Design of an IoT-Driven Software Architecture for an Automated Robotic Fueling System in Open-Pit Mining

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Abstract: The fueling process for haul trucks in open-pit mining operations is traditionally manual, leading to inefficiencies, operational delays, and increased costs. This paper presents the design of an automated robotic fueling system aimed at optimizing fueling operations by automating key tasks such as fuel nozzle positioning, authorization, and process monitoring. The proposed system leverages Internet of Things (IoT) technology and a cloud-based architecture to enable real-time monitoring and seamless integration with existing mine infrastructure. The physical design of the system follows the German Guideline VDI 2206 methodology, while the cloud platform is structured using the Attribute Driven Design (ADD) 3.0 methodology to ensure scalability and adaptability. Additionally, interface prototypes were developed, including an Human-Machine Interface (HMI) and a responsive web application, to provide real-time data visualization and operational control. The results of this study demonstrate the potential of automation to improve fueling efficiency, enhance safety, and reduce downtime in mining operations.

1 INTRODUCTION

The mining industry is vital to the global economy, supplying essential minerals such as copper, gold, and zinc. Peru ranks among the world's top producers of silver, copper, and zinc, with mining contributing 14.3% of its GDP and over 50% of total exports in 2019 (Walter et al., 2021).

Open-pit mining, which covers 1.47% of Peru's territory (MINEM, 2024), is the predominant extraction method. Ore hauling represents approximately 45% of total mining costs (Quiquia and William, 2015), making it one of the most significant expenses. While strategies such as optimizing vehicle speed, route planning, and acceleration management help reduce costs, the fueling process remains a critical bottleneck in large-scale operations. Manual procedures, including shutdown, credential logging, spill tray positioning, nozzle connection, and monitoring, introduce inefficiencies, increase the risk of errors, and extend downtime.

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This paper presents an automated fueling system that streamlines key tasks, including nozzle positioning, authorization, and process monitoring (Pouresmaieli et al., 2022). The system minimizes human intervention and optimizes fueling time through automation. Its design follows the German Guideline VDI 2206 (Gausemeier and Moehringer, 2002) for the physical system, while the cloud platform solution is developed using the Attribute Driven Design (ADD) 3.0 methodology (Cervantes and Kazman, 2024) to ensure seamless integration.

The paper reviews current fueling practices, details system design, explores cloud integration, and introduces the user interface. It concludes by highlighting key features and their impact on mining operations.

2 LITERATURE REVIEW

Automated fueling systems for dump trucks in mining operations have advanced significantly, integrating robotics, computer vision, LiDAR sensors, and artificial intelligence (AI) to enhance efficiency, safety,

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and precision.

Several commercial solutions have emerged to meet industry demands. Robofuel (Scott Automation, 2023) employs a robotic arm with a 3D sensing system to accurately position the fuel nozzle, minimizing leaks and improving efficiency for haul trucks and excavators. Pitstop (Rotec, 2025) features a hydraulic delta robot with an adaptive nozzle, reducing connection times to 75 seconds and disconnection to 30 seconds, achieving a refueling speed of 1200 L/min. RAPID (Stratom, 2024) integrates LiDAR and cameras for precise nozzle positioning, operating in harsh mining environments at a rate of 600 gallons per minute (GPM).

Other systems incorporate AI to optimize refueling parameters. The Fuelmatics 5000 (Auto-Energy, 2022) utilizes an XYZ positioning system with three nozzles and vapor recovery, while the Robotic Refueling System (Autofuel, 2024) includes a robotic arm for cap opening, license plate recognition, and automated payment, making it compatible with existing fueling stations.

Patented innovations further demonstrate progress in this field. A multi axis robotic arm covered in carbon fiber with a telescoping system, allowing fast diesel fueling at up to 38 GPM while vapor capture (Hollerback, 2013). Another patent introduces a robotic arm integrating 3D vision technology for precise fuel cap localization, improving nozzle-cap coordination (Censtar Science & Technology Corp ltd, 2024). A separate patent presents a two-phase system using industrial cameras to optimize nozzle positioning, ensuring efficient fueling across various vehicle models (Hazakhstan Robotics Zhongshan Co Ltd, 2022).

