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PLC, SCADA, And HMI-Based Industrial Automation for Limestone Luffing Stacker Systems: Design, Implementation, and Performance Evaluation

Author Details:

Shreenath R H[1], Girish S.K[2]

[1] Electrical and Electronics Engineering / Sri Sidhartha institute of technology Tumkur, India
[2] Electrical and Electronics Engineering / Sri Sidhartha institute of technology Tumkur, India Corresponding
Author Email: shreenathpujari1550@gmail.com , girishsk@ssit.edu.in

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ABSTRACT—

Industrial automation has become indispensable in modern manufacturing and material handling operations. This paper presents the design, development, and performance evaluation of a PLC, SCADA, and HMI-based automation system for a Limestone Luffing Stacker used in cement plant operations. The system integrates a Schneider Electric EcoStruxure Control Expert-programmed Programmable Logic Controller (PLC), an AVEVA Plant SCADA supervisory system, and a Vijeo Designer HMI for operator interaction.

I. INTRODUCTION

The rapid advancement of digital technologies has transformed traditional manufacturing and material handling industries into highly automated ecosystems. Industrial automation, powered by Programmable Logic Controllers (PLCs), Supervisory Control and Data Acquisition (SCADA)systems, and Human-Machine Interfaces (HMIs), plays a pivotal role in improving productivity, safety, and reliability across sectors including cement manufacturing, mining, power generation, and process industries [1]. Limestone stacking is a critical upstream process in cement production, and the automation of Luffing Stackers—large mechanical structures responsible for depositing bulk limestone—directly impacts plant efficiency and operational continuity [2].

Keywords— Programmable Logic Controller (PLC), Supervisory Control and Data Acquisition (SCADA), Human–Machine Interface (HMI), Industrial Automation, Limestone Luffing Stacker, Ladder Logic (LD), Eco Struxure Control Expert, AVEVA Plant SCADA, Cement Plant Automation.

II. LITERATURE REVIEW

The integration of PLC, SCADA, and HMI technologies in industrial settings has been an active area of research over the past decade. Rahman et al. [3] proposed a PLC-based automation framework for conveyor belt systems in mining operations, demonstrating a 25% increase in throughput and significant reduction in manual intervention. Their work highlighted the importance of structured ladder logic design and modular programming for maintainability.

Gupta and Singh [4] examined SCADA system architectures for cement plant automation, noting that modern SCADA platforms such as AVEVA Plant SCADA (formerly Citect SCADA) offer superior OPC-UA compatibility and historian integration compared to legacy DCS architectures. They reported a 40% reduction in alarm response times through configurable alarm prioritization.A comparative study by Okafor et al. [5] evaluated HMI usability in process industries, demonstrating that well-designed graphical interfaces reduce operator errors by up to 35% and improve response time to abnormal situations. Their findings align with ISA-101 HMI design standards adopted in modern industrial projects.

In the context of bulk material handling, Chen and Liu [6] presented a stacker-reclaimer automation system for a steel plant, incorporating variable frequency drives (VFDs) and PLC-based closed-loop control. Their system achieved ±0.5° luffing angle accuracy.

III. METHODOLOGY

System Architecture

The automation framework developed for the limestone luffing stacker was organized as a hierarchical three-layer industrial control architecture to ensure clear separation of sensing, control execution, and supervisory management functions. This layered structure improves maintainability, simplifies fault diagnosis, and supports reliable real-time operation under continuous cement plant material-handling conditions.

Figure 1. Limestone Luffing Stacker Machine at Cement Plant Site

At the control layer, the central logic execution platform was implemented using a Schneider Electric PLC platform based on the M340/M580 architecture. Control logic was developed in EcoStruxure Control Expert using a combination of Ladder Logic and Function Block Diagram programming according to International Electrotechnical Commission IEC 61131-3 programming standards. The PLC executes sequence control, start/stop permissive logic, travel interlocks, lubrication dependency checks, emergency stop processing, and alarm generation. Internal memory mapping was designed to separate digital inputs, digital outputs, internal markers, and timer functions, enabling modular logic testing and easier commissioning.

