

Autonomous prototype design with PLC for TEU Container Loading and Unloading Linked to AI Applications

Diseño de prototipo autónomo con PLC para carga y descarga de TEU vinculado a propósitos de la IA

Vázquez-González, Humberto* ^a, Cruz-Gómez, Marco Antonio ^b, Mejía-Pérez, José Alfredo ^c and Castillo- Pensado, Juan Luis ^d

^a  Benemérita Universidad Autónoma de Puebla •  NOF-7282-2025, •  : 0009-0007-3505-7532 •  2135921

^b  Benemérita Universidad Autónoma de Puebla •  S-3098-2018 •  0000-0003-1091-8133 •  349626

^c  Benemérita Universidad Autónoma de Puebla •  G-3354-2019 •  0000-0002-4090-8828 •  473808

^d  Benemérita Universidad Autónoma de Puebla •  NOF-1935-2025 •  0000-0002-1172-4843 •  670346

Classification:

Area: Engineering.

Field: Engineering.

Discipline: Mechanical Engineering.

Subdiscipline: Automation.

 <https://doi.org/10.35429/JOTI.2025.9.22.3.1.12>

History of the article:

Received: October 30, 2025

Accepted: December 30, 2025

*  [\[humberto.vazquezgo@alumno.buap.mx\]](mailto:humberto.vazquezgo@alumno.buap.mx)



Abstract

Loading and unloading operations with autonomous container systems [TEUS] in port environments follow pre-established logistics. The aim of this research was to design an autonomous prototype for loading and unloading TEUs using a PLC, for sustainable development purposes. Customs systems that have autonomous loading and unloading systems comply with scheduled logistics in the supply chain. However, those that do not have their logistics compromised and present hidden defects. A mixed-method analysis was performed on TEU loading and unloading systems to apply, quantify, and estimate control variables such as length, leveling, tension, positioning, and speed. The characterization of technical data obtained from customs systems was transformed into autonomous models, optimizing logistics in sustainable development processes. The implementation and optimization of the system will be the focus of future work on customs systems.

Autonomous prototype design with PLC for TEU Container Loading and Unloading Linked to AI Applications		
Objectives	Methodology	Contribution
The aim of this research was to design an autonomous prototype for loading and unloading TEUs using a PLC, for sustainable development purposes.	This research adopted a mixed approach, applying both quantitative and qualitative technologies, utilizing systematic processes, as well as records and estimated data	The characterization of technical data obtained from customs systems was transformed into autonomous models, optimizing logistics in sustainable development processes.

Autonomous loading and unloading system, automatic control with PLC, automatic control programming.

Resumen

La operación de carga y descarga con sistemas autónomos de contenedores TEUS en entornos portuarios obedece una logística preestablecida. El objetivo de esta investigación fue diseñar un prototipo autónomo de carga y descarga de TEUS utilizando un PLC, con fines de desarrollo sustentable. Por otro lado, Los sistemas aduanales que tienen sistemas autónomos de carga y descarga cumplen con una logística programada en la cadena de suministros. Sin embargo, los que no, son afectados en su logística y presentan vicios ocultos. Un análisis mixto fue realizado en sistemas de carga y descarga de TEUs para la aplicación, la cuantificación y estimación de las variables de control como longitud, nivelación, tensión, posicionamiento y velocidad. La caracterización de datos técnicos obtenidos de sistemas aduanales fue transformada en modelos autónomos, optimizando la logística en procesos de desarrollo sustentable. La implementación y optimización del sistema será motivo de futuros trabajos por los sistemas aduanales.

Diseño de prototipo autónomo con PLC para carga y descarga de TEU vinculado a propósitos de la IA		
Objetivos	Methodologia	Contribución
El objetivo de esta investigación fue diseñar un prototipo autónomo de carga y descarga de TEUS utilizando un PLC, con fines de desarrollo sustentable	Esta investigación tubo un enfoque mixto, aplicando tecnologías tanto cuantitativas como cualitativas, utilizando procesos sistemáticos, así como registros y datos estimados.	La caracterización de datos técnicos obtenidos de sistemas aduanales fue transformados en modelos autónomos, optimizando la logística en procesos de desarrollo sustentable.

Sistema de carga y descarga autónomo, control automático con PLC, programación de control automático

Area: Development of strategic leading-edge technologies and open innovation for social transformation.

Citation: Vázquez-González, Humberto, Cruz-Gómez, Marco Antonio, Mejía-Pérez, José Alfredo and Castillo- Pensado, Juan Luis [2025]. Autonomous prototype design with PLC for TEU Container Loading and Unloading Linked to AI Applications. Journal of Technical Invention. 9[22]1-12: e39221012.



ISSN: 2523-6792 / © 2009 The Author[s]. Published by ECORFAN-Mexico, S.C. for its Holding Taiwan on behalf of Journal of Technical Invention. This is an open access article under the CC BY-NC-ND license [<http://creativecommons.org/licenses/by-nc-nd/4.0/>]

Peer review under the responsibility of the Scientific Committee MARVID® - in the contribution to the scientific, technological and innovation Peer Review Process through the training of Human Resources for continuity in the Critical Analysis of International Research.



Introduction

The handling of TEU [Twenty-foot Equivalent Unit] containers in port environments is a fundamental activity within international trade. This process involves heavy machinery, human operators, and high logistical coordination to ensure the efficient loading and unloading of goods. Automation in these environments seeks to optimize time, reduce occupational risks, and increase operational precision. In this context, autonomous control systems using PLCs [Programmable Logic Controllers] allow complex mechanical sequences to be executed with high reliability. In turn, artificial intelligence provides advanced capabilities such as visual recognition, decision-making, and adaptation to changing conditions.