Research has also contributed to system advancements. Studies on industrial robots and Kinect V2 (Lam and Phung, 2021) demonstrate improved user interface and error prevention. Vision perception technologies, such as binocular cameras and deep learning algorithms, have been explored to enhance positioning accuracy and automate fueling (Guo et al., 2021).

These innovations not only improve the precision and safety of fueling haul trucks but also create opportunities for broader industrial applications, driving further advancements in automation (Bi et al., 2021).

3 SYSTEM PROPOSAL

The proposed autonomous robotic fueling system, shown in Figure 1, is designed to optimize refueling for mining dump trucks in open-pit environments. It connects and disconnects the fuel nozzle in approximately 56 seconds, improving efficiency and reducing downtime. Compared to Pitstop, which requires 75 seconds for connection and 30 seconds for disconnection (Rotec, 2025), the proposed system reduces total fueling time by nearly 33%, further enhancing operational performance.

A key component is the robotic arm, which provides extended reach, high precision, and repeatability. To ensure reliability in harsh mining conditions, it is enclosed in a protective cabin that shields it from dust, debris, and extreme temperatures. Structural components are made of stainless steel 304, offering high resistance to corrosion and mechanical wear, enhancing durability and operational lifespan.

This section details the robotic arm configuration and its controller, followed by the mechanical and electronic design of the automatic connection tool for precise fuel nozzle attachment. The electrical panel design is then examined, covering energy supply, control, data processing, and communication. Finally, the monitoring interface and signaling systems that ensure operational safety are introduced.

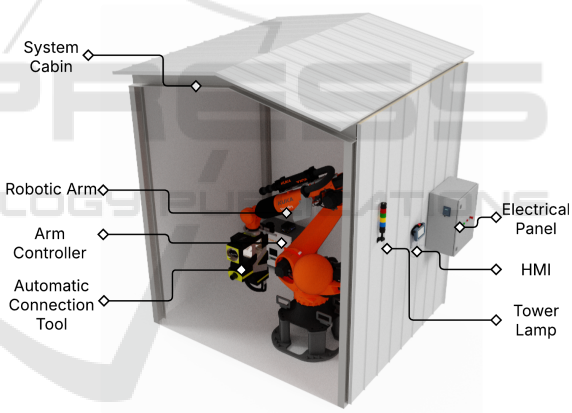

Figure 1: Perspective-isometric view of the Automated Fueling System.

3.1 Robotic Arm Configuration

The selection of the robotic arm was based on an analysis of dimensional reach and load capacity requirements. A reach of 2902 mm was determined after evaluating various dump truck models, ensuring a minimum safety distance. The estimated load capacity, based on the preliminary design of the connection tool, was approximately 60 kg.

Given these requirements, the KUKA KR-120 3100 F was chosen for its ability to meet both reach and load demands. Its foundry configuration ensures reliable operation in harsh environments, featuring IP65 protection for the structure and IP67 at the end effector, providing resistance to dust and water ingress. With a repeatability of ±0.05 mm, it delivers consistent performance over prolonged operations and across large fleets.

The arm is managed by the KR-C5 control system, housed in a Basic Cab configuration, enabling full operational control.

3.2 Automatic Connection Tool

An automatic connection tool, shown in Figure 2, was designed to ensure a precise and reliable connection between the fuel nozzle and the fuel tank.

At the core of the system's automated positioning is a 3D vision system with high spatial resolution, operating alongside an industrial PC responsible for processing tank cap position calculations via a pose estimation algorithm. Image data is transferred at high speed using 10GigE Ethernet technology, enabling computations in under 2 seconds. The processed spatial data is then sent to the robotic controller for precise tool positioning.

