

Development of Intelligent Mechatronic Integration System for Silk Reeling Machine

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In this study, an intelligent mechatronic integration system was developed for an eco-friendly silk reeling machine. The proposed system, termed an “environmentally intelligent silk reeling machine”, utilizes recycled plastics such as acrylonitrile butadiene styrene and polylactic acid to produce 3D printing filaments. Integrated sensing modules monitor key parameters including temperature, extrusion speed, and filament diameter in real time, enabling precise process control and consistent material quality. The system also features remote monitoring capabilities, allowing users to manage operational status and efficiency through networked sensing feedback. In response to the growing issue of plastic waste from mass-produced products, this design emphasizes both economic feasibility and environmental sustainability. By converting discarded plastic bottles and other waste materials into reusable 3D printing filaments, the system not only reduces environmental pollution but also lowers material costs, demonstrating a practical approach that combines smart sensing technology, mechanical innovation, and green manufacturing.

1. Introduction

In recent years, environmental sustainability has become a critical global issue as the consumption of plastics continues to rise at an alarming rate. It is estimated that nearly nine trillion plastic bottles are produced annually in the United States alone, and only a small fraction of them are effectively recycled. Most discarded bottles do not easily decompose, occupy large volumes in landfills, and release harmful microplastics into soil and water, creating one of the most pressing ecological threats of modern times. Plastic materials, while lightweight, durable, and inexpensive, pose significant disposal challenges owing to their non-biodegradable nature. The plastic identification code system, composed of three chasing arrows forming a triangular loop, categorizes plastics into seven distinct types to facilitate recycling. However, despite

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advances in classification and waste management technologies, large-scale, cost-effective plastic recycling remains underdeveloped. These environmental concerns underscore the urgent need for innovative systems capable of transforming discarded plastics into reusable materials and simultaneously addressing sustainability goals and promoting circular economy practices.^(1–3)

Additive manufacturing, particularly 3D printing, has emerged as a transformative technology that bridges digital design and material reuse. By reading cross-sectional data from digital models and extruding molten plastic layer by layer, 3D printers can fabricate complex geometries with high precision. The demand for eco-friendly, low-cost filament materials has consequently grown, stimulating interest in using recycled plastics as feedstock. Common materials such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polyethylene terephthalate (PET) can be recovered from waste bottles and reprocessed into 3D printing filaments.^(4–6) This approach not only reduces the environmental burden of plastic waste but also lowers the material cost for additive manufacturing industries. However, the reprocessing of plastics into usable filament requires a system capable of maintaining stable temperature gradients, extrusion pressure, and filament diameter. The inadequate control of these parameters can lead to filament brittleness, inconsistent feeding, or print failure. Hence, the integration of intelligent sensing, precise thermal management, and automated control mechanisms becomes essential for developing efficient and sustainable recycling systems that ensure consistent material quality and operational reliability.

In response to these challenges, in this study, we propose an eco-intelligent silk reeling machine—a mechatronic system that integrates mechanical design, sensor technology, and control intelligence for the efficient recycling of waste plastics. The developed system is capable of melting, extruding, cooling, and winding discarded plastic products, such as ABS and PLA, into high-quality filaments suitable for 3D printing. The hardware architecture comprises key functional components including a motor-driven propelling screw for extrusion, a heater and melting furnace for temperature control, a feeder system for material input, a cooling fan and nozzle for filament formation, and a winder for collection. Each module is governed by a microcontroller-based control system that coordinates their operations in real time. Furthermore, a Bluetooth-enabled sensor interface allows wireless data acquisition and communication between the machine and a dedicated mobile application (APP), enabling users to remotely monitor and adjust system parameters such as extrusion speed, temperature, and motor torque. This integration of mechanical automation with smart sensing technologies enhances both process efficiency and environmental value, representing a step toward intelligent, eco-friendly manufacturing.

The proposed intelligent mechatronic integration system exhibits several novel features that distinguish it from a conventional filament extrusion or recycling system. First, it adopts a fully modular design, allowing flexible operation and easy maintenance while improving system scalability. Second, it integrates multisensor feedback for closed-loop control, ensuring precise temperature regulation and uniform filament thickness. Third, the system includes a mobile APP developed for real-time monitoring and remote control, enabling users to track operational data such as motor current, temperature profiles, and extrusion rates through Bluetooth communication. In contrast to conventional low-cost recycling devices that mainly emphasize

mechanical extrusion, the originality of the proposed system lies in the integration of distributed sensing modules, real-time wireless monitoring, and proportional–integral–derivative (PID)-based adaptive feedback control into a unified intelligent recycling platform. The developed system incorporates temperature sensors for thermal-zone monitoring, rotary encoder sensing for extrusion and winding speed measurement, current sensing for motor loading analysis, airflow and cooling-state sensing for thermal stabilization, and tension-related sensing for filament winding regulation.