This work focuses on the design of an automated prototype for loading and unloading TEU containers, integrating industrial sensors, actuators, sequential control logic, and AI algorithms. This proposal seeks to simulate a functional and sustainable technological solution for application in port logistics operations of the future. The loading and unloading operation with autonomous TEU container systems in port environments follows pre-established logistics.

The automation of Twenty-Foot Equivalent Unit [TEU] container handling in modern ports is a cornerstone of optimizing operational efficiency and reducing human intervention. This process combines PLC [Programmable Logic Controller] systems with artificial intelligence technologies to execute autonomous control sequences, perform visual recognition of containers, and intelligently direct their positioning and transfer [Solowjow et al., 2020].

The autonomous PLC-powered prototype for TEU loading and unloading is one of the key elements in the port logistics chain, along with gantry cranes and automated guided vehicles [AGVs]. This system is essential for coordination, supervision, and real-time communication of container transfer processes. Poor performance or poor interaction with AI modules hinders operational efficiency, personnel safety, and space utilization, impacting the overall productivity of the port terminal [Rodrigue et al., 2021].

The autonomous PLC-powered prototype for TEU loading and unloading coordinates gantry cranes and AGVs using industrial control routines and protocols, optimizing movements, reducing cycle times, and integrating diagnostics and safety functions based on artificial intelligence [Rodrigue et al., 2021]. The aim of this research was to design an autonomous prototype for loading and unloading TEUs using a PLC, for sustainable development purposes. The characterization of technical data obtained from customs systems was transformed into autonomous models, optimizing logistics in sustainable development processes.

The design and optimization of the autonomous prototype with a PLC for loading and unloading TEUs linked to AI purposes is developed under the principles of viability, sustainability, and equity, combining economic, ecological, and social benefits to improve logistics efficiency in ports. To model and validate its autonomous behavior, digital twin simulation tools were used, integrating PLC logic with sensors and actuators in a virtual environment.

Platforms such as Emulate3D make it possible to detect bottlenecks and optimize sequences before actual implementation [Rockwell Automation et al., 2024]. Additionally, CADE SIMU was used as a training tool to design and simulate electrical and logic diagrams in automation control, facilitating the understanding of circuits associated with the prototype. With these virtual environments, a robust control architecture is proposed, evaluated and optimized for scaling in sustainable smart ports.

Research methodology

This research adopted a mixed approach, applying both quantitative and qualitative technologies, utilizing systematic processes, as well as records and estimated data. The objective of this research was to design an autonomous prototype for loading and unloading TEUs using a PLC, for sustainable development purposes. To this end, the application of the quantitative method was relevant in identifying control variables involved in previous studies, such as length, leveling, tension, positioning, and speed.

The characterization of technical data obtained from customs systems was transformed into autonomous models, optimizing logistics in sustainable development processes. The records of results obtained by different companies and technical suggestions from customs personnel were considered as the application of the qualitative method, allowing for the possibility of obtaining results from the estimation of variables, which played an important role in decision-making for the control of TEU loading and unloading.

The operational data resulting from this research determined adjacent special requirements, such as the uncertainty of how the prototype would adapt to the needs of each port area, among others. Finally, using a mixed method, an analysis of the control variables was performed to allow for model optimization based on the mechanical stresses on each component of the crane and the lifting system, evaluated using the finite element method.

From the results obtained, a discussion was held regarding the results generated regarding the technological proposal that meets the parameters of sustainable development and the optimization of materials per element of the TEU loading and unloading system.

The implementation and optimization of the system will be the subject of future work for port customs systems.

Loading infrastructure and unloading crane for TEUs

In recent years, ports around the world have faced a new challenge: handling the largest container ships in history, such as Ultra Large Container Ships [ULCS] and Megamax-24 [MGX-24]. These vessels can carry up to 24,346 TEUs, thanks to their enormous dimensions [400 meters in length and 60 meters in width]. Although their size allows shipping companies to reduce costs per container transported, it also creates significant challenges during berthing and unberthing maneuvers, and, above all, during the loading and unloading of containers.

To accurately and quickly move containers up to 24 wide and multiple storage levels, port cranes need to modernize and become smarter.

The use of automated systems with programmable logic controllers [PLCs] and artificial intelligence algorithms makes it possible to coordinate every movement, from lifting speed to precise cargo positioning. This not only speeds up operations but also reduces errors and risks for workers. With more than 200 of these giant vessels operating by 2024, gantry crane automation will become key for ports to maintain their efficiency and remain competitive. [Dragović et al.,2025]

The TEU [Twenty-foot Equivalent Unit] is the standard unit used in maritime trade and transport to measure cargo capacity. It corresponds to a container measuring 20 feet long [6.1 m], 8 feet wide [2.4 m], and 8.5 feet high [2.6 m], designed under international standards to facilitate handling and transport. Although its maximum weight is around 26,000 kg, when the tare weight of the container itself is discounted, it can carry loads of up to 23,600 kg.