The connection process follows three distinct phases to ensure accuracy and efficiency. In the first phase, a gripper secures the fuel tank's screw cap while a rotary module applies the required torque for removal. In the second phase, the fuel nozzle is positioned using a linear actuator, which moves it 50 mm horizontally along precision-guided ball rails. The final phase initiates fuel flow by lifting the nozzle lever with another linear actuator, supported by an internally designed mechanism. Disconnection follows the same sequence in reverse.

To protect internal components, a robust protective casing shields the tool from dust, moisture, and mechanical impacts, ensuring durability in harsh environments. Finally, the tool is securely attached to the robotic arm's end effector using a bayonet coupling, enabling quick and reliable installation.

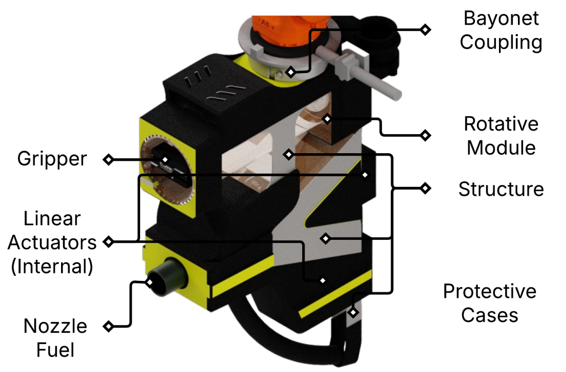

Figure 2: Isometric view of the Automatic Connection Tool.

3.3 Electrical Panel

The electrical panel, illustrated in Figure 3, is housed in a protective enclosure (600×800×400 mm) and contains the essential components for energy protection, control, supply, data processing, and communication.

For energy protection, the panel includes differential and circuit breakers, ensuring safe power distribution across the system with 40 A, 20 A, 10 A, and 6 A outputs. Energy control and supply are managed using industrial contactors and regulated power supplies, delivering stable power to DC devices, including linear actuators.

A programmable logic controller (PLC) governs system operation, managing control via I/O interfaces and Ethernet ports. Relay outputs are connected to intermediary relays for safe contactor control, while dedicated inputs handle start, stop, and emergency stop functions. The panel also houses a servo drive, responsible for regulating the rotary module.

For connectivity and expandability, the panel integrates an Ethernet switch, allowing the PLC to expand its network connections. An IO-Link module connects components such as the gripper and tower lamp, while an industrial IoT gateway centralizes data for cloud processing.

The panel is designed for an organized layout, incorporating structured wiring distribution and dedicated terminal blocks for earth, neutral, and relay connections, ensuring efficient operation and maintenance.

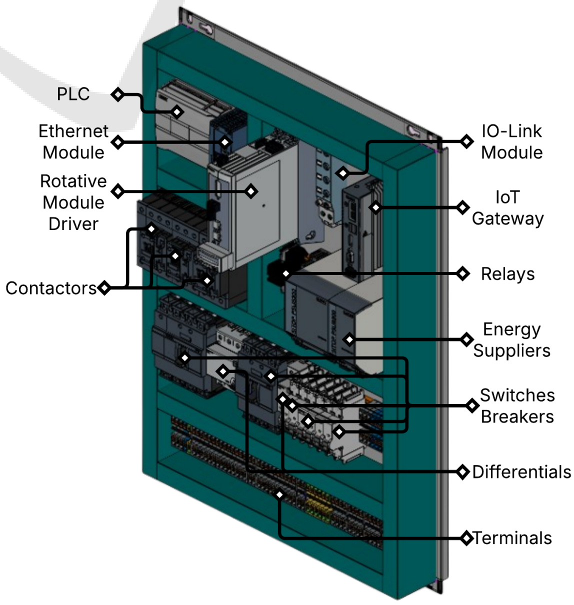

Figure 3: Internal isometric view of the Electrical Panel.

