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Real-Time Monitoring and AI-Based Control of Industrial Robots Using Cloud-Hosted Web Applications

1st Ravi Shankar Garapati

Sr. Software Engineer

ORCID ID: 0009-0002-1945-5796

Abstract—**Intelligent control mechanisms find increasing application in the control of continuous production machines, such as industrial robotic arms, through data derived from real- time monitoring systems. These systems, made available on cloud-hosted web apps, can contribute significantly to increasing robot operation predictability and flexibility. Latency remains a limiting factor when physical control is performed remotely; this shortcoming is addressed here by a monitoring system that extracts real-time and historic robot status data, used by an artificial intelligence (AI) agent to continuously optimize the control parameters of an industrial robot operated on a local and dedicated manufacturing floor. The research comprises three principal components: a real-time robotic monitoring system, an AI-based robot control system, and a public-facing web app that visualizes robot information and conveys control commands to the robotic control system. High-frequency and low-latency WebSocket communication between the web app and both monitoring and control systems ensures near-seamless and real- time robotic operation control. Remote data visualization and control functionality can ultimately support predictive robot maintenance in Industry 4.0 production settings.**

Index Terms—**Real-time monitoring, AI control, cloud-hosted web applications, industrial robots,Smart buildings, energy optimization, integrated circuits, energy consumption optimization, cloud-controlled factory, cloud-controlled industry, cloud control, cloud control policy planning, web-integrated, web-integrated artificial intelligence system, web-integrated AI, web-integrated AI system, web-integrated artificial intelligence.**

I. INTRODUCTION

Real-time monitoring and artificial intelligence (AI)-based control constitute an important part of the cyber-physical aspects of Industry 4.0. Cloud-hosted web applications allow engineers and operators to access robots and robot controllers from anywhere with an Internet connection. The interactive nature of these cloud clients allows real-time control of industrial robots and robot controllers, enabling seamless and low-latency interaction with these important systems. Industrial robots are an interesting use case for real-time data acqui- sition and control. They usually operate on cyclical paths and use many sensors to monitor their own operation and the surrounding environment. Due to their repetitive nature, any kind of anomaly can be an indicator of an underlying failure that will need to be addressed. Incoming sensor data can therefore be used together with data-driven AI agents to steer the robot's path in the most efficient way possible, which can also prevent future dangerous operations. Implementing such a solution on a cloud-hosted web application allows the control agents to interact with the robot and its sensors from anywhere in the world.The underlying architecture enables data security throughout the control process and seamless, low-latency interactions with the robot for optimal control. Cloud computing enables the possibility of using powerful algorithms and offers enhanced computing power and data storage. On the one hand, such control with AI is important to obtain good quality scheduling and predictive maintenance. On the other hand, the online status of the scheduling and AI control can be analyzed with the help of real-time monitoring. These features can be realized through a web application hosted on cloud platforms.

A. Background and Significance

Industrial robotics aims to provide a seamless interface for a variety of machine hardware. Although robots have been under development for decades, their use is typically constrained to specific, controlled environments. In recent times, the number of Industry 4.0 applications is increasing. Indeed, cloud com- puting is a critical aspect of Industry 4.0: virtualized resources can be served on demand over the Internet, following a pay- as-you-go business model. The hardware resources offered in the cloud can be used to provide various types of services, such as databases, IoT, infrastructure, software, and platform. Monitoring and controlling industrial systems are crucial to Industry 4.0. Real-time monitoring and AI-based control of industrial robots are possible by utilizing cloud computing resources.

II. BACKGROUND

Industrial robotics have evolved to embrace artificial intelligence (AI) technologies that orchestrate robot movement and task execution, fostering unprecedented levels of autonomy. The synergy of cloud computing and AI offers robust solutions for real-time scenarios, notable among them being real-time robot status monitoring and AI-based control al- gorithms. Embedding AI-based control into a cloud-hosted web application empowers users to remotely manage and optimize robot performance. Such instruction necessitates con- tinuous real-time data updates to sustain low-latency, seamless cloud–robot interactions. The continual advancement of infor- mation and communications technology has heralded a new