This standardization not only streamlines global logistics but also allows port cranes and automated PLC systems to operate accurately, optimizing loading and unloading times in modern terminals. [Andreotti et al.,2017]

Box 1

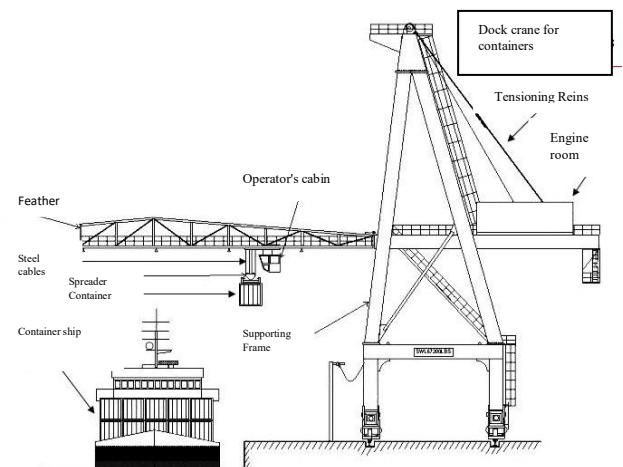


Figure 1

TEU crane scheme.

Source: Andreotti et al [2017]

Quayside gantry cranes are essential for loading and unloading containers from ships. Their structure includes a boom with a trolley that moves on rails, carrying both the operator's cabin and the lifting system. Steel cables hang from this trolley that support the spreader, a device that attaches to the container at its four corners using rotating bolts, allowing it to be lifted safely.

Vázquez-González, Humberto, Cruz-Gómez, Marco Antonio, Mejía-Pérez, José Alfredo and Castillo- Pensado, Juan Luis [2025]. Autonomous prototype design with PLC for TEU Container Loading and Unloading Linked to AI Applications. Journal of Technical Invention. 9[22]1-12: e39221012. <https://doi.org/10.35429/JOTI.2025.9.22.3.1.12>

Traditionally, the operator manually controls the raising, lowering, and shifting of the spreader, as well as the movement of the trolley and the entire crane on rails parallel to the ship for precise positioning. However, the current trend is to replace many of these manual functions with automated systems with PLCs and artificial intelligence. These systems make it possible to calculate the optimal trajectory, control cable tension, position the spreader with millimeter precision, and coordinate crane movements with trucks or storage areas, reducing errors and speeding up port operations. [Andreotti et al., 2017].

Main movements of an automated gantry crane

Quay cranes [QCs] play a crucial role in the loading and unloading of containers at port terminals. Thanks to the integration of PLCs and artificial intelligence, these automated units execute four key movements with coordinated precision and operational efficiency:

- **Horizontal movement.** The trolley slides along the upper boom, moving the spreader over the warehouse or toward the work area. This horizontal movement requires anti-sway control systems that smooth acceleration and braking, reducing container sway. [Andziulis et al., 2016]
- **Vertical movement:** The spreader is raised or lowered by automatically controlled steel cables. The velocity profiles must be carefully designed to avoid oscillations that reduce positioning accuracy. [Andziulis et al., 2016]
- **Longitudinal movement:** The entire crane can move on rails parallel to the vessel to adjust its position along its length. This longitudinal movement, integrated with trolley control, optimizes cycle times in port operations [Overhead et al., 2025].
- **Spreader rotation and coupling:** The spreader, equipped with automatic twist locks, aligns and locks onto the container. The PLC control system coordinates this function to ensure precise gripping and release, minimizing errors and optimizing safety [ContPark, et al. 2024].

- **Spreader rotation and coupling:** The spreader, equipped with automatic twist locks, aligns and locks onto the container. The PLC control system coordinates this function to ensure precise gripping and release, minimizing errors and optimizing safety [ContPark, et al. 2024].

Integration of automated cranes using PLC.

The integration of these four movements into a PLC-controlled system enables precise orchestration of the entire operational sequence. Automated algorithms coordinate trolley movements, lifting, and the position of the ground crane, ensuring that each container is handled without direct human intervention. This approach reduces downtime, increases productivity, and improves safety in modern automated terminals [Andziulis et al., 2016].

STS gantry cranes for container loading and unloading feature a structural configuration composed of three main sections: main beam, upper frame, and lower frame.

The main beam is made of a large metal profile, reinforced with reinforced concrete to withstand dynamic loads. It functions as a double-supported beam with cantilevers at both ends, with the seaward-facing cantilever, known as the boom, articulated to facilitate lifting and lowering maneuvers during port operations. This boom is typically constructed as a double box-type girder, which improves rigidity and stability in twin-lift operations and facilitates trolley movement. Currently, the use of lattice structures for the boom is preferred due to their lower weight and greater structural efficiency under cantilever conditions.

The upper structure, composed of stay beams, ensures the overall stability of the crane in any trolley position and transmits transverse forces to the posts. The lower structure, composed of posts, diagonal beams, and end beams, evenly distributes loads to the running gear, provides rigidity to the assembly, and houses a counterweight on the landward side to balance the cantilever.

Their structural design must consider dead loads, wind loads in longitudinal and transverse directions, extreme trolley positions, as well as accelerations of the trolley and the crane itself, to ensure safety and operational efficiency in modern port environments.

Container gantry cranes rely on trolley and spreader systems whose configuration directly influences structural design and operational efficiency. The trolley's weight is a critical factor, as it can triple between models, significantly affecting material fatigue and structural safety factors. There are lightweight versions, which reduce travel power and rolling resistance, and rotating trolleys, which, through a rotating substructure, allow for more precise load orientation.

The spreader is the key element for container handling, designed to operate from the apexes of the standardized units. It integrates hydraulic and electrical mechanisms that allow three main movements: telescopic extension of beams [for different container sizes], rotation of flippers [metal positioning guides], and operation of twist-locks, which secure containers through controlled rotation. Modern spreaders can include rotation around a vertical axis, anti-sway systems, and safety sensors to prevent accidental release.