3.4 Monitoring and Signaling

Process data, including fuel level, filling velocity, user information, and operational stage, is displayed on a human-machine interface (HMI), allowing the fuel station operator to monitor fueling in real-time. The HMI communicates with the PLC via an Ethernet connection, ensuring accurate process tracking and seamless data exchange.

System status signaling is managed by a tower lamp, which provides visual and auditory alerts throughout the fueling process. The lamp emits intermittent lighting and audible alarms to indicate system operation and is controlled by the PLC via an IO-Link interface, ensuring timely and reliable signaling.

4 CLOUD-PLATFORM SOLUTION DESIGN

The development of the system requires a platform capable of monitoring the entire operation in real time. This is achieved through the design of a cloud platform architecture that leverages Internet of Things (IoT) sensors integrated into the system. The design process is carried out using the ADD 3.0 methodology, which is structured into seven systematic steps. Before initiating the design process, it is necessary to define the architectural drivers, including use cases, quality attributes, architectural constraints, and architectural concerns, as a foundational prerequisite (López et al., 2021; Ruiz-Navarro et al., 2021).

4.1 Architectural Drivers

User cases

The functional requirements represent the specific capabilities or functionalities that the system must deliver. These requirements are defined and detailed through use cases, as outlined in Table 1.

Quality Attributes

These are measurable characteristics of interest to users that define how effectively the system performs its functions. They are outlined in Table 2.

Architectural Constraints

These are restrictions or limitations imposed on the architecture. Constraints may arise from business decisions, regulatory requirements, or legacy systems. In this design process, they primarily reflect technical choices, as presented in Table 3.

Architectural Concerns

These represent the interests, needs, and expectations of all stakeholders involved in the system, as outlined in Table 4.

Table 1: Use Case Description.

ID	User Case	Description
UC-1	Authenticate User	The user authenticates in the system to access the functions of the automated system.
UC-2	Start Filling Cycle	The truck operator starts the fuel filling cycle in the system.
UC-3	Stop Filling Cycle	The truck operator stops the fuel filling cycle upon completing the process or in case of emergency.
UC-4	Record Incident	The operator or the system records an incident occurring during the filling or maintenance process.
UC-5	Generate Automatic Maintenance	The system detects and automatically schedules maintenance based on incidents or alerts generated during the filling cycle.
UC-6	Generate Manual Maintenance	The administrator or station supervisor can manually create a maintenance request for the equipment or system.
UC-7	Generate Operation Report	The system generates a detailed report of operations, including fillings, incidents, and recorded maintenances.

4.2 Design Process

The previously defined architectural drivers are used to iteratively design the architecture, as outlined in the following sections.

4.2.1 Architectural Priorities: Input Review, Goal Definition, and Element Selection

Following the ADD 3.0 methodology, the initial steps establish a solid architectural foundation. Step 1 reviews and validates architectural drivers to ensure alignment with system objectives. Step 2 defines the iteration's goal, addressing all drivers to finalize the architecture in a single cycle. Step 3 selects and refines key components, ensuring the architecture is fully developed within this iteration.

Table 2: Quality Attributes Scenarios.

ID	Quality Attribute	Scenario
QA-1	Security	A user attempts to access the system without valid credentials, and the system denies access 100% of the time.
QA-2	Reliability	The operator wants to manually record an incident, and the system generates it correctly 100% of the time.
QA-3	Reliability	The system automatically generates a maintenance request correctly 100% of the time when there is a critical system incident.
QA-4	Reliability	The administrator generates a maintenance request correctly 100% of the time.

Table 3: System Constraints.

ID	Constraint
CON-1	Use AWS as the cloud service provider for the deployment model.
CON-2	Access to the monitoring system must be through a web browser using a device connected to the mine's Wi-Fi network.
CON-3	Use a communication protocol oriented to IoT.
CON-4	Use an IoT-oriented reference architecture based on AWS services.
CON-5	Use a relational database for compatibility with the mine's database.

