Grenze International Journal of Engineering and Technology, January Issue

Design and Implementation of a Cartesian-based Automatic Ironing Robot using Vision-Guided Steam and Vacuum End-Effector

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***Abstract*— Ironing garments has become a day-to-day routine of mankind. In the era of development of home automation processes such as monitoring and control of lighting, climate analysis, home appliances, etc., ironing garments automatically can become one of the simple steps that can be climbed on towards the future. This paper explains the designing and implementation of Automatic Ironing Machine by using the novel combination of Machine Vision, Robotics and Control Systems. This system operates by a vision-based approach to analyze the garment, identifying key features like boundary detection and determining optimal ironing paths by using Edge Detection methods used in image processing. A Cartesian robot, equipped with a custom-designed end effector incorporating a vacuum system and steam generation system for executing the ironing process. The combination of all these systems ensures precise and efficient ironing. Experimental results demonstrate the feasibility of the proposed approach in achieving wrinkle-free garments with minimal user intervention, paving the way for a new era of smart home laundry solutions.**

***Index Terms*— Automatic ironing machine, robotic control, computer vision, image processing, vacuum system, home automation, Cartesian robot.**

I. INTRODUCTION

As we know, home, food, water, and clothes are the most important factors of living. And along with trends, the most growing one is garments. We are using so many clothes day by day for our living. For ease of washing clothes, there are automatic washing machines that are getting modified each day. Even cloth picking from their own room has been implemented.

But still there is a lack in the process of ironing and its technological modifications for making the ironing garments become easy. There are industrial machines as well as dry cleaning centers for cloth washing and ironing. But on a domestic level we still lack technological modifications in ironing.

As the ironing is a time-consuming and labor-intensive task, humans avoid the effort to do that. For someone with a busy lifestyle or limited mobility, this time-consuming and physically demanding ironing process becomes hard. Ironing needs an ironing bed as well as physical influence; they need more space while doing it manually, and people get exhausted easily. This fatigue may even affect their lifestyles also.

Grenze ID: 01.GIJET.12.1.68

Also, manual ironing causes inconsistent results and damage to the garment as well as the one who was using it. Without proper care and technique, we may burn the garment. And there will be inconsistent results, such as wrinkles and creases becoming difficult to remove. It can damage delicate fabrics or cause garments to shrink or stretch. Therefore, the damage caused cannot be reversed. It is also applicable to humans themselves. While ironing, placing the iron and ironing clothes without care can cause scalding ourselves. It can result in scratches to fatal injuries that can't be recovered.
To address these challenges, we propose the development of an Automatic Ironing Robot. This robotic solution aims to automate the ironing process by detecting garment boundaries and performing consistent, high-quality ironing with minimal human intervention.

II. Literature Review

Ironing methods have evolved a lot from manual ironing to sophisticated automatic ironing solutions and is progressing on AI-driven methods. Initially manual iron boxes where heated using coal of fire to heat up the soleplate. It was highly dangerous for garments because of continuous burning of coal and substances as well as led to scalding ourselves. Later it evolved to electrical iron boxes which can heat up the soleplate by providing electricity to the heating element in the iron box and to reduce accidents the bi-metallic strip helps to cut off the supply as per the temperature range adjusted for different garments manually. Overtime steam ironing methods are introduced in industries and to domestic uses in the form of iron boxes which helps in garment care and less accidents with maximum efficiency. Automatic ironing machine projects and products are been researched and explored extensively for recent years. Because not just a development of a product but also it paves a way for home automation projects. From the few studies made till now, Fan Li proposed a theoretical solution for precision and adaptable intelligent ironing machine equipped with mechanical arms and sensors to optimize temperature and pressure according to the fabric type [3]. Pachupate and Bhunje developed a multipurpose integrated ironing system with folding mechanism for domestic use which is done by a pressing mechanism [11]. Shaikh Abdul Malik and Dr. Tuljapure focused and developed a cost effective semi-automatic ironing system with simplicity in pressing mechanism and energy efficiency [2]. Rather than just domestic ironing methods, Haotian Jiang proposed a theoretical steam ironing mechanism with advanced robotic technologies and machine learning algorithms [1]. Chandhra Prasad proposed a rolling mechanism than a pressing mechanism which is focused on precise ironing and enhanced robotic efficiency through optimized motion planning and lightweight end effector design [4]. Bhargav and team proposed an automatic saree ironing machine which focuses on fabric-specific ironing techniques [9] while at the same time Kazuyoshi Ishida and team proposed a bed sheet ironing mechanism which focuses on fabric spreading techniques and these two systems are proposed a semi-automatic ironing machines for larger garments. Nur Akmal Haniffah and team recently proposed an ironing machine prototype which combines modern technology and automation techniques for identifying specific fabric types and sizes for efficient ironing [10]. As each of these literature works reviews on different unique possibilities and advancements through robotic movements, system efficiency, system design, ironing methods and mechanisms, etc. In this project we will trying to unify all those concepts and reduce the gaps in implementing such a mechanism into real world scenario.