These sensor-assisted monitoring mechanisms enable the continuous acquisition of physical parameters during filament production, allowing the system to dynamically adjust heating power, motor speed, and cooling conditions to maintain stable extrusion quality and operational safety. This sensor-centered design transforms the platform from a simple plastic extrusion machine into an intelligent sensing-assisted manufacturing system suitable for sustainable smart manufacturing applications. Fourth, the system emphasizes energy efficiency and environmental responsibility, using minimal power during operation and maximizing the reuse of waste plastics. In addition, the design follows a mechatronic integration approach, combining electromechanical coordination, embedded system control, and intelligent sensing into a single platform. Through iterative design optimization, component fabrication, and experimental verification, the system demonstrates superior performance in producing consistent, high-quality recycled filaments. Overall, the developed eco-intelligent silk reeling machine not only provides a cost-effective solution for plastic recycling but also serves as a practical model for sustainable smart manufacturing systems that align with Industry 4.0 principles and the vision of a circular, low-carbon economy.

2. Methodology

The overall structure of the intelligent silk reeling machine consists of software modules, a human–machine interface (HMI), and several functional modules. The system software includes a Bluetooth sensor receiving subroutine, which transmits data to the eco-intelligent silk reeling machine program. As shown in Fig. 1, the program manages four key control subroutines: feeder

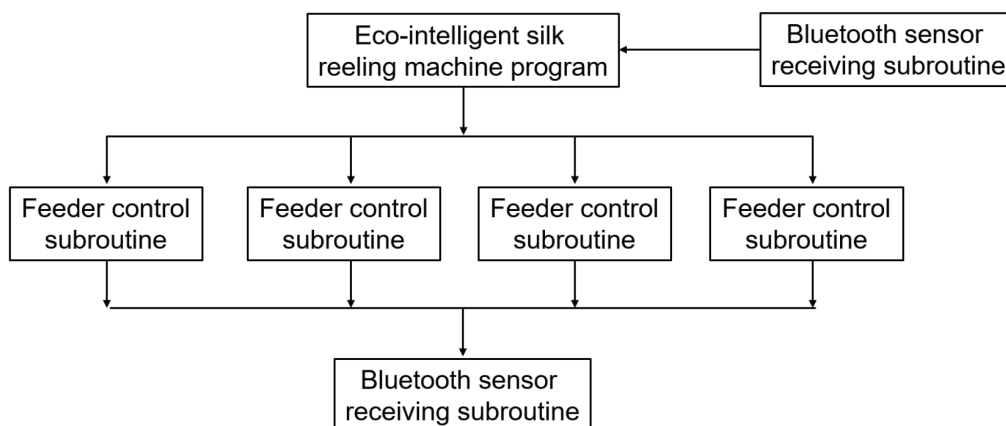


Fig. 1. System overall architecture.

control, heater control, cooler control, and winder control. These subroutines exchange sensing data through the Bluetooth sensor receiving module to maintain synchronized and stable operation. As illustrated in Figs. 2 and 3, the proposed system consists of an eco-friendly micro-reeling machine and an intelligent handheld monitoring device. The reeling machine is constructed on a base equipped with a motor-driven feed screw for extrusion, together with a crushing unit, melting furnace, nozzle, cooling unit, and winding device arranged sequentially along the processing path. Multiple heaters are positioned around the feed screw to maintain uniform thermal conditions during extrusion. The intelligent silk reeling machine integrates wireless communication, real-time monitoring, and automated feedback regulation within a unified sensing and control architecture.