There are three main types of spreaders: simple [for occasional and manual or semi-automatic operations], those designed for container cranes [with stability and advanced controls for large operations], and occasional automatic spreaders, which combine lightness with advanced functionality to adapt to different operations.

Finally, the use of anti-sway systems and centralized hydraulic controls is essential to optimize productivity and safety in port operations with large cranes. [Bouza et al., 2017]

Crane Control and Movement Analysis for Loading and Unloading TEUs with PLC-Based Automation Systems

Container loading and unloading operations in ports, especially with Ultra Large Container Ships [ULCS] and Megamax-24 vessels, face significant challenges due to their size and volume. Traditionally, these maneuvers rely on human operators to coordinate lifting, moving, and docking movements of containers, which entails high operating costs, labor risks, and long operating times [UNCTAD et al., 2023] and [Rodrigue et al., 2024].

While semi-automated cranes with anti-sway or travel-assist systems exist, many lack full integration to coordinate horizontal, vertical, longitudinal, and docking movements of the spreader. This limits their efficiency, especially in terminals seeking to reduce operating times and handle increasing TEU flows [Liebherr et al., 2024].

In the last decade, port automation technologies have evolved toward the use of sensors, PLC systems, and advanced control software. These innovations enable real-time monitoring and control, reducing human intervention and optimizing container positioning [Konecranes et al., 2023] and [ScienceDirect et al., 2024].

This project proposes the design of a PLC control system for container cranes, capable of integrating and coordinating the four operational movements [carriage movement, spreader raising/lowering, crane travel on rails, and container docking]. The goal is to increase efficiency, reduce risks, and offer a scalable alternative for ports that manage high-capacity vessels.

Functional study of the autonomous prototype for loading and unloading TEU containers

The term "port terminal" usually refers to those TPCs that have automated their storage equipment or their maneuvering mode to handle TEUs. This only corresponds to a small part of automation, since with Industry 4.0 there is a trend toward fully automated TPCs. In this project, this development will be carried out in the automation of STS quay cranes with the integration of automatic control with PLC. The methodology addresses the functional approach to automation; it is applicable in newly built terminals during their design phase and also in terminals in operation that can and wish to be automated, with the goal of achieving full automation. Automation aims to reduce human resources involved in handling STS cranes.

On the other hand, the automation of container port terminals is a strategic initiative that addresses three key needs:

- Operational efficiency.
- Increased safety and hygiene.
- Contribution to sustainable development. [Martín et al. 2014]

A thorough understanding of the operational dynamics and structural design of an autonomous prototype with Programmable Logic Controllers [PLCs] for loading and unloading TEU containers is essential to optimize its performance and ensure its integration with artificial intelligence [AI] systems for port automation. Understanding how their components—gantry cranes, spreaders, translation systems, and PLC control—interact allows for the development of solutions that improve efficiency, reduce operating times, and minimize human risks in high-demand logistics environments [Rodrigue et al., 2024] and [UNCTAD et al., 2023]. Automation within heavy-lift terminals [HLTs] has a significant growing trend, with a focus mainly on modern heavy-lift terminals, where it is estimated that automation could significantly improve terminal productivity similar to conventional terminals.

Over more than 25 years of evolution, the automation of heavy-lift ports has significantly revolutionized the industry. It is known that currently more than 1,100 cranes are operating without a driver worldwide, and several thousand automated guided vehicles [AGVs] perform transfer operations from the dock to the yard or vice versa, becoming a standard product in modern port systems. Therefore, the growing direction of automation is very significant. Automation in the port systems sector. Among the benefits of automation are a reduction in the number of employees, very low chances of failure due to human error, but most importantly, the equipment can be working 24 hours a day, 7 days a week, thereby reducing operating costs and human labor. Automation in port terminals ranges from infrastructure, such as the cranes responsible for stacking TEUs, to data management.

Automation dates back to the 1990s, having been incorporated into automated decision-making, helping to minimize berths, continuing with orderly stowage, and ending with sophisticated yard planning. By 2010, these automated cranes could automatically store and retrieve TEUs throughout the stacking yard. A survey was conducted, stating that carefully planned automated terminals would reduce operating expenses by between 25% and 55%, while increasing productivity by 10% and 35%, overcoming the complexity of the port automation process by guiding it toward the concept of Port 4.0. [De la Peña et al., 2020].

Talking about the integration of AI within port areas and the integration of cloud platforms in ports like Rotterdam is transforming loading and unloading operations by TEU cranes, as well as the analysis of IoT applications in the industrial space, which indicates that the logistics and transportation industry in recent decades has been in constant change, both on land and sea, due to the increasing implementation of cloud-based platforms within the port and throughout the supply chain.

The combination and integration of cutting-edge technologies, such as IoT sensor systems and artificial intelligence [AI] algorithms, allows the collection, processing, and analysis of data in real time, helping to optimize precision, safety, and, most importantly, streamline TEU loading and unloading maneuvers.

The cloud is being combined with sensor technologies to prepare the port area for autonomous maritime transport. In collaboration with IBM, a smarter supply chain is being developed; information will be integrated into the cloud in order to collect and translate data into information. This integration is expected to increase safety reliability, while reducing loading and unloading times has a significant economic impact, reducing operating costs [Team et al., 2019].

