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Developing a Vision-Based Measurement System for Capacitor Winding Machines

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Abstract

The goal of this project is to develop an upgraded measurement system for capacitor winding machines used in high-performance capacitor manufacturing. Existing manufacturing processes usually require operators to manually inspect and adjust critical product parameters to maintain quality and process consistency. In the specific case of this high-performance capacitor manufacturing process, operators use a magnifying glass to measure the edge alignment between two continuously wound capacitor films, ensuring that the required film extension offset is maintained at 0.5 mm within a tolerance of ±0.2 mm during the winding process. This manual process is labor-intensive, requires extensive operator training, reduces manufacturing flexibility, and limits overall productivity. The objective of this project is to develop a system capable of measuring capacitor film extension with accuracy equal to or exceeding human vision inspection while providing real-time operator feedback, warning indicators, and optional automated motor-speed correction. Several sensing approaches were evaluated for the film extension measurement, including capacitive sensing, laser profiling, and machine vision. The proposed system integrates a Keyence VS-C500X vision sensor, because capacitive sensing and laser profiling were sensitive to material variation, noise, and increased signal processing requirements. The proposed system also includes a real-time control module and a human-machine interface (HMI) that facilitates real-time processing, system coordination, and operator interaction. Experimental results show that the system consistently achieved the required ±0.2 mm tolerance while enhancing usability and reducing operator workload.

Keywords
Vision inspection, capacitor winding, industrial automation, edge detection, human-machine interface

1. Introduction

As demand for high-performance film capacitors continues to increase in applications such as medical equipment, power electronics, and renewable energy systems, studies on film handling, capacitor fabrication, and performance evaluation have highlighted the importance of achieving statistical control in the manufacturing process to improve capacitor reliability, performance, and production yield (Feng et al., Tan and Wu 2022, Zhang et al. 2025). High-performance capacitor manufacturing requires precise control of capacitor film extension during the winding process to ensure electrical reliability and manufacturing consistency; therefore, manufacturers require improved automation and inspection systems capable of maintaining strict quality standards while reducing dependence on operator skill.

In the existing production environment at the specific manufacturing facility, operators manually inspect and adjust a critical capacitor film extension of approximately 0.5 mm using magnifying lenses and directed lighting as shown in Figure 1. This manual process depends heavily on operator experience, visual interpretation, and environmental conditions, resulting in long training periods, labor-intensive operation, inconsistent measurement repeatability, and limited production flexibility. Incorrect extension measurement can result in defects including end-spray lifting, inaccurate capacitance values, insulation failure, or catastrophic capacitor burnout (Valentine et al. 2019). Therefore, maintaining the extension within a tolerance of ±0.2 mm is critical for ensuring product reliability and long-term operational performance.

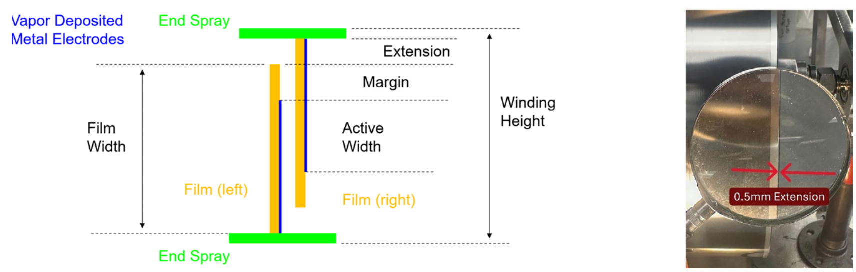

Figure 1. Schematic diagram (left) and amplified image (right) of capacitor extension

To address these challenges, this project investigates the development of an automated sensing and control system capable of measuring capacitor extension in real time while providing continuous operator feedback and optional closed-loop motor-speed control. The proposed system integrates industrial vision sensing, programmable logic control, and human-machine interface (HMI) technologies to improve manufacturing accuracy, repeatability, and operational efficiency.

1.1 Objectives

The primary objectives of this project are summarized as follows:

1. Develop a measurement system capable of detecting capacitor extension with precision equal to or greater than human visual inspection.
2. Create a real-time visual feedback system for continuous operator monitoring.
3. Develop an interactive HMI for system monitoring and operator control.
4. Implement an optional automated motor-speed response based on measured extension values.
5. Improve manufacturing efficiency while reducing operator training requirements and labor dependency.