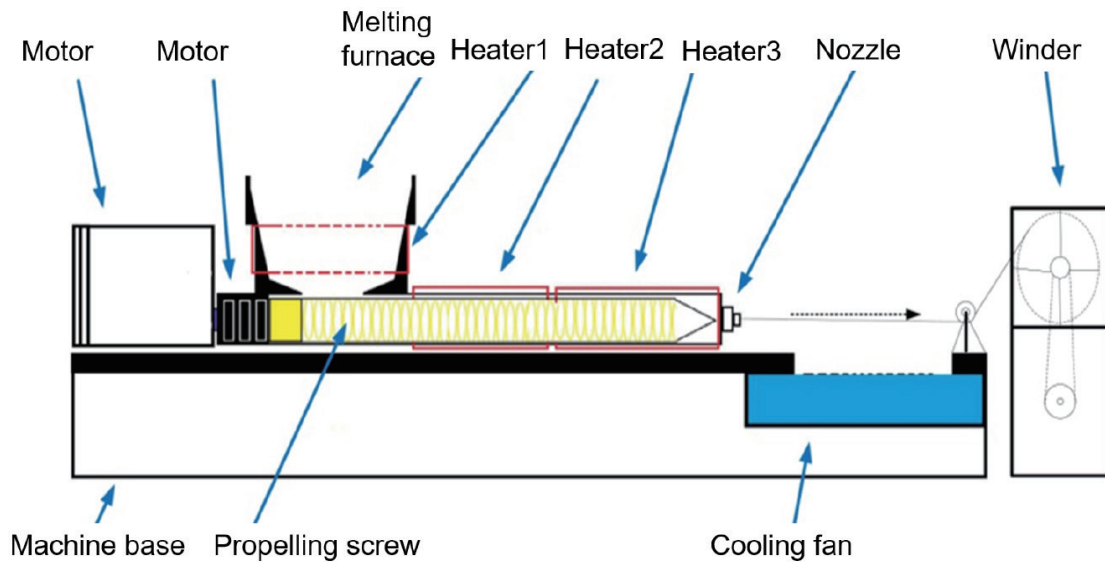


Fig. 2. (Color online) Silk reeling machine structural diagram.

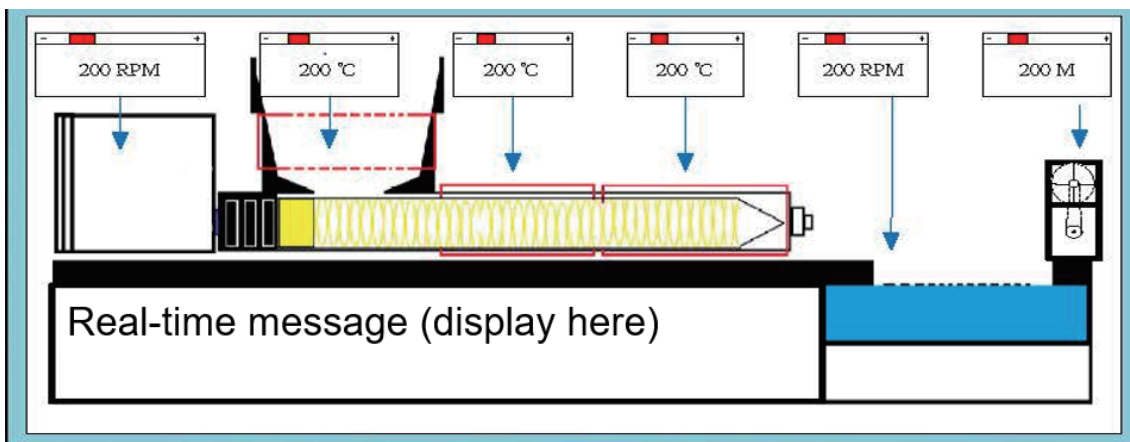


Fig. 3. (Color online) APP real-time monitoring system diagram.

Through a built-in Wi-Fi module, the controller communicates with smartphones or tablets, allowing users to remotely monitor operational parameters and adjust settings such as temperature, motor speed, and winding rate through a sensor-based interface. During operation, waste plastics are first crushed into small fragments, then transferred into the melting furnace, melted, extruded through the nozzle, cooled, and finally wound into recycled filaments suitable for 3D printing. Commercial plastic pellets can also be directly processed to produce customized filaments. To ensure operational stability and extrusion precision, the system incorporates distributed sensor modules and PID-based closed-loop control. Load, position, temperature, airflow, rotary encoder, and tension sensors continuously monitor feeding consistency, heating conditions, cooling performance, and winding stability.

The sensing architecture was designed to enable the continuous monitoring of multiple physical parameters during filament recycling and extrusion. K-type thermocouple temperature sensors were installed along the heating zones and melting furnace to monitor thermal distribution within the extrusion chamber over a working range of approximately 0–300 °C. Rotary encoder sensors mounted on the motor shaft and winding mechanism were used to measure rotational speed and extrusion stability in real time. Current sensing modules were integrated into the motor-driving circuit to estimate motor loading and operational power consumption during filament production. In the feeder section, load and position sensing elements were utilized to monitor material feeding consistency and detect possible blockage conditions. In addition, airflow-related cooling monitoring and tension sensing mechanisms were incorporated near the cooling and winding regions to maintain stable filament solidification and uniform winding behavior. The collected sensing signals are transmitted to the Arduino-based controller through analog and digital input channels for real-time processing and feedback regulation.

The acquired sensing data are transmitted to the main controller for the dynamic adjustment of heating power, motor speed, and cooling intensity. This integrated sensing and control framework improves extrusion quality, production efficiency, and operational reliability while supporting energy-saving and sustainable recycling objectives. Specifically, thermocouple-based temperature sensors are installed near the melting furnace and extrusion zones to continuously monitor thermal distribution during filament formation. Rotary encoder sensors attached to the motor and winding mechanism are used to measure rotational speed and extrusion consistency, while current sensing modules are utilized to estimate motor loading and operational power consumption. In addition, airflow and cooling-state sensing modules are employed to regulate the cooling process and reduce filament deformation during solidification. All sensing signals are collected through the Arduino-based embedded controller and processed using a PID-assisted feedback strategy to achieve real-time adaptive control. These experimental sensing configurations not only improve process stability and filament diameter uniformity but also demonstrate the sensor integration characteristics required for intelligent manufacturing and IoT-enabled recycling systems.