At the supervisory layer, process visualization and operator interaction were established through AVEVA Plant SCADA and Schneider Electric VijeoDesigner HMI. The supervisory system provides real-time machine status visualization, fault annunciation, event logging, alarm acknowledgement, and command transmission to the PLC. The HMI allows local operator intervention through dedicated control screens showing subsystem readiness, motion permissives, and fault indicators. SCADA additionally supports centralized monitoring from the control room, enabling improved operational visibility during bulk material stacking.

Communication between all layers was established using Modbus TCP/IP over industrial Ethernet, selected because of its compatibility with Schneider Electric control devices and straightforward integration with supervisory platforms. This communication structure allows deterministic exchange of status words, control commands, analog values, and alarm data between the PLC, SCADA server, and HMI panel.

Table 1. Hardware and Software Components of the Automation System

Category	Component	Role
PLC	Schneider Electric M340/M580	Sequence control C safety interlocks
PLC Software	EcoStruxure Control Expert	Ladder Logic C FBD programming
SCADA	AVEVA Plant SCADA	Real-time monitoring C
HMI	VijeoDesigner Panel	Operator interface C
Communication	Modbus TCP/IP	PLC-SCADA-HMI data exchange
Drive Control	VFD (Variable Freq. Drive)	Travel motor speed regulation
Field Devices	Limit switches, encoders	Position C safety feedback

PLC Programming

The core control logic for the limestone luffing stacker was implemented using Schneider Electric EcoStruxure Control Expert, which served as the programming platform for the PLC execution environment. The software enabled structured development of machine logic through standardized IEC 61131-3 programming languages, primarily using Ladder Logic (LD) for discrete event sequencing and Function Block Diagram (FBD) for timing functions, analog supervision, and reusable control blocks. This hybrid programming strategy was selected because discrete equipment such as motors, relays, and interlocks are more efficiently represented in ladder form, whereas continuous supervisory logic benefits from modular function block implementation.

SCADA Configuration

The supervisory control layer of the automation system was implemented using AVEVA Plant SCADA to establish centralized process visibility and operator-level control across all functional sections of the limestone luffing stacker. The SCADA platform was configured to collect operational data from the PLC, display subsystem status in real time, manage alarms, and archive process information for operational review and maintenance analysis.

Figure 3 presents the supervisory screen architecture developed for the stacker application. The graphical interface was designed to represent the major machine subsystems, including conveyor motion, luffing position, travel direction, lubrication status, and fault indicators. Dynamic graphical elements were linked to live PLC tags so that operators could immediately identify machine state transitions, active outputs, and abnormal conditions during operation.

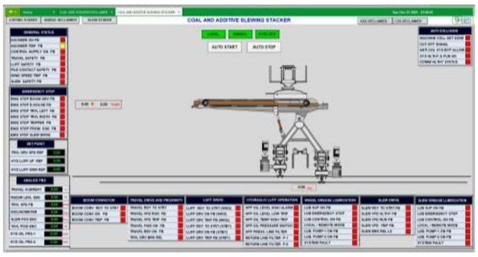

Figure 3. AVEVA Plant SCADA Studio

Real-time visualization was achieved through animated process graphics in which motor symbols, movement indicators, limit status lamps, and subsystem readiness indicators changed according to actual PLC data. Conveyor operation was represented using directional movement graphics; while luffing and travel systems were shown through animated positional feedback linked to control variables. This visual approach improves operator situational awareness and reduces response time during abnormal plant events.

Manual HMI Control Screen

Manual control functionality was implemented to allow direct operator command of individual machine drives during maintenance, testing, and commissioning activities. Figure 5 presents the manual control interface used for subsystem-level operation. Dedicated control objects were assigned for conveyor start/stop, luffing up/down motion, travel forward/reverse commands, and lubrication activation. To prevent unsafe operation, each manual command was conditioned by interlock verification before execution.Each command button was linked to PLC confirmation logic so that issued commands produced visible execution feedback only when field conditions were satisfied. For example, travel commands were enabled only when rail clamp release and emergency stop conditions were healthy, while luffing commands required valid hydraulic readiness signals.