4.2.2 Design Concept Selection to Satisfy Architectural Driverss

As part of step 4, the architectural design and hosting decisions follow an IoT service-oriented architecture optimized for real-time monitoring and control. Sensor data is collected through a robust control system, processed efficiently, and displayed via a user-friendly web application while generating detailed incident logs during fuel-filling operations. To meet these requirements, the following AWS-based services were selected:

Smart Farm on AWS Reference Architecture (AWS, 2024a) was selected for its IoT compatibility (CON-3), seamless AWS integration, and real-time processing (CRN-4). Its modular design ensures interoperability with mining equipment (CRN-1) and simplifies maintenance (CRN-2). It also provides secure access control (QA-1) and reliable incident logging with automated maintenance (QA-2, QA-3). Alternatives like Siemens Industrial Edge on AWS (AWS, 2024b), Connected Restaurants Using IoT, AI & ML (AWS, 2022), and Edge Inference for Agriculture (AWS, 2020) were discarded due to misalignment with fuel monitoring, unnecessary edge processing, and higher costs.

Table 4: System Concerns.

ID	Concern
CRN-1	Ensure compatibility with existing equipment and technology in the mining environment.
CRN-2	Design the system based on modularity criteria to facilitate updates and maintenance.
CRN-3	Ensure proper management of incident records for compatibility with the mine's database.
CRN-4	Ensure real-time information processing.

Edge Computing minimizes latency by processing data locally, enabling real-time monitoring and instant responses to critical events (UC-2, UC-3, UC-4). It leverages IoT protocols (CON-3) and integrates with AWS IoT Greengrass (CON-4) for scalable, robust processing.

IoT Device Management Platform enables seamless cloud connectivity, real-time data exchange, and efficient incident management. It supports predictive maintenance, device configuration, and diagnostics to ensure operational continuity (UC-4, UC-5). Compliant with IoT protocols (CON-3), it leverages AWS IoT Core for centralized management (CON-4).

Data Storage securely manages incident logs, sensor data, and reports, ensuring scalability and accessibility for analysis (UC-4, UC-7). AWS S3 provides cost-efficient storage while complying with AWS security protocols (CON-1).

Data Visualization Tools provide intuitive interfaces for analyzing operational data, improving system health and performance insights (UC-7). AWS QuickSight powers dynamic dashboards for actionable decision-making (CON-1).

Event-Driven Code Execution automates actions like maintenance alerts and safety responses (UC-4, UC-5). AWS Lambda ensures efficient, reliable event processing (CON-1, CON-3).

Centralized Security Alerts coordinate responses to security threats, protecting system access and data (UC-1, CON-2). AWS IoT Device Defender monitors and mitigates vulnerabilities.

Real-Time Notifications alert users about incidents and maintenance needs, ensuring prompt responses and operational efficiency (UC-4, UC-6). AWS SNS guarantees reliable, immediate message delivery (CON-1).

Application Programming Interface (API) Communication Interface enables secure, reliable integration between the web application and backend services (UC-1, UC-2, UC-6). It adheres to industry standards and ensures consistent data exchange via Wi-Fi (CON-2).

A relational Cloud Database Service was selected to ensure compatibility with the mine's existing relational database (CON-5). This choice enables structured management of incident logs and operational data, ensuring integrity and consistency (CRN-3). The cloud-based approach provides scalability, high availability, and fault tolerance, supporting real-time processing and seamless integration with local databases (CRN-4). A secure endpoint will facilitate reliable data exchange between the cloud and on-premise infrastructure via the system's API.

4.2.3 Instantiation of Architectural Elements

As part of step 5, the following design decisions instantiate the architectural elements to meet system requirements.

AWS IoT Greengrass enables local machine learning and data processing, collecting sensor data and responding to critical events in real time. This minimizes latency and reduces dependency on constant server connectivity (UC-2, UC-3, UC-4). It adheres to IoT protocols (CON-3), integrates with AWS architecture (CON-4), and ensures reliability and security (QA-2, QA-3).