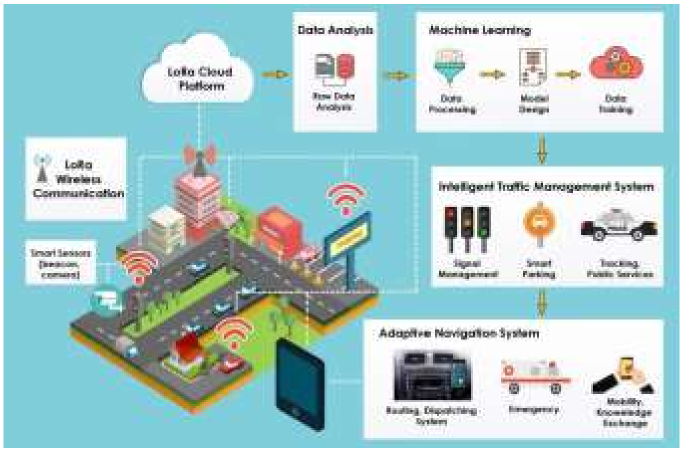

Fig. 1. Real-time traffic monitoring system

era of industrial production modes. Industry 4.0 epitomizes this transformation, emphasizing intelligent management and resource planning. Industry 5.0, emerging from the fusion of the Internet of Things and artificial intelligence, delineates the next stage of global manufacturing, steering industries toward autonomy and intelligence. Real-time status monitoring of industrial robots has thus garnered widespread attention. Furthermore, the ever-changing industrial landscapes and the imperative for sustainable development have exerted considerable pressure on the industrial economy. In response, cloud computing and artificial intelligence have been leveraged to address real-time challenges, with AI-integrated robot-control strategies and their deployment within cloud-hosted web applications gaining renewed focus.

A. Overview of Industrial Robotics

Industrial robots are automated devices designed to perform repetitive work within industrial spaces, such as manufacturing workshops or production lines. Since the first industrial robotic arm was installed in 1961, the application of these devices has increased exponentially. Today, companies use industrial robots to perform a multitude of tasks, ranging from spray painting vehicles to moving items within an assembly line. These robots enhance productivity, generate extra revenue and profit, and serve as a valuable resource for other activities. However, deciding to employ a robot represents only the first step of the process; the robot requires supervision during its operation within the workshop or production line to ensure it distributes its accumulated useful life evenly among its mechanical components. Supervising the workload of each robotic device will directly influence the maintenance schedule.

Equation 01: Full constrained QP (single-shooting MPC)

Decision vector $\zeta = [x_1^\top, u_0^\top, \ldots, x_N^\top]^\top$

Minimize $J(\zeta)$ from above s.t. linear dynamics constraints and box constraints. The KKT system for active-set QP is:

$$[HAA^\top 0][\zeta\lambda] = [-fb] \tag{1}$$

where H is block-diagonal with Q, R, S, and AA encodes dynamics

Control-variable optimization (tracking + energy/jerk regularization)

Design target: follow [reference or variable here] while smoothing torque/jerk and honoring constraints.

1. Horizon cost (discrete MPC/LQR form)

$$J = \sum_{k=0}^{N-1} \left(\| x_k - x_{k,\mathrm{ref}}\|_Q^2 + \| u_k\|_R^2 + \| \Delta u_k\|_S^2\right) + \| x_N - x_{N,\mathrm{ref}}\|_{Q_f}^2 \tag{2}$$

with $\Delta u_k = u_k - u_{k-1}$ (jerk/actuation smoothing proxy).

2. Constraints

$$u_t \le u_k \le \bar{u},\ \ v_t \le \dot{q}_k \le \bar{v},\ \ q_t \le q_k \le \bar{q},\ \text{ and dynamics} \tag{3}$$

$$x_{k+1} = A_d x_k + B_d u_k \tag{4}$$

3. Solution sketches

Unconstrained ⇒ Discrete-time LQR: compute P from the DARE and feedback $u_k = -Kx_k$ with

$$K = (R + Bd^\top PBd)^{-1} Bd^\top PAd \tag{5}$$

Constrained ⇒ QP per horizon; KKT conditions give a sparse linear system each control step.

As the manufacturing industry advances toward Industry 4.0, a stage involving the integration of Internet of things, cyber physical systems, big data, cloud computing, cyber security, and artificial intelligence, robots operating within industrial spaces should be supervised in real time via supervision systems hosted in the public cloud. The benefits of these solutions include reduced operational costs, improved human–machine interaction, and more effective use of dataset analysis generated by the robot itself. A real-time robot supervision system, hosted in a public cloud, will receive information related to the movement of each joint-playing axis, while the AI-based control mechanism analyzes real-time data to continuously evaluate the robot's status.