3. Results and Discussion

The development of the proposed intelligent mechatronic system encompassed component selection, frame fabrication, mechanical assembly, circuit design, and the creation of a mobile APP for system monitoring and control. The silk reeling machine was built according to precise dimensional schematics, integrating key subsystems such as the heater, feeder, and winder on a robust aluminum frame to ensure stability and thermal endurance. The assembly emphasized accurate alignment among the extrusion nozzle, screw, and winding unit to maintain uniform filament diameter and smooth extrusion. Each subsystem—including the heating, feeding, winding, and temperature display modules—was designed with standardized interfaces for modular replacement and ease of maintenance. The electronic control architecture centers on an Arduino Pro Mini microcontroller, incorporating modules for LED 7-segment temperature and motor speed display, Bluetooth communication for wireless monitoring, and a motor driver for precise winder control. Sensor inputs for temperature, current, and rotational feedback enable closed-loop control through real-time processing. The physical implementation, as shown in Fig. 4, was optimized for compactness and thermal protection, with careful grounding and signal isolation to reduce electromagnetic interference and protect the microcontroller.

To improve sensing reliability and measurement stability, the sensor modules were calibrated prior to system testing under repeated operation conditions. The thermocouple sensors were calibrated against reference temperature measurements to minimize thermal reading deviations during extrusion heating, while the rotary encoder feedback was verified through repeated rotational speed measurements. Current sensing signals were additionally filtered through the embedded control circuit to reduce electrical noise generated by the motor-driving system. The integrated multisensor configuration enabled the synchronized monitoring of temperature variation, motor operation, filament extrusion behavior, and winding conditions, allowing the

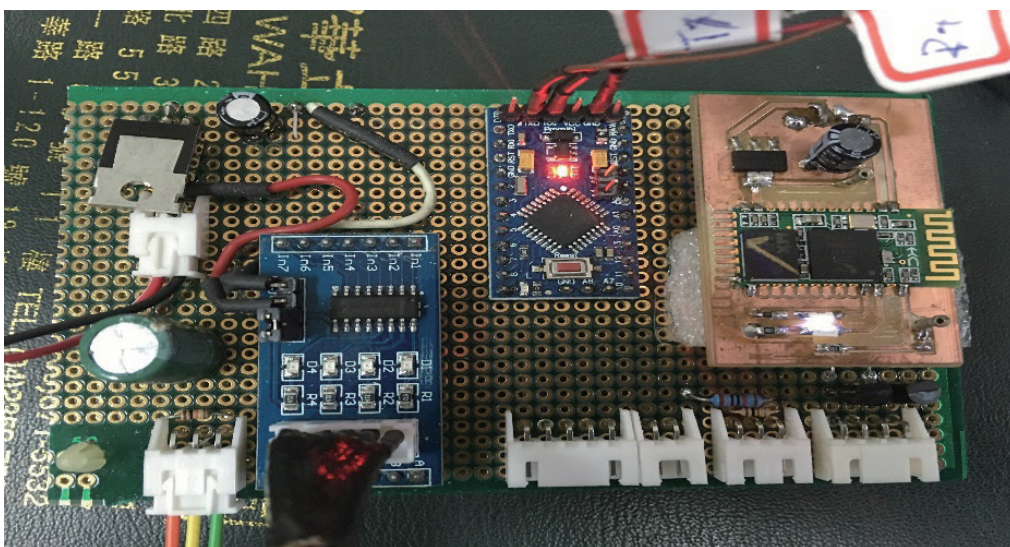


Fig. 4. (Color online) Physical implementation of the designed circuit, single-chip controller Arduino Mini Pro and Bluetooth sensor module.

PID-based controller to dynamically adjust heating power, motor speed, and cooling intensity during operation. This sensor-assisted control framework significantly improved filament diameter stability, operational safety, and process repeatability, demonstrating the practical value of integrating intelligent sensing technologies into sustainable manufacturing systems.

Bluetooth communication allows seamless interaction between the control board and an Android mobile APP for the remote supervision of extrusion temperature, feed rate, and winding tension, as well as real-time parameter adjustment. The app also supports data logging and diagnostics for trend analysis and predictive maintenance. Combining hardware integration, embedded control, and sensor-based monitoring, the system achieves high operational stability and consistent filament quality, demonstrating a practical step toward sustainable and intelligent manufacturing. The system testing phase included several key evaluations: temperature control testing, alarm response verification when the temperature exceeded preset limits, green energy performance measurement (power consumption analysis), and cross-device APP testing using Android smartphones from different manufacturers. These tests were conducted to validate the reliability, responsiveness, and adaptability of the intelligent control framework under various operational conditions.

