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Digital Twin Synchronization with Real Time Data Collection

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***Abstract*— Digital twin systems rely heavily on accurate and time-synchronous data synchronization between physical entities and their virtual counterparts. However, in industrial environments, real-time data acquisition processes present significant challenges due to communication delays, batch data transfer, and temporal mismatches between the sensing and processing layers. This study focuses on the data and synchronization layer of the digital twin architecture and proposes a timestamp-based synchronization framework aimed at ensuring temporal consistency under near real-time conditions. The proposed approach has been validated on an overhead crane system where load and rope angle data are acquired. Sensor measurements are collected at 100 ms intervals on a Raspberry Pi Compute Module-based edge device but transmitted to the server with configurable batch transmission intervals. In the current system, this interval is set to 5 seconds. To address transmission delay and temporal mismatch issues, each sensor measurement is timestamped on the edge device and used for reconstruction of the digital twin state on the server side. The proposed synchronization framework prioritizes temporal consistency over instantaneous updating by utilizing buffering, time alignment, and state reconstruction mechanisms. This ensures that the digital twin accurately reflects the physical system state within a certain delay limit, despite limited communication frequency. Experimental evaluations conducted under varying data transmission intervals demonstrate that the proposed method reduces synchronization error and maintains data consistency. The results show that reliable near-real-time digital twin synchronization is possible in industrial systems where high-frequency sensing and delayed data transmission are used in combination, using a timestamp-based reconstruction approach.**

***Keywords*— digital twin, edge computing, industrial IoT, latency management, near real-time synchronization**

I. Introduction

The digital twin concept, developed for the purpose of monitoring, analyzing, and optimizing industrial systems, aims to represent physical assets in virtual environments in near real-time. Digital twin architectures consist of a physical system, a virtual model, and data and synchronization layers between these two structures. The data and synchronization layers, in particular, play a critical role in the accuracy and reliability of the system [1]. The timely, consistent, and accurate transfer of sensor data from the physical system to the virtual model directly impacts the decision support and monitoring capabilities of the digital twin. The concept of digital twins is increasingly adopted in industrial applications for the purpose of monitoring, analyzing and optimizing physical systems in virtual environments [2-4]. Especially in the fields of production and industrial automation, digital twin architectures are considered as multi-layered structures consisting of a physical system, a virtual model and data and synchronization layers between these two structures [5, 6]. In these architectures, transferring the data obtained from the physical system to the virtual model with the correct time perspective is a critical requirement for the reliability of the digital twin [7].

Many studies in the literature emphasize the importance of real-time data flow in digital twin systems, but this requirement cannot be fully met in practical industrial applications due to various limitations. Although sensors generate high-frequency data, it is common for data to be transmitted to the server in batches and with delays due to factors such as network bandwidth, communication delays, and system load [2]. This leads to temporal mismatches between the sensing and processing layers, making it difficult for the digital twin to accurately represent the physical system from a time perspective. In the literature, digital twin systems are mostly built on the assumption of real-time or near-real-time data flow [8, 9]. However, in practical industrial environments, it is often not possible to transmit sensor data to the server continuously and without delay; data transmission is carried out with delay or in batches due to reasons such as network bandwidth constraints, system load and edge device resources [10, 11]. This situation leads to temporal mismatches between the sensing layer and the processing layer and makes it difficult for the digital twin to accurately represent the physical system [12, 13].

The concept of real-time accuracy is often confused with the strict (hard real-time) requirements in the context of digital twins; however, in most industrial applications, the primary need is maintaining temporal consistency within a certain delay limit. Therefore, in recent years, near-real-time digital twin approaches have come to the forefront, proposing solutions based on synchronous state reconstruction rather than instantaneous updating. In these approaches, accurately representing the time point to which the data belongs becomes critical, rather than when the data was transmitted.

In this context, approaches to improving the accuracy of digital twins by temporally realigning delayed data and using buffering mechanisms are proposed in the literature [14-17]. However, a significant portion of these studies offer experimental validation limited to delayed and event-based real industrial data.