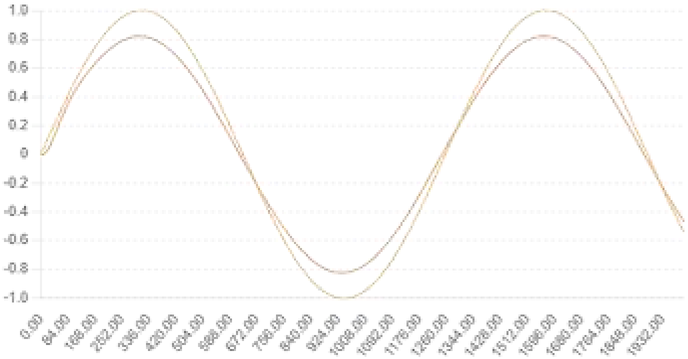

Fig. 2. Trajectory Tracking with 40 ms Delay (R=0.1)

channel	unit	sampling rate Hz	source
joint position	rad	250	Robot controller
joint velocity	rad/s	250	Robot controller
motor current	A	1000	Drive/DAQ
end effector force	N	200	Force-torque sensor

B. *Cloud Computing in Industrial Applications*

Cloud computing is a rapidly growing network-based technology that allows the on-demand provision of shared and virtualized computing resources, supplied remotely by a third-party cloud service provider. With its virtually unlimited processing power, cloud computing offers the ability to utilize sophisticated algorithms, such as advanced artificial intelligence (AI) techniques, deep neural networks, and machine learning, to derive control inputs and resolve computationally intensive problems in real time and at a low cost. Its integration enables systems to handle high Plex Levels of Automation and Digital Enterprise by supervising, coordinating, modeling, and controlling beyond mere control control. All of these benefits make cloud control particularly interesting for industrial control systems, which continue to adopt increasing levels of networking and information technologies to achieve the goals of Industry 4.0. An industrial control system (ICS) is a complex set of technologies capable of supporting industrial control functions in an array of production environments. It monitors and controls processes, operations, and equipment. However, the cloud can be a vulnerable interface between the physical and network environments of an ICS, and as the number of cyber–physical components continues to grow, the potential attack surface widens considerably. To address these security concerns, an analysis based on the CIA triad model presents two approaches for establishing encryptions that also protect the system's sensitivity levels—achieving the required confidentiality, integrity, and availability of the delivered service through the cloud.

III. REAL-TIME MONITORING SYSTEMS

Real-time monitoring of industrial robots demands the continuous update of control parameters to reflect operational conditions. The availability of real-time data provides an overview of the robot's current status and a suitable basis for control mechanisms that aim to optimize operational performance. The monitoring system's structure is presented here, followed by the description of the data acquisition procedure. The main goal of the monitoring system is to perform real-time control of an industrial robot by providing status information to an artificial intelligence model deployed in a software agent. Such real-time control requires low response times, which are guaranteed by deploying the web application in a cloud environment. A cloud-hosted web application can interact with the real robot during mission execution due to the low latency achievable through proximity placement of the cloud server. The monitoring system enables the control of the robot through the artificial intelligence model by collecting updated values of actuator electric currents, joint positions, and speeds. These data are collected during the job execution of the real robot and are transmitted to the artificial intelligence model in input to establish the operation parameters for the following iteration.

A. *Architecture of Monitoring Systems*

Monitoring systems for industrial robots comprise modules performing specific functions, such as data acquisition, analysis, processing, feedback, and transmission. The primary objective of a real-time monitoring system is twofold: tracking the status of the robot itself and continuously supervising the production process to promptly identify the status of the parts being produced. The architecture of a typical process monitoring system is depicted in Figure 1.

Data Acquisition (DAQ) is critical for real-time monitoring, bridging the physical and cyber components of the system. A DAQ system comprises hardware and software designed to sample physical conditions and relay the resulting data to a computer. Together with sensors, the DAQ system forms the front end of the monitoring system, characterized by the number and type of sensors and the DAQ hardware.

In a comprehensive setup, groups of sensors are placed at one or several resource stations across a production process. Sensor data is acquired through corresponding DAQ hardware components—each associated with its set of sensors—and transmitted to a computer.

