has been used, avoiding unnecessary motor travel over clean sections.

4) The firmware is fully open-source and structured as a readable finite-state machine, which supports modification and extension for future development.

5) Component costs are modest, making the system viable for institutions operating within constrained equipment budgets.

B. *Limitations*

1) Electromagnetic adhesion is only effective on boards with a ferromagnetic steel backing. Boards with aluminium, wood, or glass substrates are not compatible.

2) The current mechanical design handles only flat, rectangular board geometries. Boards with integrated projection screens or non-rectangular profiles would require design changes.

3) Light-coloured markers such as yellow require manual adjustment of the IR sensor sensitivity potentiometer, which is a usability inconvenience for non-technical users.

4) Open-loop stepper control does not compensate for positional drift that could accumulate on larger boards over many cleaning cycles.

5) There is no obstacle detection capability beyond board edge sensing, meaning any unexpected object on the board surface during operation could cause the device to travel over it.

XII. APPLICATIONS

The most direct application for the Smart Duster is in educational institutions with high whiteboard usage, including engineering colleges, schools, and coaching centres. Institutions maintaining large numbers of classrooms with limited maintenance staff would benefit most from reducing the cleaning workload on faculty.

Corporate training facilities and boardrooms represent a secondary application domain where cleaning interruptions carry a direct productivity cost. Any meeting-intensive environment where whiteboard use is frequent could benefit from automated cleaning between sessions.

The electromagnetic adhesion and infrared navigation architecture has potential for adaptation beyond cleaning. The same attachment mechanism could carry a sensor payload for surface inspection tasks on steel structures, or be adapted for cleaning glass partition walls fitted with a ferromagnetic frame.

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These extensions would require modifications to the sensing and control subsystems but could use the mechanical and adhesion architecture largely as developed.

XIII. FUTURE WORK

Several specific improvements are identified for subsequent development iterations.

Replacing the pair of TCRT5000 IR sensors with a small camera module and an embedded convolutional neural network would enable marker colour discrimination and more reliable detection of partially cleaned areas. This would also allow the device to skip genuinely blank sections without relying on calibrated reflectance thresholds.

Wireless connectivity via a Wi-Fi or Bluetooth module would allow the device to be controlled from a teacher's phone, eliminating the need for the onboard keypad and enabling remote status monitoring. A rechargeable battery pack would make the device fully wireless by removing the dependency on a mains connection, which would improve deployment flexibility and eliminate cable management concerns.

Encoder-based closed-loop position feedback would eliminate the residual positional uncertainty inherent in open-loop stepper operation. For larger boards where many cleaning rows are executed per session, this would prevent drift accumulation across the cleaning sequence.

Extending the coverage algorithm to handle non-rectangular board geometries, such as boards with integrated projection areas or irregular boundaries, would widen the range of environments in which the device could be deployed without modification.

XIV. CONCLUSION

This paper has presented the complete design, implementation, and experimental evaluation of the Smart Duster, an electromagnetically attached, sensor-guided autonomous whiteboard cleaning device. The system was developed in response to a practical and consistently overlooked problem: the repeated manual interruption of teaching sessions for board maintenance, which consumes instructional time and contributes to physical fatigue for educators.

Four integrated subsystems were developed and characterised: electromagnetic adhesion using a pot-core coil for reliable board attachment; stepper motor actuation via a lead-screw mechanism for precise lateral traversal; infrared reflectance sensing for written-content detection and board edge identification; and Arduino Uno firmware implementing a six-state deterministic finite-state machine for coordinated system control. The prototype was constructed using commercially available, low-cost components selected for their accessibility in an academic project context.

Experimental results across all defined performance metrics confirmed the viability of the approach. Adhesion force exceeded the design target, positioning accuracy was sub-millimetre, detection reliability exceeded 96% for standard dry-erase markers, and complete board coverage was achieved in all five cleaning trials. A 50-cycle endurance run demonstrated hardware reliability without thermal or mechanical failure.