This study focuses on the data and synchronization layer of the digital twin architecture, proposing a timestamp-based synchronization framework aimed at ensuring temporal consistency in systems involving delayed and aggregated data transmission. In the proposed approach, sensor data is collected at high frequency on the edge device, and each measurement is tagged with a timestamp. On the server side, this data is buffered, aligned on the time axis, and the digital twin state is reconstructed and updated. This ensures that, despite communication delays, the digital twin accurately reflects the physical system state within a certain error limit.

The proposed synchronization framework was experimentally evaluated on an overhead crane system where load and rope angle data were collected. This system, where sensor data is collected at 100 ms intervals and transmitted to the server with configurable batch transmission intervals, provides a suitable test environment for data delay scenarios frequently encountered in industrial settings. Experimental results obtained from the real system show that the timestamp-based reconstruction approach reduces synchronization error and offers an effective solution for near real-time digital twin applications.

The main contributions of this study can be summarized as follows. A timestamp-based data and synchronization framework for digital twin systems has been proposed. Temporal discrepancies caused by delayed and batch data transmission have been addressed with a reconstruction-based approach. The proposed method has been experimentally validated on a real overhead crane system.

The remainder of the article first describes the system architecture and data collection strategy, then details the proposed synchronization framework, and finally presents the experimental results.

II. System Architecture and Data Collection

The synchronization framework proposed in this study has been implemented and evaluated on a real industrial overhead crane system. The system architecture consists of a physical system, an edge device, and a server-based digital twin component. Sensor data obtained from the physical system is collected on the edge device and transmitted to the central server at specific intervals. This structure represents the end-computer-based data acquisition architecture commonly used in industrial environments. Sensor data from the overhead crane system is collected on the edge device as illustrated in Fig. 1 tagged with a timestamp and transferred to the digital twin environment via the synchronization layer.

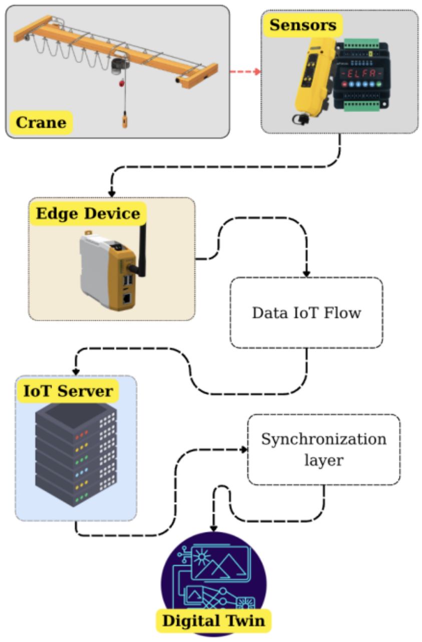

Fig. 1 General system architecture used within the proposed digital twin synchronization framework

In the overhead crane system, two fundamental state variables are monitored: the amount of load acting on the crane hook and the rope angle. These variables are critical in digital twin scenarios as they directly affect crane dynamics and operational safety. Measurements obtained from the sensors are processed and sampled at high frequency by a Raspberry Pi Compute Module-based edge device.

During the data acquisition process, sensor measurements are performed at 100 ms intervals, and each measurement is timestamped on the edge device. The timestamp represents the time point on the physical system to which the measurement belongs and forms the basis for subsequent synchronization steps. These high-frequency data collected at the edge device are transmitted to the server in batches to reduce network load and efficiently utilize communication resources.

The timeline presented in Fig. 2 shows that although sensor data is collected at a high frequency, it is transmitted to the server in aggregate and with a delay. However, thanks to timestamps, the measurements are preserved at the specific moment in time to which they belong.