B. *Data Acquisition Techniques*

The acquisition of real-time data for monitoring and control of industrial robots represents the first focus area. The acquisition of robots status data can be categorized in three broad groups: from the robot controller; from external devices mounted in the robot structure; and from external devices placed in the robot environment. The first group represents the most suitable alternative for real-time monitoring and control because the data is obtained directly from the robot controller, so the monitoring is continuous and with negligible latency. The real-time data is read through standard communication interfaces, such as Ethernet and field buses, or proprietary ones, such as KUKA Rnet, FANUC FOCAS, and ABB PCSDK. In the remaining groups, the data is extracted by specific sensors and external devices, instead

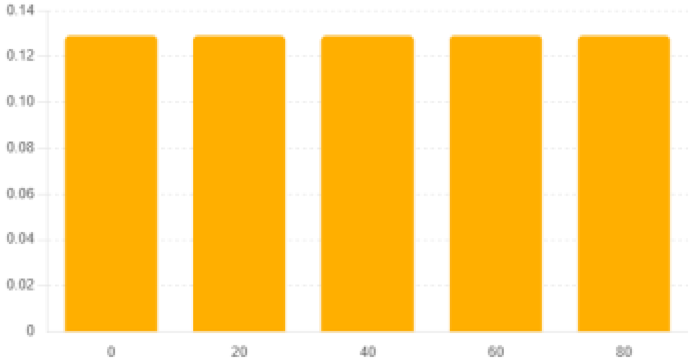

Fig. 3. Effect of Network Delay on Tracking Error

of from the robot control system. For proximity sensors, force and torque sensors, laser scanners, cameras, and microphones, the sampling frequency and the proximity to the robot affect the definition of the extracted information content, so the analysis can be done at different level (from current robot movement to the entire environment) and at different time scales (from real-time to batch or post-downtime).

Equation 02: Cloud-based learning & model updates (online SGD with drift)

1. Streaming loss
For model θ and incoming batch B_t:

$$L_t(\theta) = |B_t| 1 \sum_{(x,y) \in B_t} \ell(f_\theta(x), y) + \lambda \|\theta\|_2^2 \tag{6}$$

2. Delay-aware SGD update
If gradient from edge/agent arrives with staleness (due to network/compute):

$$\theta_{t+1} = \theta_t - \eta_t w(s_t) \nabla L_t(\theta_t - s_t) \tag{7}$$

where $w(s_t) \in (0, 1]$ down-weights stale gradients (e.g., $w(s) = \frac{1}{1+\alpha s}$).

3. Adaptive step size (Robbins–Monro conditions for convergence):
$\sum_t \eta_t = \infty$, $\sum_t \eta_t^2 < \infty$. In practice, use Adam/RMSProp with gradient clipping under bounded delay.

IV. AI-BASED CONTROL MECHANISMS

Data-driven intelligent control of robot manipulators has attracted much attention. By incorporating externally collected data, control of robot manipulators can become more adaptive in complex situations. The varying condition of an item affects the proper parameters for robot execution, which in some cases can be seen through the image of the item. Therefore, the control of the robot needs to be adaptive to the item detected. The images can be collected by cameras installed in the vicinity, such as in the real-time monitoring system. Real-time monitoring provides valuable information for AI-based control, allowing the robot to adapt automatically to the different characteristics of each item through machine learning. The online monitoring system of the industrial robot plays an essential role in assisting the operation and maintenance process, which in turn reduces the downtime of a production line.

The rapid and non-invasive tool wear monitoring method combines Raman spectroscopy and Gaussia, which use the Gaussian process regression (GPR) algorithm. The algorithm enables more reliable estimations of residual tool life. Several artificial intelligence approaches based on electrical signals generated during the machining process provide useful information about the health condition of a manufacturing tool. A real-time controlling system is developed, in which the vibration signal of the spindle is continuously monitored, and tool movement is modulated if the operating vibration level exceeds a pre-defined threshold, thus preventing severe injury to the tool.

A. Machine Learning Algorithms

Machine learning is considered a subset of artificial intelligence that enables a model to learn from data, identify patterns, and make decisions with minimal human intervention [1]. These algorithms build a mathematical model based on sample data and then use this model to make predictions or decisions without explicit programming for that task. Machine learning algorithms are divided into three broad categories: supervised learning, unsupervised learning, and reinforcement learning.

Supervised learning involves building a model based on input data that is labeled with the corresponding correct answers. This model is then used to predict the labels of unknown data. Conversely, unsupervised learning algorithms attempt to find hidden patterns or intrinsic structures within data that is not labeled. At last, machine learning can also be done by means of reinforcement learning, a category in which algorithms are designed to maximize the reward during learning by taking suitable actions.