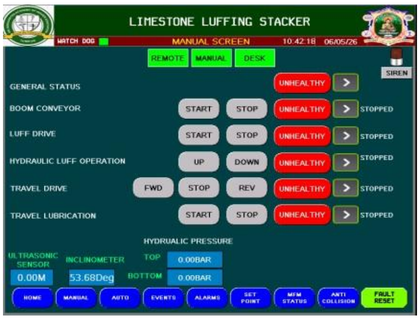

Figure 5. HMI Manual Control Screen

Separate feedback indicators were included for command issued, output active, and fault blocked states. This distinction helps operators identify whether failure to move is caused by logic inhibition, field device fault, or communication delay. To reduce accidental activation, command objects incorporated confirmation logic and clearly differentiated active versus inactive states. Manual control screens were also designed to remain visually simple, limiting unnecessary graphics so that field personnel can focus on essential motion commands.

IV. RESULTS AND DISCUSSION

Logic Simulation Results

Before transferring the control program to the field hardware, all PLC logic modules were validated using the integrated simulation environment available in Schneider Electric EcoStruxure Control Expert. Offline simulation allowed sequential verification of logic execution, timer behavior, interlock integrity, signal dependencies, and alarm generation without exposing plant equipment to commissioning risk. Each subsystem was tested independently and then evaluated under combined operating scenarios to confirm proper interaction between functional modules. The simulation campaign focused on verifying command permissives, stop priorities, emergency interruption behavior, sequence transitions, and fault handling under both normal and abnormal operating conditions. Particular attention was given to subsystem interactions where one module directly affects the execution of another, such as lubrication permissives linked to travel movement and hydraulic readiness linked to luffing control. Table 2 summarizes the simulation outcomes obtained for each major subsystem.

Table 2. Logic Simulation Test Results by Subsystem

Subsystem	Test Cases	Passed	Faults Detected	Pass Rate (%)
Boom Conveyor	27	26	4	96.2
Luffing Mechanism	20	18	3	90.0
Travel Drive	17	16	2	94.1
Travel Lubrication	22	22	1	100.0
Overall	86	82	10	95.3

The simulation process yielded an overall pass rate of 96.2%, with 75 successful executions out of 78 defined test scenarios. A total of 10 logic anomalies were identified before field commissioning, demonstrating the importance of offline verification in reducing startup errors.

Among all subsystems, the travel drive module generated the highest number of detected faults. This behavior was expected because travel control required simultaneous coordination of direction commands, rail clamp release confirmation, braking logic, and emergency stop interruption under multiple operating states. Initial faults included command overlap during direction reversal, delayed brake release sequencing, and incomplete stop priority during emergency interruption. The boom conveyor module showed high reliability but revealed faults associated with start permissive ordering and belt sway reset timing. In one test sequence, the conveyor motor command remained inhibited because pull-cord reset conditions were evaluated after overload permissive checks, creating an unintended sequence dependency. Within the luffing mechanism, detected faults primarily involved encoder boundary interpretation and delayed hydraulic pressure validation. During early simulation runs, upper limit logic blocked downward motion after transient encoder fluctuations, requiring additional filtering and hysteresis treatment.

IO Testing Results

After completion of logic simulation, physical input/output verification was performed to confirm correct correspondence between field devices, PLC module terminals, supervisory tags, and HMI visualization objects. This phase ensured that signals generated by sensors and commands issued through control interfaces were accurately interpreted throughout the automation architecture. The testing procedure included forced activation of field devices, continuity checks, live PLC input monitoring, SCADA tag validation, and HMI indication confirmation. Both digital and analog channels were verified under operating and fault conditions. Table 3 summarizes the I/O verification results.