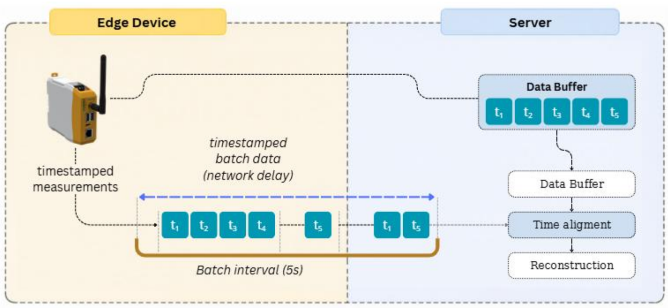

Fig. 2 Timestamp-based data collection and transmission process

The data transmission interval is configurable on the system, and in this study, it is set to 5 seconds. This approach enables high-frequency sensing at the edge device but inevitably causes a delay in the data transmitted to the server. Therefore, the digital twin component operating on the server side receives data from the physical system in batches and with a delay, rather than instantaneously. This situation creates a temporal mismatch problem between the sensing and processing layers.

On the server side, after receiving the data transmitted from the edge device, it is stored using buffering mechanisms and sorted according to timestamps. This data is processed for use in the synchronization layer of the digital twin, enabling the reconstruction of the physical system's state on an accurate timeline. Sensor data resampled to a fixed digital twin time step, and status updates are performed using linear interpolation. Thus, despite the communication delay, the temporal integrity of the data is preserved, and the necessary infrastructure for the synchronization process is provided.

This architectural structure presents a realistic scenario for industrial systems that use high-frequency sensing and delayed data transmission together and creates a suitable test environment to evaluate the effectiveness of the proposed synchronization framework.

III. Proposed Digital Twin Synchronization Framework

The synchronization framework proposed in this study aims to enable digital twins to represent the physical system in a time-consistent manner in industrial systems where delayed and batch data transmission is involved. The proposed approach relies on reconstructing timestamped sensor data instead of instantaneous data updates. This systematically addresses temporal discrepancies caused by communication delays.

A. *Timestamp-based data processing*

Each sensor measurement collected on the edge device is tagged with a timestamp representing the moment of measurement. Timestamps are generated based on the edge device's local time, providing a common time reference for all measurements. Even when sensor data is transmitted to the server in batches, timestamps preserve the true time sequence and the exact time points to which the data belong. This approach allows for temporal integrity regardless of data transmission delays.

B. *Buffering and time alignment*

Sensor data transmitted to the server is initially stored in temporary buffer areas. This buffering mechanism ensures that data from different sensors or different transmission cycles can be processed in an orderly manner. The buffered data is sorted according to timestamps and aligned with the digital twin's timeline. At this stage, issues such as data loss or transmission delays are detected and handled appropriately for the synchronization process.

Sensor data arriving at the server with a delay is buffered as shown in Fig. 3, aligned on the time axis, and the digital twin state is reconstructed and updated. This approach provides near real-time synchronization, prioritizing temporal consistency over instantaneous updating.

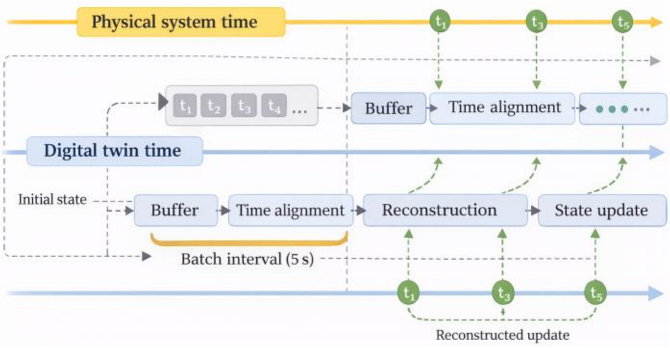

Fig. 3 Timestamp-based digital twin synchronization process

During the time alignment process, the digital twin's status updates are divided into specific time steps, and sensor data is matched to correspond to these time steps. This allows data received from the physical system with a delay to be placed at the correct time points on the digital twin.