B. Control Strategies for Robotics

Implementing AI control over industrial robots through a cloud-hosted web application that collects data in real time for prediction and control calls for a novel approach to creating control models of industrial robots. The key challenge lies in ensuring a seamless, low-latency interaction between robots and cloud-apps designed to optimize the performed task.

The rapid advancements in cloud computing have led to a rapid growth of the services provided through unlocking the cloud resources and services for accomplishing sophisticated

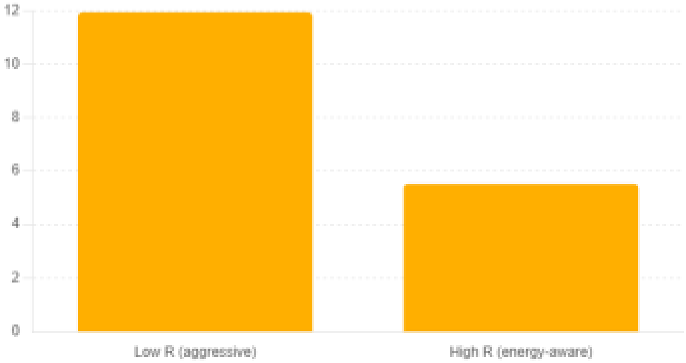

Fig. 4. Energy-Performance Trade-off via LQR R-weighting

tasks, such as intelligent robot control and applications.

The pivotal aspect of the robot control or parametrization lies in the manner in which the data used for such control are gathered. In other words, the acquisition of the robot's real-time data is what enables the generation of control instructions. On the other hand, it is precisely the detection of a potentially harmful manufacturing operation condition that should be communicated and employed to modify the robot's operative parameters. In either case, the data, issued by the robot itself or detected by the artificial intelligence designed for it, must be received and interpreted via a web service with the ability to control the real-time system of the robot.

Equation 03: Web-interface integration (latency budget and stability margin)

1. Latency budget

$$TRTT = Tsense + TDAQ + T\hat{} + Tproc + T\_ + Tact \quad (8)$$

2. Sampling & discrete delay

With sampling period T_s and total delay $T_d \approx mT_s$ (integer m), the closed loop sees an extra factor z^{-m}.

3. Rule-of-thumb stability bound

For a loop with gain crossover frequency ω_c and phase margin ϕ_m, the maximum allowable delay is approximately

$$T_{d,\max} \approx \frac{\phi_m}{\omega_c} \quad (9)$$

V. CLOUD-HOSTED WEB APPLICATIONS

Industrial robots are widely used in manufacturing and other industrial applications to increase efficiency and safety. When the application of robots moves toward industry control, robots need to be monitored and controlled continuously because real-time monitoring and AI-based control can reduce unexpected errors during the operation of the robots. Cloud computing offers access to resources, virtualized data, and services, and creates services and applications. Naturally, the functionalities of monitoring and controlling industrial robots can be delivered as services remotely through cloud-hosted web applications. These applications gather data from industrial robots, transmit that data to a cloud database, and, with the aid of AI algorithms in the cloud, deliver control instructions back to the robots in real time.

An established AI control framework for industrial robots includes the ability to predict performance indicators and determine optimal control inputs. By storing monitoring data within the cloud infrastructure, the cloud also becomes a suitable platform for process-based monitoring. Cloud robotics strives toward seamlessly integrating robots with the Internet, using information services to support predictability, interop- erability, cloud-handling, and other smart robotic functions. Reliable interaction between robots and smart cities neces- sitates real-time bidirectional communication, which requires advanced safety and privacy management of the cloud. The many faces of cloud computing introduce a variety of issues and challenges in design and implementation.

A. Design of Web Applications

Web applications are designed to be hosted in the cloud, establishing the infrastructure to ensure seamless and fluent interaction with the robotic systems, that is, real-time control of industrial robots. The applications act as a web service and are invoked whenever an operation is requested, which results in restarting the platform inside the service, but guarantees the resources assigned for a real-time application. The purpose is to continuously receive the information from the industrial robot, store it in a database, and utilize it for control. For this reason, the connection with the real-time monitoring system maintained in the background remains active such that the data can be acquired and re-injected into the system at any given time—whether for detection or for such control.