III. System Design and Operation

A. Mechanical Subsystem

The mechanical structure is a belt-driven Cartesian robot constructed using 20x40 mm aluminum extrusion bars, forming a 1000 mm (X) by 800 mm (Y) working area. This frame was chosen for its balance between rigidity, weight, and modularity. V-slot wheels are mated with universal gantry plates to allow smooth and low-friction motion across aluminum rails.

Figure 1: Physical prototype of the mechanical subsystem

The motion is actuated using three NEMA17 stepper motors (1.8° step angle, 42 N·cm torque), driven via GT2 timing belts (10 mm wide) and 20-tooth pulleys. The hanger mechanism, responsible for rotating the garment after ironing one side, is actuated by an MG996R servo motor. It is coupled to a 20 cm aluminum extrusion using custom 3D printed couplings. The system is anchored to a plywood base using a steel stand to prevent vibration.

B. Electronics and Control Subsystem

The control system is built around an Arduino Uno microcontroller equipped with a CNC Shield R3. Motion control is implemented using three DRV8825 stepper motor drivers, enabling micro stepping resolution suitable for fine path following. The drivers are powered by a 24V DC power supply which steps down from the standard 230V AC supply.

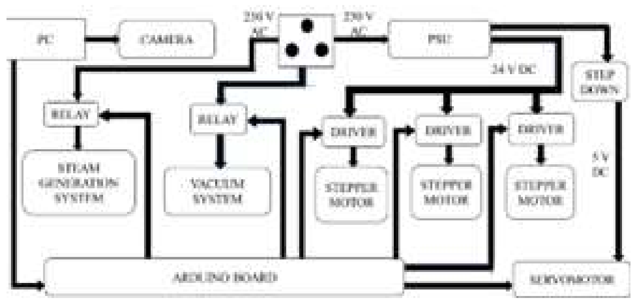

Figure 2: Electronics control block diagram.

Relay modules are used for switching high-power components such as the vacuum blower and the steam generator. A 12V DC submersible water pump is used to deliver water from a tank positioned at the top of the frame into the heating element of the end-effector.

C. Vision and Image Processing Subsystem

A Smars® HWC-86L 1080p HD webcam is mounted at a calibrated height on the robotic frame to capture images of the vertically hung garment. The captured image undergoes edge detection using the Canny algorithm, followed by contour filtering in OpenCV to isolate the largest continuous boundary assumed to represent the garment. Contours are translated to physical coordinates using a pixel-to-mm scale. This scale was calibrated based on the known garment size and distance from the camera, yielding an approximate resolution of 0.5 mm/px. The resulting set of coordinates defines the trajectory of the end-effector.

D. End-Effector Design

The ironing end-effector combines two subsystems: steam delivery and vacuum hold. The steam mechanism uses a modified commercial iron box where a submersible pump feeds water into the heating element [7]. A drip tube was ultimately adopted to stabilize flow rate and allow for efficient steam generation. The vacuum system initially tested 12V and 24V diaphragm pumps, but they failed to generate sufficient suction force for porous garments. A high-speed blower motor integrated with a 1-meter extension hose and flat nozzle proved most effective. The vacuum activates only during ironing strokes to conserve energy.

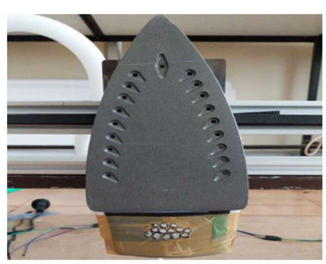

Figure 3: Design of the ironing and vacuum end-effector.