AWS IoT Core manages IoT devices and communication via MQTT, ensuring reliable data transmission for incident detection and management (UC-4, UC-5). It complies with IoT protocols (CON-3), integrates with AWS architecture (CON-4), and prioritizes reliability and security (QA-2, QA-3).

Amazon S3 securely stores incident logs, reports, and maintenance records, ensuring scalable and accessible data management (UC-4, UC-7). It complies with AWS restrictions (CON-1) and Wi-Fi access (CON-2), prioritizing security and reliability (QA-1). Amazon QuickSight provides interactive visualizations for data-driven decision-making (UC-7), adhering to AWS restrictions (CON-1) and ensuring reliability (QA-2).

AWS Lambda automates critical tasks by processing sensor data, detecting incidents, and triggering maintenance (UC-4, UC-5). It retrieves and prepares data from the mine database via API Gateway, ensuring seamless integration for analysis and visualization. This service adheres to AWS standards (CON-1), supports IoT protocols (CON-3), and enhances reliability and security (QA-2, QA-3).

AWS Security Hub centralizes security alerts, protecting against unauthorized access and ensuring data integrity (UC-1). It complies with Wi-Fi security protocols (CON-2) and prioritizes robust security measures (QA-1).

Amazon SNS delivers real-time notifications to users about incidents or maintenance, improving operational response times (UC-4, UC-6). This service adheres to AWS restrictions (CON-1), emphasizing reliability and security (QA-1, QA-3).

Amazon API Gateway ensures secure, efficient communication between the web application, backend services, and the mine database via a dedicated endpoint. It enables seamless access to system functionalities (UC-1, UC-2, UC-6) with secure Wi-Fi connectivity (CON-2) while ensuring real-time data availability (CRN-4) and compatibility (CON-5). Acting as a secure intermediary, it facilitates efficient data exchange between local and cloud-based systems.

AWS DynamoDB was chosen for its compatibility with the mine's database (CON-5) and efficient incident management (CRN-3). Its scalability ensures real-time processing and peak performance (CRN-4). Integration with AWS Lambda and IoT Core enhances reliability (QA-2, QA-4), while its NoSQL architecture enables flexible data storage.

4.2.4 Design Visualization and Evaluation

Upon completing the previous steps, step 6 illustrates the final architecture in Figure 4. In step 7, a comprehensive evaluation of steps 1 to 6 confirmed that the established goal was successfully achieved. This iteration effectively addressed the primary functionalities, quality attributes, architectural constraints, and concerns, ensuring the completeness of the cloud platform architecture design process. For brevity, the Kanban board has been omitted.

5 INTEGRATION

The AWS-based cloud architecture enables real-time monitoring of the automated fueling process, integrating the physical system, data sources, and end users

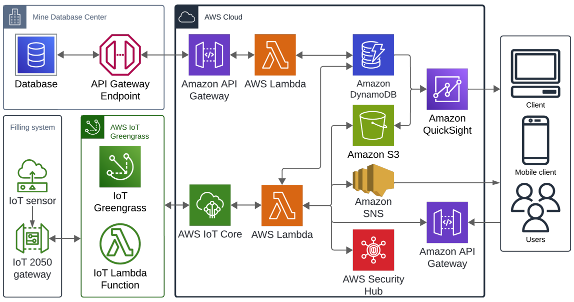

Figure 4: Cloud-Platform architecture diagram.

through IoT technology. As illustrated in Figure 5, data from the fleet management system and fuel suppliers is transmitted via IoT MQTT protocols to the cloud, where it is processed, stored, and made available for analysis. The system connects to a centralized mine database through an API integration service, ensuring secure data retrieval and storage.

Mine operators can access the system via a dedicated user interface, which provides real-time insights through reports and dashboards generated by the business intelligence service. This interface allows users to monitor fueling operations, track key performance indicators, and respond to alerts efficiently.