B. Integration with Robotics Systems

Real-time monitoring systems acquire data on robot status and condition in industry, enabling rich information flow to improve productivity and machine safety. When controllers exploit this data—particularly by integrating artificial intelligence (AI) support—robot control reaches a new level of intelligence. Industrial robots continue to gain prominence in contemporary manufacturing, while cloud computing has become a prime technological advance. Together, these trends have led to cloud robotics, a dynamic, mobile, connected, and safely shared robotic service platform with exceptionally broad application prospects. Cloud robotics management systems design and implement cloud-hosted web applications for robot control. The architecture enables real-time status monitoring to deliver intelligent cloud control of industrial robots. Interaction between the system and the robot must be seamless and sensitive: the system requests data as needed, and the robot immediately provides real-time information. This strategy shields operators from robot-control complexities and offers a friendly interface. In practice, the system functions as a user input medium, with each operator

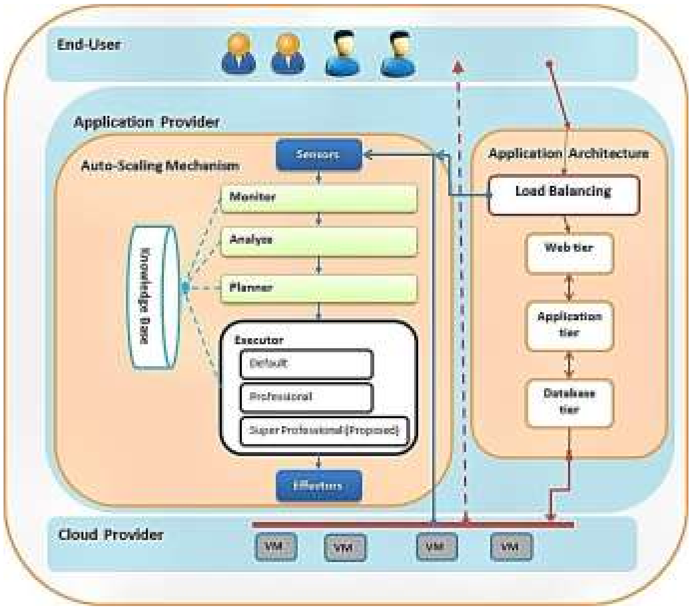

Fig. 5. Cloud-based Web Application Development

command instantaneously executed by the robot. Operating through a publicly accessible IP address, the system stores interaction data to enhance robot control precision, such as scheduling future maintenance during low-activity periods. Employing an artificial neural network (ANN), the system translates user instructions into robot control commands, thereby preventing damage from incorrect inputs.

Equation 04:Total energy optimization over horizon

1. Instantaneous mechanical power

$$P(t) = \tau(t)^{\top}\omega(t), \text{ where } \omega^{\cdot} = \dot{q} \tag{10}$$

2. Discrete total work (absolute, to penalize bidirectional effort)

$$E = \sum_{k=0}^{N-1} |\tau_k^{\top}\omega_k| \, T_s. \tag{11}$$

3. Include in MPC objective

Augment J with ρE or, convexly

$$\rho \sum_{k} |\tau_k|_1 T_s / \rho \sum_{k} |\tau_k|^2 T_{s_2} \tag{12}$$

VI. Data Security and Privacy

Cloud computing impacts companies of all sizes and across nearly all industries, providing more capability, capacity and power than ever before. These benefits come with its own risks and companies must assess security risks when moving to the cloud. Human errors or security bugs in cloud platforms may cause a risk to user data privacy. Cloud service providers allow users to manage security, but users must trust their cloud service providers not to reveal their private data and have little knowledge about the cloud-control operation. Although cloud computing faces many security challenges, highly sensitive information such as health data can also benefit from the cloud's capabilities. Homomorphic cryptography can provide confidentiality and allow search in encrypted data. In cloud robotics, it is possible to encrypt computations, enabling a robot to outsource an execution of tasks to the cloud without disclosing the sensitive information that is embedded in the program, such as security-aware log analysis or privacy-aware input–output processing.