2. Literature Review

The manufacturing of high-performance capacitors has received research attention due to growing demand in medical equipment, power electronics, renewable energy systems, electric vehicles, and so on (Zhang et al. 2023). Metallized film capacitors are widely used due to their low dielectric loss, self-healing capability, and high current-handling performance (Pan et al. 2026). Film capacitor manufacturing involves the precise processing and winding of thin polymer dielectric films, combined with metallized electrode layers to produce compact, high-reliability energy storage devices (Godec et al. 2013). The manufacturing process generally includes film extrusion, vacuum metallization, slitting, tension-controlled winding, flattening, drying, end-spray metallization, encapsulation, and electrical testing. During winding, precise control of film alignment, tension, and extension is critical because small dimensional variations can significantly affect capacitance, insulation performance, and long-term reliability (Chen et al. 2026).

Manufacturers of film capacitors are increasingly pursuing scalable manufacturing solutions capable of supporting increased production demand while maintaining strict quality standards. They continuously seek improved automation, dimensional inspection, thermal performance, and defect reduction throughout the manufacturing process. Recent research and industrial developments emphasize the integration of machine vision systems, laser measurement technologies, and advanced process monitoring techniques to improve process stability and product consistency (Azamfirei et al. 2023). These automated systems enable real-time inspection and feedback during high-speed winding and fabrication operations, helping reduce operator dependency and human error while improving measurement repeatability, manufacturing consistency, and overall production efficiency. In addition, advanced monitoring and control systems provide manufacturers with improved data collection and process optimization capabilities, supporting higher production throughput, reduced scrap rates, and improved long-term reliability of high-performance film capacitor products (Zhang et al. 2021).

Given the requirement to measure a capacitor film extension of approximately 0.5 mm within a tolerance of ±0.2 mm, multiple sensing technologies were evaluated for suitability within a production environment. Improper extension measurement can result in poor electrical connection between the capacitor film and end spray, potentially causing out-of-spec capacitance values or catastrophic failure. Therefore, sensor technologies were evaluated according to accuracy, repeatability, environmental robustness, and integration capability.

2.1 Vision-Based Measurement Systems

Vision-based measurement systems are widely used in industrial inspection and web-handling applications for dimensional measurement and alignment control (Sioma 2023). These systems typically utilize cameras, telecentric lenses, and controlled illumination to ensure accurate measurement with reduced perspective distortion and lighting variation. Image-processing software such as OpenCV is commonly used for edge detection, dimensional analysis, and defect inspection. Commercial systems such as the Keyence VS-C500X integrate built-in processing software capable of performing accurate dimensional measurements with high spatial resolution.

Previous studies indicate that vision systems offer several advantages, including flexible software processing, high measurement precision, visual feedback capability, and lower hardware cost relative to industrial laser profilers. However, literature also identifies several limitations including sensitivity to vibration, dust, lighting conditions, and film transparency. In addition, image-processing systems often require frequent recalibration and may introduce computational delays at high production speeds (Ren et al. 2022). Although vision systems are theoretically capable of detecting dimensional variations smaller than 0.5 mm, maintaining consistent performance during long-duration production remains challenging due to environmental variability.

2.2 Laser Profiling Systems

Industrial laser profiling systems are extensively used for precision dimensional inspection and edge tracking in automated manufacturing systems. Commercially available systems such as the Keyence LJ-V7000, Baumer OXS200, and Micro-Epsilon scanCONTROL provide high-resolution profile measurements with integrated controllers and industrial communication interfaces.

Research demonstrates that laser profilers offer excellent measurement accuracy, repeatability, and robustness under varying material and lighting conditions (Meana et al. 2024). Their proven reliability in automated manufacturing environments makes them suitable for continuous web inspection and edge-position monitoring. Nevertheless, studies also report limitations including higher implementation cost, precise alignment requirements, and sensitivity to optical noise caused by reflective or transparent film materials (Lazarević et al. 2019). Certain capacitor film compositions additionally require extensive filtering and signal-processing techniques to achieve stable measurements, potentially increasing system complexity and reducing real-time responsiveness.