E. Operational workflow

The process begins with the user manually hanging a garment onto the rotating hanger frame. The garment is vertically suspended and stabilized for image capture.

Figure 4: Image Acquisition and Edge Detection

The garment detection process begins with image capture using a webcam mounted at a calibrated height on the robotic frame [6]. The captured RGB image is resized to 640×480 pixels and subjected to a multi-stage pre-processing pipeline. First, a Gaussian blur filter is applied to reduce high-frequency noise, followed by grayscale conversion. The resulting intensity image is processed using the Canny edge detection algorithm, configured with threshold values of 50 and 150. This operation extracts edge structures corresponding to garment boundaries and surrounding textures. To enhance edge continuity and minimize fragmentation, a morphological dilation is applied using a 5×5 kernel. The resulting binary edge map is passed to the OpenCV find Contours function, with only external contours retrieved. A validation filter removes small and irrelevant contours by checking the area and bounding box dimensions relative to the full image size. Only contours occupying more than 10% of the image area and exceeding 20% of the image width and height are retained. The largest valid contour, assumed to correspond to the primary garment region, is approximated using the Douglas–Peucker algorithm (approxPolyDP) to reduce point density while preserving boundary fidelity. To ensure accurate robotic path planning on the garment surface, it is essential to translate pixel-based contour coordinates into real-world measurements. This process allows the system to move the ironing end-effector in physical space based on the detected boundary in image space.

The conversion is based on the pinhole camera model, where a 3D world point (X, Y, Z) is projected onto the 2D image plane as pixel coordinates (u, v). For a planar garment surface placed at a fixed distance Z = 750 mm from the camera, and assuming negligible perspective skew, the mapping from pixel to world coordinates is described by the inverse of the camera's intrinsic projection.

The calibrated camera matrix K used is:

$$K = \begin{bmatrix} 569.75 & 0 & 339.38 \\ 0 & 568.89 & 215.55 \\ 0 & 0 & 1 \end{bmatrix}$$

The distortion coefficients obtained from OpenCV calibration are: Distortion Coefficients = [-0.409, 0.133, 0.004, -0.00089, 0.037]

Before applying the transformation, lens distortion is corrected using OpenCV's cv2.undistort() function, which ensures linear mapping across the image.

Given a pixel coordinate (u, v), the real-world position (X, Y) at depth Z is obtained using:

$X = (u - c_x) \cdot Z / f_x$

$Y = (v - c_\gamma) \cdot Z / f_\gamma$

where (f_x, f_γ) are the focal lengths and (c_x, c_γ) is the optical center (principal point) of the camera.

Substituting values from the camera matrix:

$X = (u - 339.38) \cdot 750 / 569.75$

$Y = (v - 215.55) \cdot 750 / 568.89$

This provides a real-world (X, Y) coordinate in millimeters for each pixel (u, v) on the image. The resulting set of converted coordinates defines the actual trajectory that the Cartesian robot follows on the garment.

The binary mask generated from the segmented cloth is used to define the ironing area. This generates a set of optimized (X, Y) ironing waypoints with uniform spacing, minimizing redundant motion while ensuring full surface coverage. The trajectory generated in Python is transmitted point by point to the Arduino via serial communication. Each coordinate pair represents a real-world position mapped from the processed image space. During active strokes, a relay module controlled by the Arduino activates the steam and vacuum-based end-effector. Simultaneously, vacuum suction below is activated through a high-speed blower to flatten the cloth. These actuators are triggered only during ironing paths. Upon completing one side of the garment, the MG996R servo motor rotates the hanger by 180° to expose the opposite side. The entire pipeline is then repeated for the second side. After ironing both sides, the robot returns to its home position. The user manually removes the garment.

F. Numerical Calculations

This section presents detailed calculations that validate the motor selection, dynamic loading and motion system suitability of the proposed automatic ironing machine. The focus is on the vertical and horizontal axis system, driven by 2 NEMA17 stepper motors in vertical axis and 1 on the horizontal axis, and its ability to support and move the mechanical load under defined speed and acceleration constraints.