The developed system demonstrates the capability of an intelligent terminal, integrating multiple functions including the heating, melting, filament extrusion, cooling, and winding of waste plastics such as ABS and PLA. Within the heating module, discarded plastic products are thermally decomposed and reprocessed into uniform filaments suitable for reuse in 3D printing or other manufacturing applications. The system continuously monitors key parameters such as temperature and motor speed, which are transmitted in real time via a Bluetooth sensor module to a remote monitoring interface. When abnormal conditions occur—such as the overheating of the melting chamber or excessive winding speed—the system automatically issues warning alerts through the mobile app to ensure operational safety and material quality. As shown in Fig. 5, the regenerated filament produced by the system exhibits a stable diameter of approximately 1.92 mm, indicating the precision of the extrusion and control mechanisms. This integration of sensing, control, and wireless communication technologies enables efficient process automation and supports the concept of intelligent recycling in sustainable manufacturing.

The handheld smart device APP was designed and implemented as the primary HMI or real-time monitoring and intelligent control of the filament recycling system. Developed on the Android platform, the APP integrates key functional modules including Bluetooth communication, timing control, safety warnings, and real-time data visualization. Through its Bluetooth module, the app establishes a stable wireless connection with the Arduino-based controller. This enables the bidirectional transmission of operational parameters such as extrusion temperature, motor speed, and winding torque. The timing function allows users to schedule or automate heating and extrusion cycles, while the warning module provides immediate alerts for abnormal sensor readings—such as overheating, motor overload, or cooling failure—thus ensuring operational safety and reliability. The real-time message interface continuously updates performance data and system status, allowing users to monitor variations in temperature, filament length, and winding speed throughout the extrusion process.

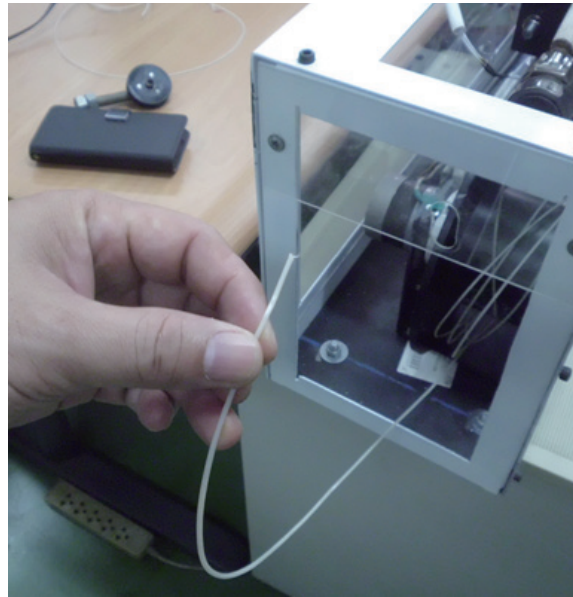


Fig. 5. (Color online) The regenerated filament produced has a diameter of 1.92 mm.

In the current implementation, the mobile monitoring platform was primarily developed for Android-based devices because of their flexibility in Bluetooth communication integration and ease of rapid system prototyping. Although the proposed wireless monitoring framework demonstrated stable real-time communication and control performance within laboratory-scale operating conditions, Bluetooth-based transmission may be limited by the communication range and scalability in larger industrial environments. In addition, cross-platform compatibility with iOS devices and desktop-based supervisory systems has not yet been fully implemented in the present study. To improve system flexibility and industrial applicability, future work will focus on developing cross-platform monitoring interfaces compatible with Android, iOS, and desktop operating systems. Furthermore, the current Bluetooth communication architecture will be extended toward cloud-connected industrial IoT platforms using Wi-Fi, message queuing telemetry transport (MQTT) protocols, and remote database integration. This extension will enable long-distance monitoring, cloud data storage, predictive maintenance analysis, and multidevice coordination. These future developments are expected to significantly enhance the scalability, interoperability, and smart manufacturing capability of the proposed intelligent recycling system.

To validate system performance, a comprehensive series of experiments was conducted, including temperature control tests, safety verification during over-temperature conditions, green efficiency (power consumption) measurements, and multibrand Android compatibility testing using devices from Samsung, Huawei, and ASUS. The results confirmed that the system achieved stable wireless communication, rapid response to remote commands, and consistent control performance across all tested platforms. Furthermore, the power consumption analysis demonstrated the system's high energy efficiency, consistent with the goals of sustainable and intelligent manufacturing. In addition to software-based control, the hardware system

incorporates several interactive components, such as the main power switch, a forced emergency power cut-off button, and a rotary dial for adjusting the heating rate and motor speed. These allow both manual operation and synchronized remote control through the mobile APP. The HMI intelligently manages the system's power switch, plastic melting temperature, and winding speed through real-time sensor feedback, dynamically adjusting parameters to maintain stable extrusion conditions. The control panel and display interface respectively present: (A) filament length, (B) current operating temperature, (C) motor rotation speed, and (D) maximum allowable temperature.