2.3 Capacitive Sensing Systems

Capacitive sensing methods represent another non-contact measurement technique commonly used in industrial monitoring applications. These systems determine displacement by measuring capacitance variation between the sensor and target material. Literature shows that capacitive sensors can achieve high sensitivity while maintaining relatively low computational requirements and simple signal conditioning (Sakthivelpathi et al. 2024).

Capacitive sensing is frequently applied in thickness measurement, proximity sensing, and precision positioning systems. However, previous studies identify several significant limitations, including sensitivity to humidity, temperature variation, contamination, and material dielectric properties (Abdollahi-Mamoudan et al. 2024, Rivadeneyra et al. 2016). In addition, surrounding air gaps may contribute additional capacitance effects that reduce measurement accuracy during extension monitoring. Limited spatial resolution for sharp edge detection also raises concerns regarding long-term repeatability and consistency during continuous manufacturing operation.

3. Methods

A tiered sensor evaluation process was conducted to determine the most suitable sensing technology for capacitor extension measurement. Based on the advantages and limitations identified during the literature review, two candidate systems were selected for Factory Acceptance Testing (FAT): the vision-based system and the laser profiling system. Representative capacitor samples were provided to vendors to evaluate their capability to accurately measure the specified extension.

The FAT results demonstrated that the vision-based system provided superior measurement resolution and improved integration capability through the use of the integrated software platform. In contrast, the laser profiling system required extensive signal filtering to reduce measurement noise and obtain stable data. This additional processing required external computing resources and introduced latency concerns that reduced real-time performance capability.

Following the FAT evaluation, a decision matrix was developed comparing both sensor technologies against the existing human-operated process. Criteria included measurement accuracy, repeatability, environmental sensitivity, ease of integration, cost, processing requirements, and long-term operational reliability.

3.1 Final System Design

The final system design consisted of four primary operational subsystems as shown in Figure 2:

1. Sensing
2. Signal Processing and Reading
3. Control
4. Operator Feedback

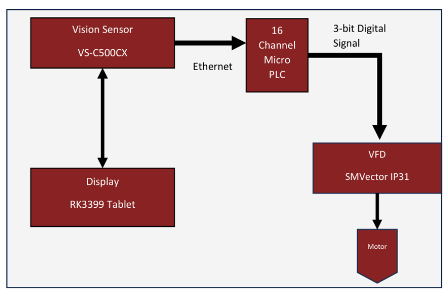

Figure 2. Block Diagram of System Design

3.1.1 Sensor System

The vision based Keyence VS-C500X with integrated VS-K software system was selected, which simplified the system architecture by combining sensing and signal processing into a single integrated platform capable of generating digital control outputs directly from measured extension values.

The vision sensor captures real-time visual data and processes extension measurements into digital control signals. The sensor additionally provides wireless operator feedback displaying measured extension values, extension magnitude, and current motor speed.

Sensor Specifications

- Real-time capacitor extension measurement
- 0–24 V digital output signals
- Integrated measurement and visualization software
- Ethernet communication capability

3.1.2 Control System

The control system consists of a PLC (Programmable Logic Controller), VFD (ariable Frequency Drive), and three-phase induction motor. The PLC receives sensor data through Ethernet communication and executes ladder logic to generate appropriate motor control signals. The VFD then adjusts motor speed according to the measured extension value.

Control Components

- Three-phase induction motor
- Maple Systems 16-channel Micro PLC
- IP31 Variable Frequency Drive (VFD)

3.1.3 Human-Machine Interface (HMI)

The HMI displays real-time extension measurements, live visual feedback, motor speed, and overall system status. The interface was developed using the Keyence VS-K software platform and refined using operator feedback from the production environment.

Features include:

- Real-time measurement visualization
- Manual sensor enable/disable controls
- Manual extension calibration input
- Raw and processed sensor data display
- Stack-light system integration for operator alerts

4. Data Collection

Data collection focused on evaluating sensor performance, measurement repeatability, lighting configuration effectiveness, and closed-loop motor response. Multiple testing phases were conducted including component testing, subsystem integration testing, full-system testing, and re-testing after system modifications.