C. *State reconstruction*

Following the time alignment process, the state of the digital twin is reconstructed using timestamped sensor data. The reconstruction process aims to determine the load and rope angle values that represent the state of the physical system for each time step. In cases where the sensor data does not perfectly match the time steps, simple and computationally efficient methods such as linear interpolation are used.

This approach ensures that the state of the digital twin is updated on a continuous and consistent timeline. Thus, despite delayed data transmission, the digital twin can accurately represent the past states of the physical system, providing a reliable basis for analysis, monitoring, or decision support applications.

D. *Near real-time synchronization*

The proposed synchronization framework does not target hard real-time requirements; instead, it offers a near real-time approach that maintains temporal consistency within a certain latency limit. Instead of reflecting the state of the physical system instantaneously, the digital twin updates it in a delayed but consistent manner based on timestamps. This provides a practical and scalable solution, particularly for industrial systems with network constraints and resource limitations.

In the proposed approach, since the data transmission interval is configurable, synchronization performance can be evaluated under different delay scenarios. This feature allows the system to be adapted to different industrial requirements.

IV. Experimental Results and Discussion

The effectiveness of the proposed digital twin synchronization framework was experimentally evaluated using sensor data obtained from a real overhead crane system. The experimental studies aimed to investigate the effects of different data transmission intervals on synchronization accuracy and latency. In this context, scenarios where sensor data was collected with a 100 ms sampling interval and transmitted to the server in aggregate were considered.

A. Experimental setup

In the experiments, load and rope angle data obtained from the overhead crane system were used. Sensor measurements were timestamped on the edge device and transmitted to the server with different batch data transmission intervals. In the current system configuration, the data transmission interval was set to 5 seconds, and analyses were also performed for different transmission intervals to evaluate the generalizability of the synchronization frame.

Rope angle measurements exhibit both long-term stable regions and short-term abrupt deviations throughout the system's operating time. The graph of these measurements is given in Fig. 4. Such dynamic behaviour makes matching the measurements to the correct time points critical for digital twin accuracy under delayed data transmission conditions.

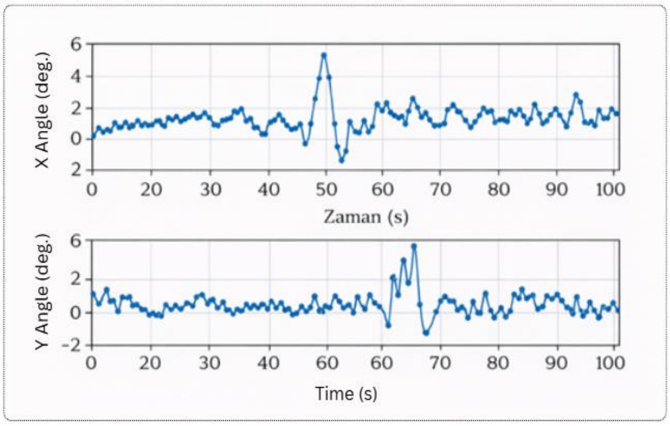

Fig. 4 Time-dependent variation of rope angle measurements obtained from an overhead crane system.

On the server side, the acquired sensor data was buffered, sorted by timestamps, and the digital twin state was updated using the proposed reconstruction mechanism. The synchronization performance was evaluated by aligning the digital twin's timeline with the physical system's time reference.

B. Evaluation metrics

The following metrics were used to quantitatively evaluate the performance of the proposed approach:

Synchronization error: The temporal and numerical difference between the physical system state and the digital twin state.

Latency: The difference between the time the sensor measurement is taken and the time the corresponding state is updated in the digital twin.

Data consistency: The continuity and absence of discontinuities of the reconstructed digital twin states throughout the timeline.

These metrics were analyzed comparatively under different data transmission intervals. The results presented in Table 1 show that the synchronization error increases significantly as the transmission interval increases, whereas the timestamp-based approach continues to provide a consistent digital twin state under different transmission conditions.