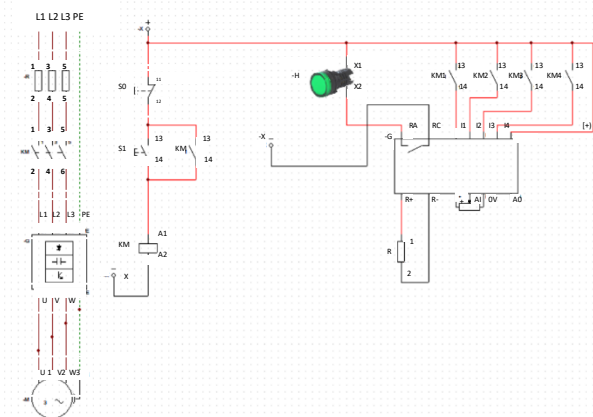
The developed prototype was an example of how several automatic control systems, such as PLCs, variable frequency drives, electric motors, and HMI [Human-Machine Interface], could be integrated to accomplish a specific task: simulating the loading and unloading cycles of TEUs, with the motor operating in both directions. These elements did not operate in isolation; communication protocols were integrated. In this particular case, the Modbus communication protocol allowed for the collection and transmission of process information in real time.

Using an HMI [Human-Machine Interface], the process information was received, viewed, and interpreted by the operator. This greatly facilitated process monitoring and enabled more accurate and, consequently, faster decision-making.

An electrical diagram layout was created using specialized automatic control software.

This design incorporated control elements such as a PLC [Programmable Logic Controller], a variable frequency drive for three-phase motors, and a three-phase motor. This design was perfectly adapted to an STS [Ship to Shore] crane for the automated loading and unloading of TEUs. [Figure 2-3].

Box 2



[First section of the prototype control and strength] [CADe, et al. 2024].

Source [CADe, et al. 2024]

The prototype is composed of automatic control equipment, the parts of which it is built are the following:

▪ S7-1200 PLC

In the autonomous prototype designed for loading and unloading TEU containers, the SIMATIC S7-1200 was implemented as the main programmable logic controller [PLC], responsible for coordinating all automation devices. This device belongs to a family of modular controllers designed for industrial applications requiring flexibility, precision, and network communication.

The S7-1200 stands out for its compact and scalable architecture, allowing its data processing capabilities to be expanded through digital and analog input or output modules. For the prototype, a 1214C CPU was used, with a capacity of 14 digital inputs, 10 digital outputs, and 2 integrated analog inputs, which ensured proper connection to the system's position sensors, control buttons, frequency inverters, and safety elements. In terms of processing capacity, this PLC operates with a reduced cycle time [0.08 μ s per Boolean instruction], which enabled precise synchronization of the electric motors and hoists used in handling the TEUs.

ISSN: 2523-6792

RENIECYT: 1702902

ECORFAN® All rights reserved.

Furthermore, its built-in 100 KB memory was sufficient for programming control routines, as well as diagnostic functions, alarms, and communication with external devices. In the prototype, industrial communication was primarily via PROFINET [Industrial Ethernet], factory-integrated into the S7-1200 CPU, which facilitated connection to the KTP400 HMI and the 4M frequency inverters responsible for motor speed control. Additionally, thanks to optional modules, the PLC can operate under the Modbus TCP/RTU and Profibus communication protocols, opening up the possibility of integrating new equipment and sensors in future stages of the project. Another key aspect was programming using the Siemens TIA Portal V13 environment [student version, 2013]. This software enabled programming in Ladder Diagram [KOP], Function Block Diagram [FBD], and Structured Control Language [SCL], ensuring efficient development. Its integrated simulator was key to testing control sequences before applying them to physical hardware, reducing time and errors during prototype commissioning. In terms of safety and reliability, the S7-1200 has international certifications such as CE, UL, cULus, and RoHS, which endorse it for applications in industrial environments. It also features basic security functions, such as password management and access control, which adds security to the programmed logic. The integration of the S7-1200 into this prototype not only served to coordinate the TEU loading and unloading system but also enabled the generation of structured process data, which can be used in subsequent analyses using artificial intelligence techniques, paving the way for predictive and, above all, more efficient control. [Siemens AG, et al., 2013]

▪ Power Flex 4M Variable Frequency Drive.

The PowerFlex 4M adjustable frequency drive [ADV] was used as an integral part of the automatic control prototype for loading and unloading TEU containers.

This device regulated the speed, frequency, and torque of AC electric motors by controlling the frequency and voltage supplied to the motor, facilitating more efficient and safer operation of the lifting and handling systems. Its technical features include an adaptable power range from 0.2 kW to 160 kW, making it versatile for small and large-scale applications in customs systems.

Vázquez-González, Humberto, Cruz-Gómez, Marco Antonio, Mejía-Pérez, José Alfredo and Castillo-Pensado, Juan Luis [2025]. Autonomous prototype design with PLC for TEU Container Loading and Unloading Linked to AI Applications. Journal of Technical Invention. 9[22]1-12: e39221012. <https://doi.org/10.35429/JOTI.2025.9.22.3.1.12>

It also has an operating range of 200 to 600 VAC, depending on the configuration. It is primarily designed to operate with three-phase induction motors.