As illustrated in Figs. 5 and 6, the system's integration of Bluetooth-based communication and sensor feedback enables seamless remote monitoring and control via smartphones or other intelligent handheld devices. Users can observe operational data in real time, adjust heating parameters, and fine-tune winding speed directly from the mobile interface. The system successfully converts waste plastics such as ABS and PLA into reusable 3D printing filaments with a stable diameter of approximately 1.92 mm, demonstrating not only precision in control but also environmental and economic benefits. In the present study, we primarily focused on the development of an intelligent sensing-assisted recycling and extrusion platform, emphasizing process stability, real-time monitoring capability, and energy-efficient filament production. The stable filament diameter obtained during the extrusion experiments indicates effective thermal and mechanical process regulation under the proposed sensor-based control framework. However, we acknowledge that the comprehensive characterization of the recycled filament materials—including tensile strength, elasticity, brittleness, thermal stability, and long-term printability—remains an important topic for further investigation. In particular, the mechanical and thermal properties of recycled ABS and PLA filaments may vary depending on recycling history, thermal degradation, material contamination, and extrusion conditions. Therefore, future work will include systematic material characterization using mechanical testing, thermal analysis, and microstructural evaluation, together with direct comparisons against commercial

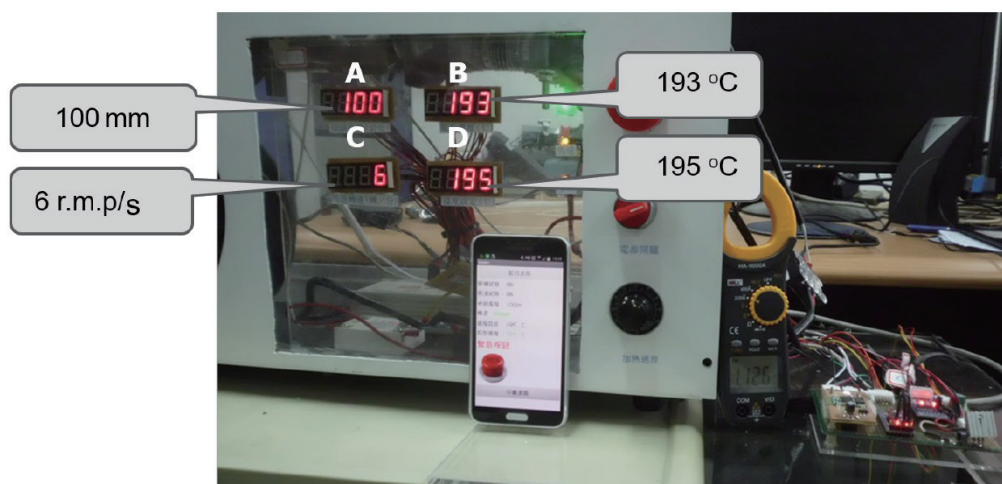


Fig. 6. (Color online) Intelligent power control switch, waste plastic melting temperature regulation, and winding speed control.

filament standards. These additional investigations will help establish quantitative relationships between sensor-monitored process parameters and the resulting material properties, thereby further strengthening the scientific and industrial significance of the proposed intelligent recycling system.

This IoT-enabled intelligent mechatronic architecture combines sensor-assisted control, real-time monitoring, and low-power operation to realize an adaptive, energy-efficient recycling process. It enhances production stability, user interactivity, and operational safety, providing a practical and sustainable solution for next-generation smart manufacturing systems. Although the developed system was designed primarily as a compact micro-reeling platform for laboratory-scale validation and decentralized recycling applications, the experimental results demonstrate the feasibility of extending the proposed architecture toward larger-scale manufacturing environments. The modular extrusion structure, distributed sensing framework, and closed-loop control strategy provide a scalable foundation for future industrial implementation. For higher-throughput APPs, the system architecture can be expanded through the integration of larger extrusion mechanisms, continuous automated feeding systems, multizone thermal control, and reinforced winding modules to support long-duration continuous operation. Furthermore, the incorporation of real-time sensor monitoring and IoT-assisted supervisory control offers the potential to improve operational stability, fault detection capability, and process synchronization under industrial production conditions. These characteristics indicate that the proposed intelligent recycling system exhibits promising scalability for future smart manufacturing and circular economy APPs.