Load Calculation and System Parameters

The total gravitational force acting on the system is:

F total = M total. g = 3.36×9.81 = 32.96 N

TABLE I: COMPONENTS MASS AND WEIGHT

Component	Mass(kg)	Weight(N)
Horizontal Bar	0.96	9.42
End Effector	2.00	19.62
X-axis Motor	0.40	3.92
Total Vertical Load	3.36	32.96

Load Distribution on y-axis Motors

The horizontal bar is modeled as a simply supported beam with: Uniform distributed load (its own weight)

Point load (x-axis motor) at x = 0

Variable point load (end effector) at position x

Using equilibrium of forces and moments:

Sum of vertical forces: R left + R right = 32.96 N

Sum of moments about the left support:

Rright×0.8 = (9.42. 0.4) + (19.62. x) = 3.77+19.62x ÷0.8

Solving:

R right(x) = 4.7088+ 24.525x (N)

R left(x) = 32.96 – R right(x) = 28.2528 – 24.525x (N)

This provides a torque vs position relationship

Maximum force per motor:

At x = 0: R left = 28.25N, T= 28.25×0.007 = 0.198N

Dynamics and Acceleration Effects

The system is accelerated during motion at a controlled rate. The dynamic effects are added to the static loading to estimate the total torque required during operation.

Motion parameters:

Pulley pitch = 2 mm, teeth =20 →circumference = 40 mm

Stepper motor = 200 steps/rev

Displacement per step: 40mm/200 = 0.2mm/step

Given speed and acceleration: Speed: 200 step/s = 0.04 m/s

Acceleration: 100 step/s² = 0.02m/s²

y-axis Acceleration Torque:

Total= 3.36×0.02=0.0672 N →F/ motor=0.0672/2=0.0336N

Total = 0.0336×0.007 = 0.0002352 Nm

Total = 0.198 + 0.000235 = 0.1982Nm

Horizontal Axis Acceleration Torque

End effector mass = 2kg

Horizontal = 2×0.02 = 0.04N →T = 0.04 ×0.007 =0.00028N

This is the total torque needed to move the x-axis at defined acceleration

Torque Availability and Safety Margin

Each NEMA17 stepper motor is rated at 0.49Nm holding torque. At 60 RPM (equivalent to 200 step/s), torque typically drops slightly due to back emf and inductance. Based on standard motor curves and empirical data, a 6% reduction is conservatively estimated.

Available = 0.49×0.94 =0.4606 Nm

Final safety margin = 0.4606/0.1982 = 2.32

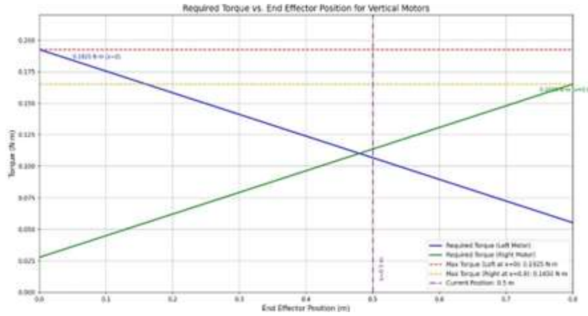

Figure 5: Required Torque Vs End Effector Position for Vertical Motors

This confirms that the selected motors operate well within safe torque limits during vertical motion, even under acceleration.

G. Servo Torque Requirement for Hanger Rotation

The vertical ironing robot includes a servo-driven hanger mechanism that rotates the garment by 180° after completing one side of the ironing process. The goal of this analysis is to verify that the selected servo motor can reliably rotate a cloth of estimated mass without exceeding its rated torque.

System Setup

TABLE II: PARAMETERS

Parameter	Value
Servo motor	MG996R (Tower Pro)
Rated stall torque (6V)	9.4 kg·cm = 0.92 N·m
Arm length (distance from rotation axis to CoM of cloth)	0.15 m (assumed half-hanger span)
Estimated cloth weight	0.4 kg

Required Torque for Rotation

This is the minimum torque needed to initiate rotation, assuming horizontal starting orientation and no friction. Real systems may encounter small frictional resistances at couplings or joints, so a safety margin is considered next.

$\tau\_required = r \times F = r \times m \times g$

$\tau\_required = 0.15 \times 0.4 \times 9.81 = 0.5886$ N·m

Servo Torque Availability and Safety Margin

MG996R offers positional control with internal gear reduction, allowing high holding torque, which is critical to maintain the cloth's orientation during ironing transitions.