The device includes overcurrent, overvoltage, and overtemperature protection, ensuring proper operation during continuous use. Regarding the communication interface, this drive supports industrial protocols such as Modbus and Ethernet/IP, making it compatible with distributed control architectures and the integration of PLC-based systems. This connectivity capability was key for real-time data collection within the prototype, allowing electrical and operating parameters to be monitored from the HMI interface. Furthermore, the PowerFlex 4M model complies with international energy efficiency and safety regulations, such as CE, UL, and cUL, ensuring that the device can be implemented in port automation projects with global quality standards. Its use in the prototype provided the ability to precisely control synchronization between motors, optimizing the TEU loading and unloading process for the purposes of applied research in artificial intelligence. [Rockwell, et al. 2019]

- **Three-phase induction motor.**

With the following specifications:

- Power: 0.12 kW
- Voltage: 220/380 VAC
- Current: 0.71 / 0.41 A
- Frequency: 50 Hz
- Speed: 2600 rpm
- Protection: IP44
- Insulation: Class B

- **KTP400 HMI**

The SIMATIC KTP400 Basic HMI is a human-machine interface device specifically designed for the monitoring and control of industrial processes in various applications such as automation. Its main objective is to serve as a link between the operator and the control system, providing clear and visual communication. Thanks to its compact design, it is used in limited spaces, but where efficient and reliable control is required. This device features a 4-inch touchscreen with TFT [Thin Film Transistor] technology, offering a clear resolution.

This screen can display up to 65,000 colors, facilitating the display of alarms, graphs, and process parameters in real time. The device also integrates function keys that allow for quick and safe operation, giving the user the ability to interact with the device both via touch and physical buttons. This combination makes the device adaptable to different operating scenarios, where ergonomics and process speed are essential. In terms of connectivity, the KTP400 integrates effectively into automation networks via PROFINET [Process Field Network] interfaces, ensuring efficient and reliable communication with programmable logic controllers [PLCs] and other SIMATIC devices. Programming and configuration are also performed using WinCC Basic V13 software, part of the TIA Portal engineering area. This integration ensures simpler commissioning, as it allows for the programming of graphic displays, alarms, data trends, and diagnostic functions in the same work environment. In terms of technical features, the SIMATIC KTP400 Basic HMI stands out for its robust design, reliability, and ease of use. It also boasts international certifications [CE, RCM] that make it suitable for operation in demanding industrial environments. Thanks to its compact size and low power consumption, it becomes an efficient option for integration into electrical control panels and operator stations. End of form The KTP400 Basic represents an efficient and affordable solution for human-machine interaction, combining functionality, versatility, and compatibility with current automation systems. An example of this is a research project. This device not only enables process visualization and control, but also the collection of real-time information that can be subsequently analyzed for improvement and optimization of industrial systems.

Feature Description

Model SIMATIC HMI KTP400 Basic

Type Human-Machine Interface [HMI]

Display 4" TFT touch screen

Connectivity PROFINET [for industrial automation]

Configuration From WinCC Basic V13 or STEP 7 Basic V13

Application Ideal for visualization on machines and in environments with limited space

In this way, the use of the KTP400 Basic HMI in an automated system contributes to the development of smarter, safer, and more productive solutions. [Siemens AG, et al. 2013].

STS cranes are the most commonly used in port areas for loading and unloading container ships. This type of crane requires several parts to make up the system. Our prototype will be adapted to the lifting and moving parts of the STS crane, making it completely autonomous and integrating AI for its manipulation and decision-making. This prototype was developed under strict international standards such as IEC 60364-4-41 [3007] [International Electrotechnical Commission], which focuses on electrical installations, protection to ensure safety, and protection against electric shock.

In an STS crane, the automatic control system is distributed across different strategic modules that allow for precise and controlled coordination of lifting, travel, and coupling movements of the spreader to the TEUs. The central processing unit, based on programmable logic controllers [PLCs], HMIs, and variable frequency drives, is located in the crane's electrical control cabin, generally situated at the top of the structure. From this point, the PLC receives signals from the sensors installed along the crane and sends commands to the variable frequency drives and actuators that control the main motors. This ensures perfect coordination of loading and unloading of TEUs. The integration of AI for decision-making and autonomous operation of STS cranes is intended. The component visible to the operator is the human-machine interface [HMI], installed in the control cabin. It displays critical parameters such as lifting height, spreader position, and load levels, allowing for manual intervention if necessary. Furthermore, the automatic control system is complemented by industrial communication protocols [Modbus] that link the crane's various subsystems, enabling integration with broader port logistics management systems. In the lifting department, we have very important elements, such as the hoisting cables, which are standardized worldwide. Crane design codes require that the minimum breaking strength of the cable be several times greater than the working load. The ASME B30.5 standard allows boom-hoist cables to have a design factor of 3.5:1 for torsion-resistant ropes [Hi-Speed, et al. 2024].

However, for load-lifting cables—such as those used in STS cranes—a design factor of 5:1 is typically used, meaning that the working load must be equal to or less than 20% of the minimum breaking strength [E-Riggin, et al. S.F.]. STS crane ropes are typically 8- or 6-strand ropes with an independent wire core [IWRC], manufactured in accordance with EN 12385-4.

In the sheave and drum section, the diameter of the sheaves and drums influences bending fatigue. US OSHA legislation 1926.1414 requires that the first layer of rope on the drum be at least 18 times the nominal rope diameter and that the sheave diameter in multi-strand systems be at least the same. Rope manufacturers' recommendations further state that the sheave groove radius should be approximately 0.53–0.55 times the rope diameter, the groove depth should be approximately 1.5 times the diameter, and the channel angle should be 35–45°, increasing to 60° for large deflection angles. [Onur, et al. 2017].

Box 4

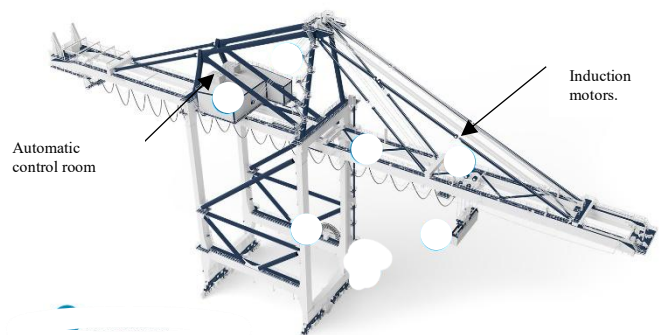


Figure 4

Graphical representation of the location and installation of the control and force devices.