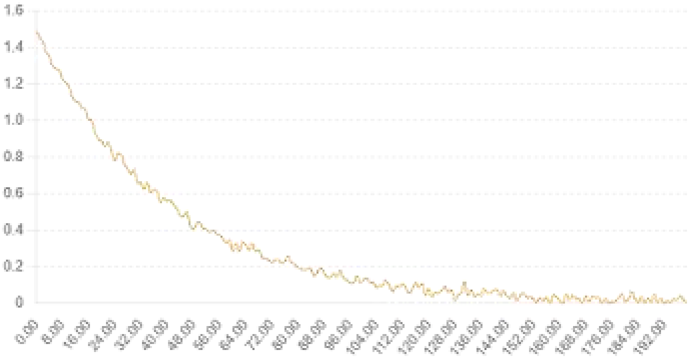

Fig. 6. Cloud-Based Model Updates: Training Loss (Illustrative)

A. Challenges in Cloud Security

Almost all the data recorded and analyzed remotely must pass through the Internet, making it potentially accessible to hackers and data thieves. Cloud security is an ongoing concern, and any data uploaded to the cloud should be stored in an encrypted format. Although SOAs offer the ability to apply encryption techniques to the transmission of data, the least secure element must be identified and secured to ensure the security of the entire communication.

B. Data Encryption Techniques

With the widespread adoption of cloud computing, increasing attention is being given to data security and privacy issues, especially for sensitive data or data generated by critical infrastructures. Transitioning from closed management to open service is an inevitable trend, as hierarchical network architectures, traditional single-point policies, or account lists cannot effectively guarantee security and privacy in open environments. Data encryption techniques can protect data through column transformation and state restructuring or by introducing a key vector. Transforming data into ciphertext before transmission or download prevents eavesdropping along the channel. However, this approach introduces the challenge of allowing the user to operate on ciphertext without the encryption phase cancelling the original function of the data. In the context of robot real-time monitoring, AI-based control, and cloud-hosted web applications, data security and privacy issues can arise during the interaction phase. Cloud security threats stem from the inherent weakness of cloud itself, cloud attributes, architecture design, technology, and application scenarios. Accordingly, network architecture, boundary defense, and data encryption in cloud service become essential to its security construction. For example, a technique based on the XOR gate and chaotic logistic parameter was proposed, generating new permutations by altering the parameter and performing permutation on the original image to hide the original relationship between adjacent pixels. For an original gray-scale image, the absolute difference between the encrypted image of adjacent pixels is changed to adequately conceal the original pixel image information.

VII. CONCLUSION

Major advances in artificial intelligence (AI) and cloud computing have fostered tighter integration among Internet of Things (IoT) applications. Industry 4.0 developments have stimulated greater utilization of intelligent industrial robots to undertake monotonous, repetitive, and dangerous manufacturing tasks. Real-time monitoring and control of robots using AI techniques offer numerous benefits to manufacturers. Real-time monitoring systems do not merely collect and present data but also instantaneously alert users regarding imminent anomalies. Similarly, robotics control systems do more than operating robots by precisely determining their trajectory, speed, and movement; they also incorporate data mining and machine learning algorithms to recommend faultless control inputs. The objectives of a real-time monitoring system for intelligent industrial robots include timely fault detection, prediction, and prevention. These capabilities facilitate proactive task planning, thereby minimizing downtime and optimizing resource utilization. AI-based control mechanisms holistically enhance operational productivity by addressing the trajectory and speed of robot movements; they encompass path planning, navigation, manipulator control, and sleep mode activation whenever possible. Advanced control mechanisms can even generate new task requests. Opting for cloud-hosted web applications ensures straightforward access to robots. To enable unified and dynamic interactions with robotic systems in real time and with minimal latency, dedicated Application Programming Interfaces (API) are developed and cloud-hosted. These solutions collectively contribute to improved efficiency and operational intelligence in manufacturing environments.

A. Emerging Trends

Real-time monitoring and artificial intelligence-based control of industrial robots integrated with cloud-hosted web applications present promising concepts in the area of Industry 4.0. Artificial intelligence (AI) supports extensive decision-making, enabling industrial robots to cope with unforeseen situations instead of being controlled solely by predefined program instructions. Monitoring data of the robots' operational status are stored in the cloud, creating the conditions for taking advantage of the communication benefits offered by cloud computing. Applications are hosted in the cloud, establishing seamless and low-latency interaction with the robots for real-time control.

The system developed offers an efficient way to send actions to the robot based on its current status gathered through sensors. The data obtained are transmitted to the cloud, where a machine learning model processes the information and determines the most suitable action to optimize the operation. Finally, the command generated by the model is sent back to the robot. From the robot point of view, actions can be sent from the web application to control every aspect of its operation towards optimization, such as the operation speed. From the user point of view, the priority lies in predicting errors or identifying the most suitable action in a specific situation, making it possible to maintain the mission of the robot, ensure its durability and implement predictive maintenance.

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