Experimental measurements included:

- Extension measurement accuracy
- Signal stability
- Lighting condition evaluation
- Motor response timing
- Sensor repeatability
- HMI functionality
- PLC/VFD communication performance

Data were collected under varying lighting conditions, sensor mounting configurations, and film surface conditions to evaluate system robustness under realistic manufacturing conditions.

5. Results and Discussion

5.1 Numerical Results

Factory Acceptance Testing confirmed that the Keyence vision system achieved the required capacitor extension measurement tolerance of ±0.2 mm while maintaining stable repeatability under controlled operating conditions. The selected sensor demonstrated improved accuracy compared to manual operator inspection and provided consistent real-time measurements suitable for automated control integration. This validation established the baseline capability of the system for high-precision measurement; however, subsequent component testing revealed that performance stability was strongly dependent on mounting configuration, illumination conditions, and surface behavior of the capacitor film.

Component testing using the Keyence VS-C500X vision sensor confirmed that while the system was capable of accurately measuring capacitor film extension, measurement stability was significantly affected by surface ripple and reflection. These effects introduced noise into the captured images, leading to inconsistent edge detection and fluctuating extension values. The resulting variability had the potential to impact downstream control logic, causing unintended motor speed oscillations or overcorrection during the winding process. To address these issues, a rigid load-bearing arm mounting system was implemented to ensure consistent sensor positioning and eliminate manual repositioning as the capacitor diameter increased during winding. In addition, the camera was angled to optimize the capture of reflected light from the film surface rather than relying on direct edge detection through the transparent film layers. This adjustment significantly reduced ripple-induced distortion, improved edge consistency, and enhanced overall measurement reliability. In parallel, multiple lighting configurations were evaluated to reduce reflection-related noise, including dome and bar lighting systems with varying wavelengths and intensities. The white dome light ultimately produced the most stable and repeatable results by providing diffuse, uniform illumination, effectively minimizing specular reflections and ensuring consistent measurements for continuous operation.

The objective of the VFD-based control system was to allow a single operator to manage multiple winding machines without manually stopping the system or unwinding excess capacitor film. To achieve this, the measured capacitor extension from the vision sensor was processed through PLC ladder logic, which translated extension thresholds into discrete motor speed commands for the induction motor via the VFD. This enabled controlled deceleration and stopping as the extension approached preset limits. During initial testing, a communication mismatch was identified between the sensor outputs and the VFD inputs due to differences in signal type and interfacing requirements (PNP sensor outputs versus the VFD's expected sinking input configuration), as well as inconsistencies in voltage interpretation and timing, which resulted in unreliable motor response. To resolve this, the PLC was used as an intermediary interface to condition and map the sensor outputs into VFD-compatible control signals, improving system stability and response consistency. In addition, the use of a DIN rail and terminal blocks enhanced wiring organization and reduced setup complexity during testing. The ladder logic configuration for the VFD control input is presented in Table 1.

Table1. VFD Control Input from Sensor

Parameter	Value
Full Response Range	$0.40 \leq \Delta x \leq 0.6$
Control Output Range	$\Delta x \leq 0.2$
Sensor Steps	$\Delta x = 0.03$
VFD Speed Steps	$\Delta s = 14$ Hz
Preset #1	60 Hz $0.0 \leq \Delta x \leq 0.06$
Preset #2	46 Hz $0.06 \leq \Delta x \leq 0.1$
Preset #3	32 Hz $0.1 \leq \Delta x \leq 0.13$
Preset #4	18 Hz $0.13 \leq \Delta x \leq 0.16$
Preset #5	4 Hz $0.16 \leq \Delta x \leq 0.2$
Preset #6	0 Hz Stop $\Delta x \geq 0.2$

These inputs are read by the VFD through the Erasable Programmable Module (EPM), which interprets the discrete signals provided by the sensor. As shown in Table 2, the sensor outputs (Fout_#) are mapped to corresponding VFD preset commands, where each input combination results in a specific motor speed output (Preset #):