The results demonstrated consistent message display, smooth data synchronization, and accurate execution of control commands across all devices, confirming the robustness of the communication protocol and user interface design. Furthermore, the integration of real-time sensing feedback into the APP allows operators to fine-tune extrusion parameters dynamically, optimizing filament quality and minimizing material waste. This user-oriented sensing interface not only enhances system intelligence and operational convenience but also supports sustainable manufacturing practices through efficient process supervision and energy-saving control strategies. The primary contribution of the present study lies in the integration of intelligent sensing, embedded control, wireless monitoring, and sustainable filament recycling into a unified mechatronic manufacturing platform. Although the current work mainly emphasizes practical system implementation and experimental validation, the developed sensing and control framework also establishes a foundation for future theoretical and analytical investigations. In future studies, more rigorous theoretical modeling will be introduced to analyze the coupled thermal–mechanical–rheological behaviors occurring during plastic melting, extrusion, cooling, and winding processes. Numerical simulations and data-driven modeling approaches may further be employed to investigate nonlinear heat transfer, extrusion dynamics, filament diameter evolution, and energy-consumption optimization under varying material conditions.

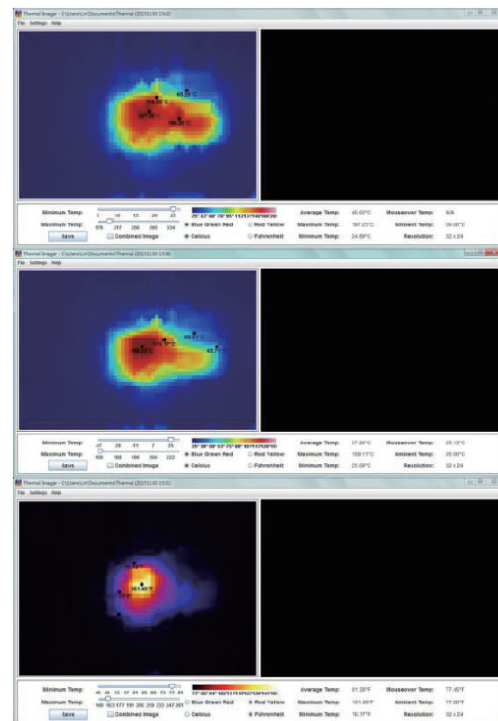
To improve measurement reliability and control consistency, repeated experimental operations and sensor calibration procedures were performed prior to system evaluation. The temperature sensing modules were calibrated against reference temperature measurements, while repeated rotational and electrical measurements were conducted to verify the stability of

motor-speed and power-monitoring signals. Under stable operating conditions, the sensing and control responses exhibited only minor fluctuations, indicating acceptable repeatability for laboratory-scale filament production. Uncertainties associated with sensor noise, thermal fluctuations, material feeding irregularities, and nonlinear rheological behaviors of different recycled plastics may still affect extrusion stability and control accuracy during long-duration operation. Although the PID-based control strategy demonstrated satisfactory performance for the ABS and PLA materials investigated in this study, more complex nonlinear material behaviors may require advanced adaptive control approaches. Therefore, future work will include investigations on fuzzy logic control, adaptive parameter tuning, and AI-assisted predictive control algorithms to improve system robustness and process adaptability under diverse material and industrial operation conditions.

In addition, sensor-derived operational data can support the development of predictive models and intelligent adaptive control algorithms for improving process stability and manufacturing efficiency. These future extensions are expected to strengthen the scientific depth and academic impact of the proposed intelligent recycling system while further advancing sensor-assisted smart manufacturing technologies. The assessment of green energy efficiency was conducted through precise electrical and thermal measurements. A clamp-type ammeter was employed to measure the current consumption of the system during operation, while an infrared thermal imager was used to detect and visualize the heat distribution across key



(a)



(b)

Fig. 7. (Color online) (a) Performance (power consumption) measurement and (b) heat source distribution map.

Table 1

Electrical operating conditions and power consumption analysis of the intelligent filament recycling system during heating and extrusion processes.

Hot machine	Operation
Voltage: 110 V	Voltage: 110 V
Current: 1.35 A	Current: 1.37 A
Time: 16 min	Time: 5 min to produce 1 m of recycled filament (extrusion speed = 20 cm/min)
Power consumption: 39.6 Wh	Power consumption: 2.5583 Wh

components, as illustrated in Fig. 7. The energy consumption analysis revealed that the proposed intelligent filament recycling system operates with remarkably low power requirements. The mechanical and thermal subsystems together consume only 0.41635 kWh of electricity to produce 1 kg of 3D printing filament (approximately 30 m in length). Here, “NT\$” refers to New Taiwan Dollars, the local currency used in Taiwan, and the electricity price of NT\$5 per kWh corresponds to the approximate industrial/commercial electricity tariff applied in this study for estimating operational energy costs. At a local electricity rate of NT\$5 per kWh, the total energy cost amounts to merely NT\$2.08, as summarized in Table 1.