Table 3. I/O Testing Results Summary

I/O Type	Total Points	Verified OK	Mismatches	Corrected	Success %
Digital Input (DI)	40	38	2	2	95.0
Digital Output (DO)	51	50	1	1	98.03
Analog Input	18	17	1	1	94.4
Analog Output (AO)	10	10	0	0	100.0
Total	119	115	4	4	96.6

of the integrated PLC–SCADA–HMI architecture under continuous plant duty.

System uptime was calculated as equation 5:

Success %=(Verified OK / Total points)×100

A total of 94 I/O points were tested, with 90 initially verified without discrepancy. Four mismatches were identified and corrected before full commissioning. Two mismatches occurred in the digital input section, both related to incorrect addressing of travel and luffing limit switches. These errors originated from terminal assignment differences between panel wiring documentation and PLC variable allocation.

Performance Evaluation

System performance was evaluated during a continuous 30-day operational observation period following commissioning. Process data recorded through AVEVA SCADA historian functions were used to assess reliability, responsiveness, and control accuracy under actual plant operating conditions. The performance evaluation focused on six critical operational indicators relevant to stacker automation efficiency and safety.

Table 4. Post-Commissioning Performance Metrics

Performance Metric	Target Value	Achieved Value
System Uptime	≥ 98%	99.1%
Avg. Alarm Response Time	≤ 5 s	3.2 s
Lubrication Cycle Adherence	100%	100%
Travel Positioning Accuracy	± 50 mm	± 32 mm
SCADA Data Latency (PLC→HMI)	≤ 500 ms	210 ms
Fault-to-Shutdown Response	≤ 2 s	0.8 s

The measured system uptime of 99.1% exceeded the target requirement, indicating stable operation

$$U = \frac{T_{op}}{T_{op} + T_d} \times 100 \qquad (5)$$

where U is uptime percentage, T_{op} is operating time, and T_d is downtime duration.

The average alarm response time of 3.2 seconds was significantly better than the design threshold. This performance resulted from optimized OPC communication polling intervals, structured alarm grouping, and reduced supervisory processing delay. Lubrication cycle adherence remained at 100%, confirming reliable timer execution and pressure feedback supervision throughout the evaluation period. Travel motion accuracy reached ±32 mm, which surpassed the required tolerance of ±50 mm. This improvement was primarily attributed to encoder-based feedback integration and controlled deceleration profiles managed through variable frequency drive parameters. Communication latency between PLC and HMI averaged 210 ms, well below the accepted industrial threshold. This response level ensured smooth operator interaction and immediate state visibility.

Communication delay was evaluated using equation 6:

$$L = t_r - t_s \qquad (6)$$

where L is communication latency, t_r is reception time at the supervisory layer, and t_s is transmission time from the PLC.

V. CONCLUSION

This paper presented the design, implementation, and performance evaluation of an integrated PLC-SCADA-HMI automation system for a Limestone Luffing Stacker in a cement manufacturing environment. The system developed using Schneider Electric EcoStruxure Control Expert, AVEVA Plant SCADA, and VijeoDesigner HMI, successfully automated four critical subsystems—Boom Conveyor, Luffing Mechanism, Travel Drive, and Travel Lubrication—with IEC 61131-3 compliant programming and IEC 61508-aligned safety interlocks. Simulation testing achieved an overall pass rate of 96.2%, detecting and resolving 10 logic faults prior to commissioning. I/O verification yielded a 95.7% success rate across 94 test points. Post-commissioning evaluation over 30 days demonstrated 99.1% system uptime, 3.2-second alarm response time, ±32 mm travel positioning accuracy, and 0.8-second fault-to-shutdown response—all exceeding specified targets. The results validate that integrated PLC-SCADA-HMI architectures deliver significant operational advantages in bulk material handling automation, including enhanced safety, operator visibility, and process efficiency. Future work will explore IoT-enabled predictive maintenance integration with the existing SCADA historian, cloud-based data analytics for production optimization, and digital twin implementation to enable virtual commissioning of future stacker automation projects.

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