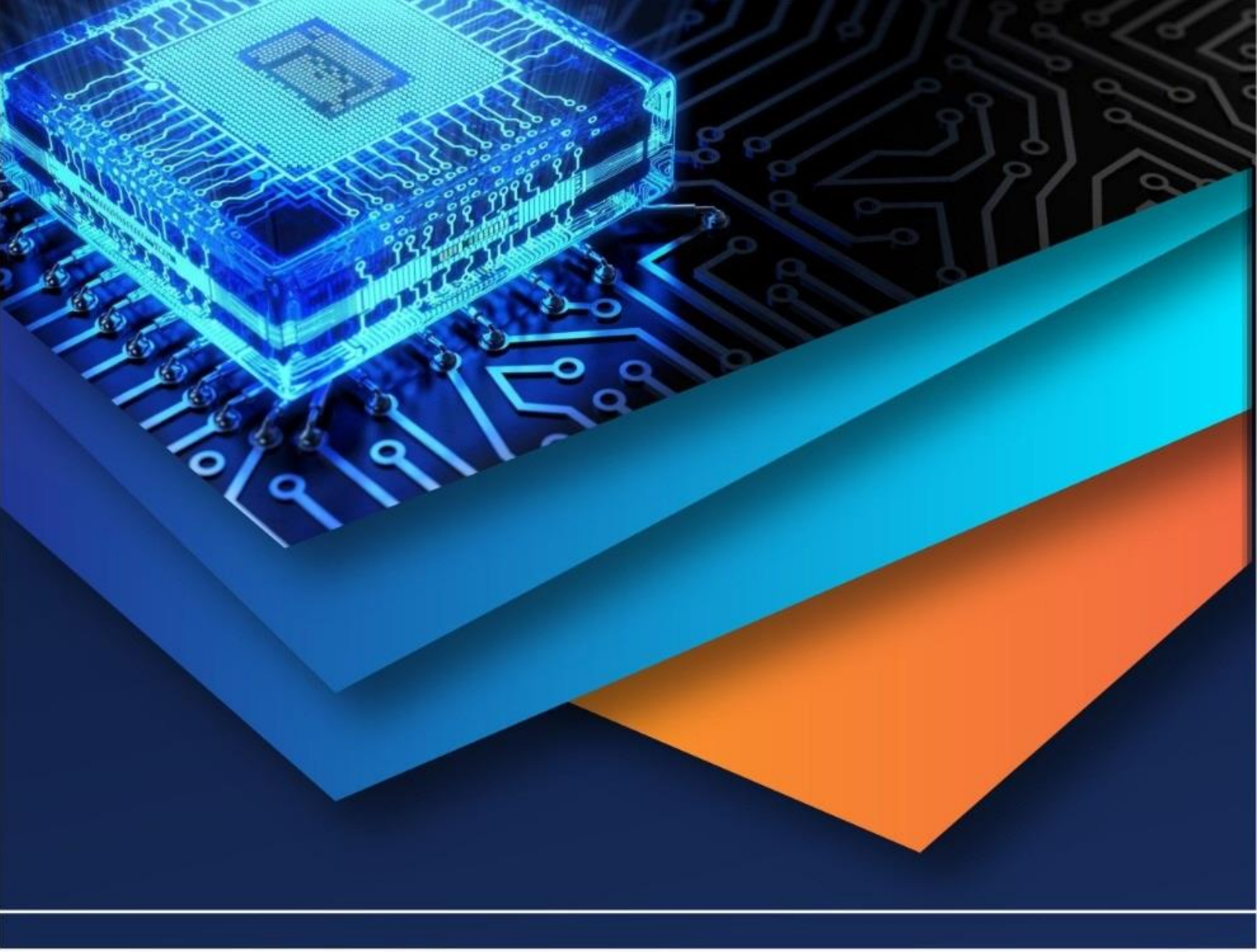
The architecture developed in this work, characterised by simplicity, modularity, and low cost, provides a credible foundation for the enhancements described in the future work section, including camera-based content sensing, wireless operation, closed-loop position control, and wider board geometry compatibility. Autonomous whiteboard cleaning addresses a genuine operational need, and the Smart Duster demonstrates that it can be achieved with accessible embedded systems technology.

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