Table 2. Preset Frequency Table

Preset #	Fout_0	Fout_1	Fout_2
Preset 1 (60Hz)	1	0	0
Preset 2 (46Hz)	0	1	0
Preset 3 (32Hz)	0	0	1
Preset 4 (18Hz)	1	1	0
Preset 5 (4Hz)	1	0	1
Preset 6 (0Hz)	0	1	1

The initial testing results revealed a communication mismatch between the sensor outputs and the VFD inputs due to differences in signal type (PNP vs. sinking input configuration) and inconsistencies in voltage interpretation and timing. This resulted in unreliable motor behavior. To address these issues, the PLC was used as an intermediary interface to condition and translate the sensor outputs into VFD-compatible control signals, resulting in improved system stability and more consistent motor response. In addition, the use of a DIN rail and terminal blocks enhanced wiring organization and helped reduce setup complexity. The implemented ladder logic successfully translated measured extension values into discrete motor-speed commands through the VFD. Motor response results confirmed stable speed transitions across all preset operating ranges.

5.2 Graphical Results

The objective of the graphical interface development was to create an intuitive and easy-to-interpret HMI that enables a single operator to efficiently monitor and manage multiple machines. This was implemented using the Keyence VS-K software, which provides integrated tools for programming and customizing the visual interface. The prototype interface, shown in Figure 3, displays real-time measurement data and includes embedded calculations to determine the current capacitor extension length.

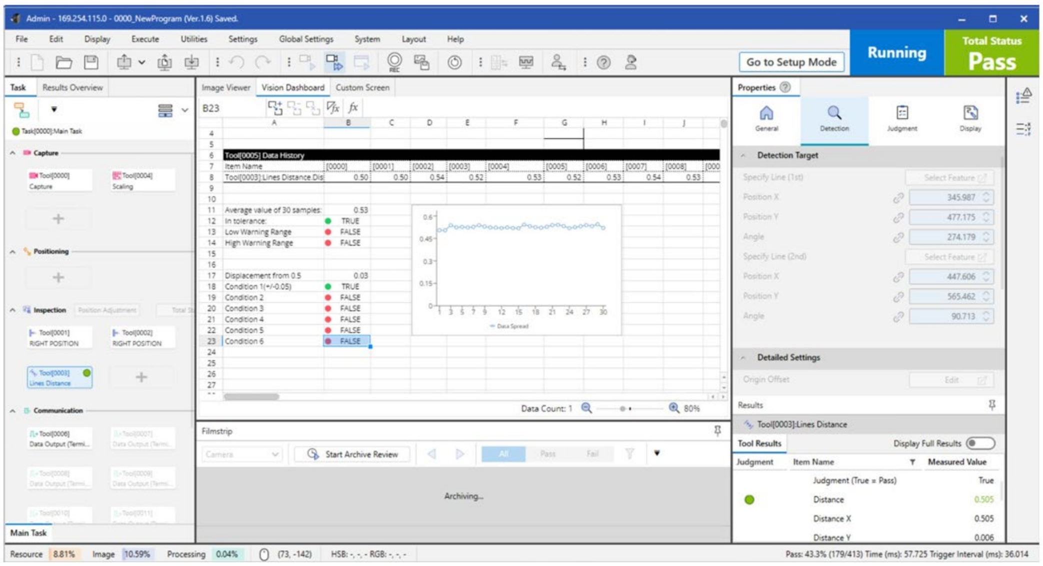

Figure 3. HMI Interface

To further improve usability, operator feedback was incorporated into the design. This feedback resulted in the integration of a stack light status system to provide immediate visual feedback: green indicates normal operation (passing), red indicates a fault condition (failing), and yellow signals that operator attention is required. The interface is shown in Figure 4.