$\tau\_$ available = 0.92 N·m (Safety Margin = $\tau\_$ available / $\tau\_$ required = 0.92 / 0.5886 ≈ 1.56)

IV. RESULTS AND DISCUSSION

A. Performance Evaluation

This automatic ironing machine system led to solve one of our problems about time efficiency. This project has improved the time required per garment to iron by approximately about 40 % compared to traditional manual ironing methods. This time efficiency is achieved through system's ability to precisely follow pre-programmed ironing paths which can be adjusted based on detected shape and orientation of each garment. Features such as automated hanger rotation, controlled steam release and consistent motion control helps in streamlined workflow minimizing manual repositioning and intervals periods between operations. These enhancements improved overall uniform ironing results in a short time period.

The vacuum system plays a vital role in maintaining garment tension during ironing, effectively replacing the need for a traditional ironing bed. Initial experiments employed 12V and 24V diaphragm-type vacuum pumps. A high-speed blower-based vacuum system was implemented. The system utilizes a 1-meter extension hose coupled with a flat suction nozzle, experimentally positioned to maintain an optimal gap between the garment and the end-effector.

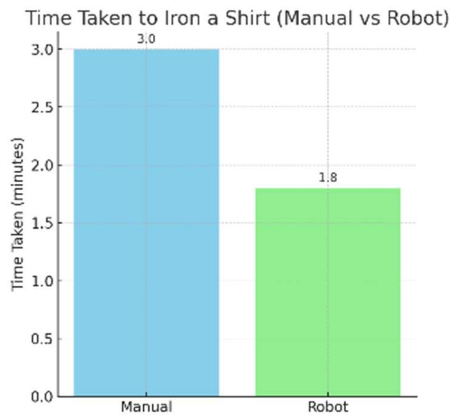

Figure 6: Vacuum System Performance

This arrangement ensured consistent suction coverage and significantly improved ironing uniformity. The vacuum operation is synchronized with the motion trajectory of the end-effector. Specifically, suction is activated when the end-effector initiates a downward stroke from the upper boundary of the garment and deactivates upon reaching the bottom boundary. The suction remains off during repositioning and is reactivated only when the subsequent ironing stroke begins at the top boundary.
The steam delivery subsystem is central to the ironing effectiveness of the robot [8]. Controlled steam release is achieved by regulating the water flow to the heating element of the end-effector. The water tank was repositioned above the Cartesian frame to enable gravity-assisted flow. The pump was replaced with a passive IV drip tube commonly used in medical applications. This setup allowed manual control of flow rate using the tube's built-in regulator and delivered a consistent, stable feed to the iron's heating element. A surface plot analysis was conducted to evaluate the combined effect of water flow rate and heating temperature on ironing efficiency.

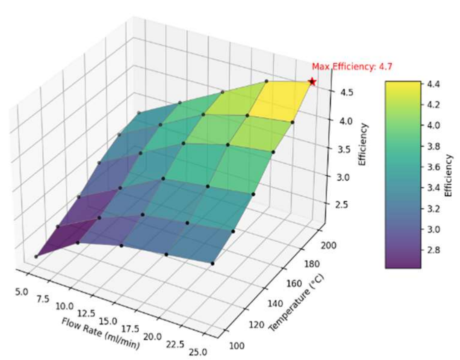

Figure 7: Flow rate vs temperature vs efficiency graph

Results show that higher temperatures and increased flow rates contribute positively to performance. A maximum efficiency of 4.7 was observed at a flow rate of 22.5 mL/min and a temperature of approximately 200°C, which corresponds to the upper operational limit of the modified steam iron. Lower flow rates, even at high temperatures, resulted in inadequate steam production and reduced ironing effectiveness. These results further validate the use of IV drip-based gravity-fed system, as it enables stable flow regulation within the identified optimal range.