To improve measurement reliability, the electrical measurements were conducted using a calibrated clamp-type ammeter under repeated operating conditions. Multiple experimental runs were performed, and the measured power consumption values exhibited only minor fluctuations, with an estimated variation of less than $\pm 3\%$ under stable extrusion conditions. In addition, the temperature sensing modules used for thermal monitoring were calibrated against reference temperature readings prior to experimentation to reduce systematic measurement deviations. These calibration and repeated-measurement procedures help ensure the accuracy and repeatability of the reported energy consumption data. When including the cost of raw ABS polymer pellets of approximately NT\$50 per kg, the total production cost per kilogram of filament is around NT\$52.08. In contrast, commercial 3D printing filaments of equivalent specifications are typically priced at NT\$600 per kg, representing a cost reduction of more than 90% achieved through the developed system. Beyond its substantial economic advantage, the system’s low energy consumption highlights its environmental sustainability. By minimizing electricity usage and promoting the circular reuse of waste plastics, the system not only reduces operational costs but also contributes to carbon emission reduction and energy conservation.

From the perspective of life cycle assessment (LCA), the proposed recycling system also demonstrates strong potential for reducing the overall environmental burden associated with filament production. Compared with conventional commercial filament manufacturing, which typically involves virgin plastic synthesis, large-scale industrial extrusion, packaging, and long-distance transportation, the developed system shortens the material supply chain by directly reprocessing locally available waste plastics into reusable filaments. This localized recycling approach can effectively reduce embodied energy consumption, transportation-related emissions, and raw material demand. In addition, the measured low electricity consumption of only 0.41635 kWh per kilogram of filament indicates a reduced operational carbon footprint during the extrusion stage. Although a complete quantitative LCA and carbon footprint analysis

were beyond the scope of the present study, the integration of energy monitoring, waste plastic reutilization, and low-power operation provides a solid foundation for future cradle-to-grave environmental assessment and sustainability optimization. Furthermore, the integration of sensor-based energy monitoring and thermal control ensures stable operation and enables continuous optimization toward greener, more efficient filament production. This combination of economic feasibility and eco-efficiency underscores the system's potential as a practical and sustainable solution for next-generation smart manufacturing and recycling applications.

4. Conclusions

In this study, we successfully developed an intelligent mechatronic filament recycling system that integrates sensor-based monitoring, closed-loop control, and IoT-enabled remote operation. By combining mechanical precision, embedded control, and a mobile HMI, the system achieves automated processing of waste plastics such as ABS and PLA into high-quality 3D printing filaments with a stable diameter of approximately 1.92 mm. The integration of temperature, torque, and speed sensors enables real-time feedback control, ensuring consistent extrusion performance and uniform filament quality. Experimental results demonstrate that the system maintains excellent temperature regulation, rapid response to over-temperature events, and high energy efficiency, requiring only 0.416 kWh to produce one kilogram of 3D filament. The Android-based app provides real-time data visualization, warning notifications, and wireless control via Bluetooth, achieving reliable communication across multiple mobile devices. The addition of manual safety mechanisms, such as the forced power cut-off and rotary adjustment controls, further enhances operational safety and flexibility. Overall, the proposed system not only reduces production costs and material waste but also embodies the principles of sustainable and intelligent manufacturing. Through the integration of IoT communication, adaptive control algorithms, and energy-efficient design, smart recycling technologies have the potential to promote circular economy practices and enable the decentralized, user-friendly production of 3D printing materials. Nevertheless, several aspects still require further investigation before large-scale industrial implementation can be fully realized. Future work will focus on expanding the range of recyclable thermoplastic materials, including PET, HDPE, and mixed-plastic waste streams, to improve the versatility and applicability of the system. In addition, production scalability will be enhanced through the development of higher-capacity extrusion mechanisms, multizone thermal management, and continuous automated feeding and winding architectures suitable for industrial throughput requirements. Advanced intelligent control strategies, such as AI-assisted parameter optimization, predictive maintenance, and adaptive closed-loop extrusion control, will also be incorporated to further improve filament consistency, energy efficiency, and operational reliability. Furthermore, future versions of the system will integrate cloud-based monitoring, industrial IoT communication protocols, and remote diagnostic functions to support smart factory environments and Industry 4.0 manufacturing frameworks. Although Bluetooth communication provides a low-cost and convenient solution for laboratory-scale wireless monitoring and mobile-device integration, its communication range, network scalability, and

resistance to industrial electromagnetic interference may limit large-scale deployment in complex manufacturing environments. For this reason, future system development will consider the integration of more robust industrial communication technologies, such as Wi-Fi-based industrial IoT architectures, long-range, MQTT-enabled cloud communication, and industrial fieldbus protocols to improve scalability, communication reliability, and multidevice coordination capabilities. In addition, while the PID-based control strategy demonstrated stable performance for ABS and PLA filament extrusion, nonlinear thermal and rheological behaviors associated with different plastic materials may reduce control accuracy under highly dynamic operating conditions. Therefore, advanced intelligent control approaches, including fuzzy logic control, adaptive control, machine-learning-assisted parameter tuning, and predictive control algorithms, will be investigated in future studies to improve system adaptability and extrusion stability for diverse recycled plastic materials and industrial-scale operating conditions.

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