Source [Encoder, et al. S.F.]

A simulation was conducted using TIA Portal software to simulate motor starts, stops, and speed changes, and to vary the motor frequency without damaging it. Varying the frequency allows the lift to be controlled at the desired speed, providing greater control over the loading and unloading of TEUs. The simulations are shown below [Figures 5, 6, and 7].

Box 5

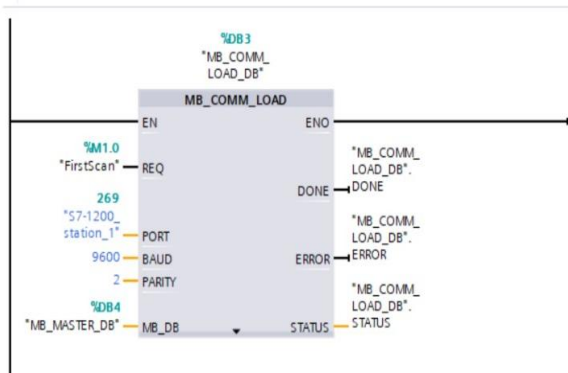


Figure 5

In the MB_COMM_LOAD block, a communication port is configured using the Modbus RTU protocol, executing functions such as the communication port, baud rate, parity, and the assignment of reference to the instance data block

Source [Siemens AG, et al. 2013]

Box 6

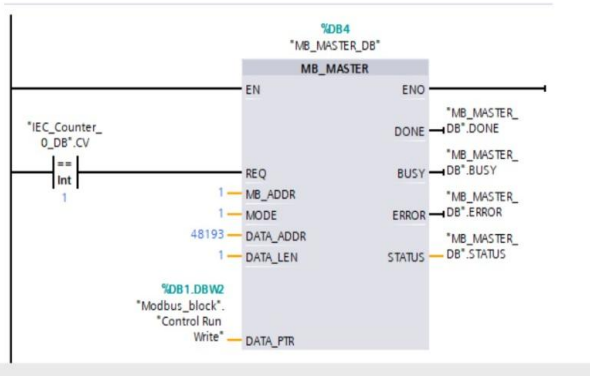


Figure 6.

In the MB_MASTER block, the PLC assigns the communication address to the drive, the address of the data to be accessed on the slave, and the data length [number of bits or words] in the Modbus function table.

Source [Siemens AG, et al. 2013]

Box 7

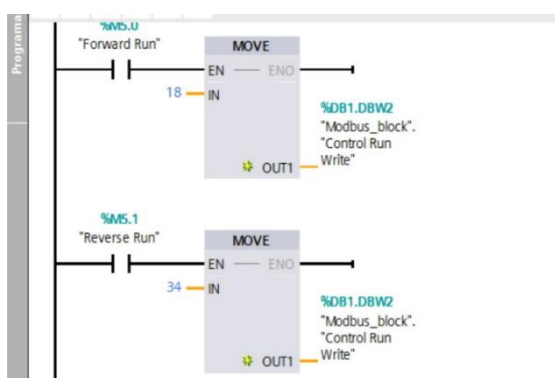


Figure 7.

In the move functions, the start, stop, reverse, and alarm commands are assigned to the slave [drive].

Source [Siemens AG, et al. 2013]

The developed prototype represents a first tangible approach to the design of an autonomous PLC system, aimed at controlling the loading and unloading of TEU containers, closely linked to the purposes of artificial intelligence [AI]. The integration of a PLC, an HMI, a frequency converter, and protection elements allowed for the creation of a robust and versatile platform that not only demonstrates the viability of automated control but also lays the groundwork for the incorporation of intelligent algorithms that optimize real-time decision-making.

The prototype demonstrates the ability to synchronize industrial devices under a secure and scalable scheme, making it an applicable model both in academia and in logistics environments that demand efficient TEU handling. Furthermore, the adopted modular infrastructure facilitates its future integration with vision systems, IoT sensors, and machine learning techniques, aimed at achieving a greater degree of operational autonomy in port terminals.

Box 8



Figure 8.

Image of the finished prototype, with its dual control and force equipment.

Source [Own elaboration]

Conclusions

The results obtained from the design of the autonomous prototype for loading and unloading TEU containers, based on a PLC [programmable logic controller] control system, demonstrated the feasibility of integrating industrial automation technologies to optimize port terminals and linking them to artificial intelligence.

The prototype was able to reproduce in a controlled manner the essential movements of an STS crane: longitudinal movement, load raising and lowering, and spreader coupling, ensuring safe and coordinated operation between the different electrical equipment.

The design proposal incorporated the analysis and selection of electrical equipment using technical criteria, ensuring system functionality under simulated operating conditions.

Through communication with HMI interfaces and industrial communication protocols, clear visualization and management of the process was achieved, reducing operational complexity and improving efficiency compared to conventional systems. In this way, the prototype contributes not only to the advancement of port automation but also to the achievement of technological innovation and sustainability objectives by offering a scalable solution that can be adapted to real-world container handling scenarios. Consequently, it is theoretically validated that the proposed mechanism does not present critical limitations in its operation and lays a solid foundation for future applications in smart ports.

Declarations

Conflict of interest

The authors declare no interest conflict. They have no known competing financial interests or personal relationships that could have appeared to influence the article reported in this article.