B. Scene Sensitivity and Boundary Detection Performance

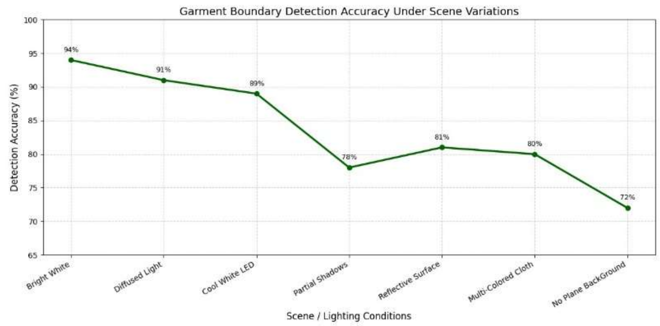

Figure 8: Detection Accuracy vs Lighting conditions

The accuracy of garment contour detection was evaluated under varying lighting and scene setups. As illustrated in Figure 8, the system achieved over 90% accuracy under bright, uniform backgrounds and typical LED or daylight environments. However, detection degraded significantly in complex scenes — especially when garments lacked a plane background (e.g., cluttered surroundings), where false contour extraction and background blending dropped accuracy to ~72%. Similarly, multi-colored or reflective fabrics resulted in moderate loss of fidelity. These results emphasize the importance of a controlled imaging environment for robust edge-based garment recognition.

B. Accuracy of Edge Detection and Path Planning

The edge detection and trajectory planning system achieved an estimated 90% accuracy in detecting garment boundaries under favorable conditions, such as color fabrics against a plain white background with uniform lighting. The resulting ironing paths enabled reliable and consistent motion of the end-effector, demonstrating effective coverage with minimal manual tuning. However, the system showed notable limitations. Low contrast scenarios, particularly white or light-color red garments on a white background, significantly reduced boundary detection reliability. In such cases, the edge detection algorithm failed to isolate clear contours, resulting in incomplete or inaccurate masks. Additionally, poor lighting, shadow interference, and background clutter introduced false positives or distorted contours. The hanger structure was sometimes misinterpreted as part of the garment boundary, as the path planning algorithm depends on identifying the largest closed contour in the image, which may not always correspond to the actual cloth. These limitations highlight the need for better visual isolation of the garment through controlled lighting and high-contrast backgrounds.

Figure 9: Edge Detection

Future work can incorporate adaptive background adjustment, image pre-processing enhancements, or selective background color modulation to improve contour extraction and trajectory accuracy.

C. Mechanical and Electrical System Performance

The Cartesian robotic system was built with measuring tools to avoid bends as well as length errors while frame making [5]. All the joints are fastened with suitable pre-insertion T-nuts as well as button head and socket head screws. The mechanical structure is fixed on a custom built stand and is again fixed on a plywood piece. Some parts such as pulley holders, servo-extrusion coupling and servo-hanger coupling are 3D printed.

The GT2 timing belt needed to be jointed manually because of length constraints. But the Cartesian robotic system efficiently moved through the following pre-processed paths without any distortions and vibrations. The motorized hanger rotation system worked well for small garments for now because of the current design.

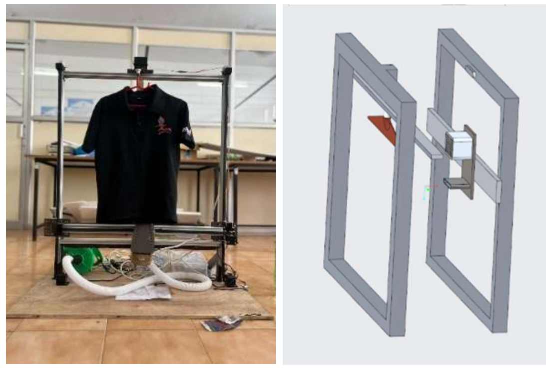

Figure 10: Automatic Ironing Machine by CREO

As mentioned earlier the 3D printed parts resulted in wear and tear causing weight hanging constraints and loosening. There were issues with motor drivers and connectivity issues too.

V. Conclusion

In this paper an automatic ironing machine with integrated steam and vacuum systems which helps in better efficiency and enhanced wrinkle removal is designed and implemented. It consists of integrated steam and vacuum systems along with a Cartesian system and hanger mechanism for ease of use in the final result. Despite of challenges faced in motor control and end effector implementation the system provided better results in reducing time, labor and power, better wrinkle removal, and better garment handling. The edge detection and motor movement along with proper control over vacuum suction timing and steam distribution have pave the way to future enhancement opportunities. Future developments like better motor control, end effector customization and advanced image processing techniques and AI integration can be done with further research and work.

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