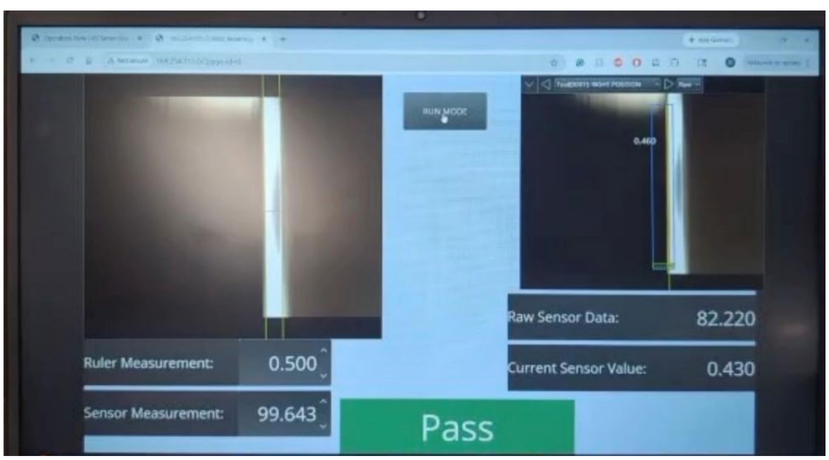

Figure 4. HMI Interface

The updated HMI includes clearer labeling to explicitly identify the machine being monitored, reducing operator confusion and improving usability on the production floor. Additional functionality was integrated to enhance operational control, including the ability to start and stop the sensor to prevent unintended system activation during manual adjustments, as well as a manual measurement input feature ("Ruler Measurement") that allows operators to directly enter measured extension values for calibration and improved accuracy when compensating for potential sensor deviations. Furthermore, the HMI displays both raw and processed sensor data, where the raw signal is represented as pixel counts and the processed output converts this value into the corresponding extension length in millimeters.

5.3 Proposed Improvements

Although the developed system successfully achieved the primary project objectives and, in several cases, exceeded expectations in measurement accuracy, several improvements are recommended for future implementation. One key area for improvement is the lighting mount design. The current system utilizes an adjustable arm rather than a fully rigid mounting structure. While this configuration proved beneficial during testing for optimizing lighting angles and positioning, it may introduce variability during long-term operation and require periodic manual adjustment, potentially affecting measurement consistency and increasing operator workload in a production environment.

Additional proposed improvements include the development of enhanced filtering algorithms, potentially incorporating AI-based image processing techniques, to better compensate for reflective capacitor film surfaces and improve measurement consistency. The integration of adaptive lighting control could further enhance measurement reliability under varying operating conditions by automatically adjusting illumination parameters in real time. In addition, expanding the HMI to include advanced data logging, trend analysis, and AI-assisted diagnostics would provide improved system monitoring, predictive maintenance capabilities, and long-term performance evaluation.

5.4 Validation

Validation testing confirmed that the developed system met or exceeded the accuracy of human visual inspection in measuring performance. Full-system integration verified successful coordination among sensing, data processing, control logic, and operator feedback modules, as indicated in Table 3. Repeated trials demonstrated stable and reliable operation under continuous production conditions, while reducing operator intervention and improving overall process consistency.

Table 3. Validation Testing Results

Measurement	Specification Requirement	Measured / Verified Result
Capacitor extension length	Target extension within ±0.2 mm tolerance	Sensor measured extension in real time
Sensor output signal	0–24 V digital output	Keyence output verified as digital ON/OFF signal
PLC/VFD input compatibility	VFD must recognize digital input states	VFD accepted PLC/sensor digital signals
Motor speed response	VFD must adjust speed based on preset logic	Motor speed changed according to selected preset
Operator feedback	System must display extension status visually	HMI displayed measured extension and system status
Full system operation	System must run automatically from measurement to motor response	Sensor, controller, and VFD operated together during full-system test

6. Conclusion

This research presented the design and implementation of an automated capacitor film extension measurement and control system for high-performance capacitor manufacturing applications. The developed system successfully achieved measurement accuracy equivalent to or exceeding human visual inspection while simultaneously providing real-time feedback and an interactive human–machine interface (HMI) for operator monitoring and control.

The integration of the Keyence machine vision system, programmable logic controller (PLC), variable frequency drive (VFD), and associated control interface demonstrated the feasibility of deploying real-time automated inspection and control within an industrial production environment. Experimental evaluation confirmed improved measurement repeatability, reduced reliance on operator judgment, and enhanced manufacturing process consistency and flexibility. Although further refinement is needed to optimize system response on extension levels and improve measurement and product consistency, the results demonstrate a scalable and industrially viable solution for Advanced Conversion that reduces operator training and labor requirements while improving process efficiency and consistency.

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