Inside the system cabin, the robotic arm, electrical panel, and monitoring components operate in synchronization to optimize fueling.

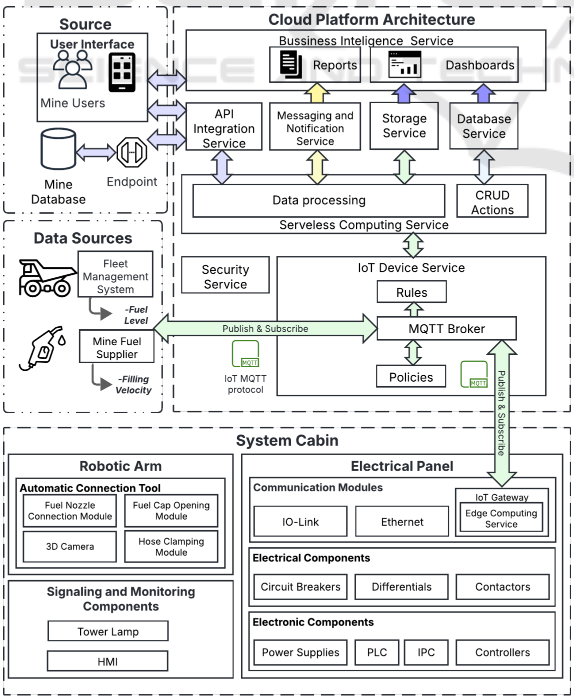

Figure 5: System Integration Diagram.

6 INTERFACE PROTOTYPING

Following the design process, the prototyping phase focused on developing user interfaces for the automated fueling system, accessible via the SIMATIC KTP700 Mobile HMI and a responsive web application.

The HMI interface (Figure 6) provides on-site operators with real-time data, including credentials, vehicle ID, fuel level, fill velocity, and process status. Intuitive action buttons streamline operation, minimizing errors.

The web application offers remote access from mobile and desktop devices, mirroring HMI functionalities such as authorization status, vehicle details, and process tracking. Cloud integration ensures secure, real-time synchronization, enabling fueling management from any location.

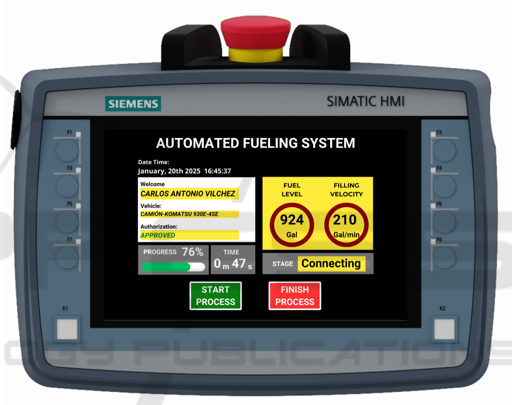

Figure 6: HMI interface Mockup.

7 CONCLUSIONS

This paper presents the design of an automated robotic fueling system for haul trucks in open-pit mining, addressing inefficiencies in the manual fueling process. The proposed system automates key tasks such as fuel nozzle positioning, authorization, and process monitoring, improving operational efficiency and reducing downtime.

The system design integrates IoT technology and a cloud-based platform, ensuring seamless communication between physical components and data sources. The implementation of the VDI 2206 methodology for the physical system and ADD 3.0 methodology for the cloud platform enabled a structured and scalable approach. The developed interface prototypes, including an HMI and a responsive web application, provide operators with real-time monitoring and control capabilities, enhancing usability and accessibility.

As a next step, future work should focus on the implementation of the cloud platform to validate the proposed ADD 3.0 design and assess its performance in real-world conditions. Further enhancements, such as predictive maintenance integration, could improve system reliability and scalability.

Overall, the proposed system demonstrates a viable solution for optimizing fueling operations in mining environments, offering potential for broader industrial applications.

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