Author contribution

Vazquez-Gonzalez, Humberto: Contributed to the research idea, information gathering, and writing of several sections of the article, based on his professional experience.

Cruz-Gómez, Marco Antonio: Contributed to the revision of the project's writing and provided general improvement suggestions, based on his professional experience.

Mejía-Pérez, José Alfredo: Contributed to the revision and writing of various sections, based on his professional experience and electrical diagram designer.

Castillo-Pensado, Juan Luis: Contributed to the revision and writing of various sections, based on his professional experience.

Availability of data and materials

This article is a literature review based on previously published data and documents. No new datasets were generated during this study.

Funding

This work was self-funded by the authors.

Acknowledgements

To the Benemérita Universidad Autónoma de Puebla; Engineering Faculty for the support in the use of its infrastructure., To the Tribology and Transport Group, BUAP, for their support in the analysis and development of the work, and 189 Disaster Prevention, Sustainable Development and Tribology Academic body, BUAP.

Abbreviations

AI	Artificial Intelligence
HMI	Human-Machine Interface
IoT	internet of Things
PLC	Programmable Logic Controller
STS	Ship-to-Shore
TEU	Twenty-foot Equivalent Unit
ULCS	Ultra Large Container Ship

References

Andreotti, J. I. [2017]. *¿Qué es el TEU [Twenty-foot Equivalent Unit]?*

Dragović, B., Dragović, A., & Dulebenets, M. A. [2025]. *The quay crane operation problem at marine container terminals: bibliometric analysis, emerging trends, and future research opportunities. Transportation Research Part E: Logistics and Transportation Review, 201, 104266.*

Vázquez-González, Humberto, Cruz-Gómez, Marco Antonio, Mejía-Pérez, José Alfredo and Castillo-Pensado, Juan Luis [2025]. Autonomous prototype design with PLC for TEU Container Loading and Unloading Linked to AI Applications. *Journal of Technical Invention. 9[22]1-12: e39221012.* <https://doi.org/10.35429/JOTI.2025.9.22.3.1.12>

Article

Rodrigue, J.-P., & Notteboom, T. [2021, enero]. *Automation in container port systems and management*. TR News, July–August 2021.

Solowjow, E., Ugalde, I., Shahapurkar, Y., Aparicio, J., Mahler, J., Satish, V., & Claussen, H. [2020]. Industrial robot grasping with deep learning using a programmable logic controller [PLC]. *arXiv*.

Basics

Andziulis, A., Eglynas, T., Bogdevicius, M., Jusis, M., & Senulis, A. [2016]. *Multibody dynamic simulation and transient analysis of quay crane spreader and lifting mechanism*. *Advances in Mechanical Engineering*, 8[9], 1–11.

Bouza, A. C. [2017]. *Diseño e implementación de un sistema experto para el control de grúas de elevación de contenedores TEUs [Tesis de grado]*. Universidad de A Coruña.

Konecranes. [2023]. *Smart Features for Container Handling Cranes*. Konecranes Global.

Liebherr. [2024]. *Container Cranes for Efficient Container Handling*. Liebherr Group.

Martín-Soberón, A. M., Monfort, A., Sapiña, R., Monterde, N., & Calduch, D. [2014]. *Automation in Port Container Terminals*. *Procedia - Social And Behavioral Sciences*, 160, 195-204.

Rockwell Automation. [2024]. *RSLogix 5000 and Studio 5000 Design Software Overview*.

ScienceDirect. [2024]. *Automation and digitalization in port container terminals*. Elsevier.

Supports.

CADe SIMU. [2024]. [Software]. En *J.L Villanueva Montoto* [4.2].

Contpark_Admin. [2024, 28 octubre]. *Quay ranes [QC] in Container Terminal Cargo: Intermodal Gantry Price and Rail Operations*. ContPark.

De la Peña Zarzuelo, I., Soeane, M. J. F., & Bermúdez, B. L. [2020]. *Industry 4.0 in the port and maritime industry: A literature review*. *Journal Of Industrial Information Integration*, 20, 100173.

Encoder de para la industria de las grúas en entornos extremos. - Leine Linde. [s. f.].

E-Rigging. [s. f.]. *Safety & Warnings for Steel Cable & Wire Rope*.

Hi-Speed Industrial Service. [2024]. *What type of wire rope is best for cranes and hoists?*

Overhead, Gantry, Jib Crane and Hoist Solution Supplier - Yuantai Crane. [2025].

Onur, Y. A., İmrak, C. E., & Onur, T. Ö. [2017]. *Investigation on bending over sheave fatigue life determination of rotation resistant steel wire rope*. *Experimental Techniques*, 41[3], 475–482.

Rockwell Automation. [2019]. *PowerFlex AC drives: Technical data*. Rockwell Automation

Rodrigue, J.-P., & Notteboom, T. [2024]. *Automation in container port systems and management*. TR News, July–August 2021.

Siemens AG. [2013]. *SIMATIC S7-1200 Programmable Controller: System Manual [Student Version, TIA Portal V13]*.

Siemens AG. [2013]. *Totally Integrated Automation [TIA] Portal V13 [Versión para estudiantes]* [Software]. Siemens AG.

Siemens AG. [2013]. *SIMATIC HMI KTP400 Basic, Panel básico de 4" para automatización industrial* [Ficha técnica]. Siemens Industry Online Support.

Team, P. T. [2019b, junio 29]. *Ports in the Cloud: The Next Step in Automation? Port Technology International*.

UNCTAD. [2023]. *Review of Maritime Transport 2023*. United Nations Conference on Trade and Development.