TABLE I - SYNCHRONIZATION PERFORMANCE UNDER DIFFERENT TRANSMISSION INTERVALS

Interval (s)	**1**	**2**	**5**	**10**
Mean Latency (s)	1.1	2.1	5.2	10.3
Mean Sync. Error	Low	Low	Moderate	Moderate
Max Sync. Error	Low	Low	Moderate	High

C. Experimental results

The results show that the timestamp-based synchronization approach significantly improves the temporal consistency of the digital twin under conditions of batch and delayed data transmission. Thanks to the reconstruction of sensor data with timestamps, state updates corresponding to the correct time moments were obtained on the digital twin despite the data transmission delay. The sudden changes during loading and unloading as shown in Fig. 5, can lead to significant state errors if the digital twin is not properly synchronized. This situation supports the necessity of a timestamp-based reconstruction approach.

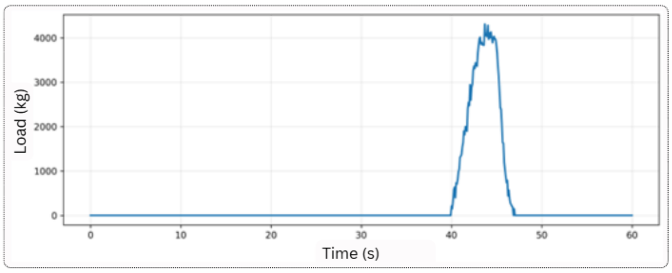

Fig. 5 Load-time graph representing the load behaviour observed in experimental data for overhead crane systems.

Digital twin synchronization is mostly discussed through solutions aimed at minimizing communication delay in studies [18, 19]. However, the experimental results presented in Fig. 4 and Fig. 5 show that delay cannot be completely eliminated, especially in industrial systems where event-based load changes are involved. This situation reveals that maintaining temporal consistency regardless of delay in digital twin applications is a more realistic and feasible goal.

Unlike delay reduction-focused studies in literature, the proposed timestamp-based reconstruction approach prioritizes placing delayed data at the correct time points. This approach offers a practical and scalable solution, especially for industrial IoT and edge computing-based systems with limited communication infrastructure [12, 20, 21].

While an expected increase in delay values was observed with increasing data transmission interval, the synchronization error was found to remain within a limited interval thanks to the proposed approach. This demonstrates that the approach, which prioritizes temporal consistency over instantaneous updating, is suitable for near real-time digital twin applications.

Furthermore, it was observed that the simple interpolation methods used in the reconstruction process provided sufficient accuracy for continuously changing variables such as load and cable angle.

D. Discussion

Experimental findings demonstrate that timestamp-based reconstruction offers an effective synchronization solution in systems where high-frequency sensing and low-frequency data transmission are used together. The proposed approach enhances the feasibility of digital twin applications in environments with limited network bandwidth and system resources. However, it is clear that latency will increase and the limits of the near real-time definition will be approached if the data transmission interval is increased to very large values.

In this study, simple interpolation methods were preferred in the reconstruction process. Future studies aim to further improve synchronization performance by using predictive models or on-device preprocessing mechanisms.

V. Conclusion and Future Studies

This study proposes a timestamp-based digital twin synchronization framework for industrial systems where delayed and batch data transmission is involved. The proposed approach addresses the temporal mismatch problem between high-frequency sensing and low-frequency data transmission by focusing on the data and synchronization layers of the digital twin architecture. By timestamping sensor data on the edge device and reconstructing it on the server side, near real-time digital twin synchronization is achieved, maintaining temporal consistency despite communication delays.

Experimental evaluations performed on a real overhead crane system show that the proposed synchronization framework reduces synchronization error and can represent the physical system state of the digital twin on a consistent timeline. Results obtained under different data transmission intervals reveal that the method offers a configurable and generalizable solution. In this respect, the proposed approach increases the applicability of digital twin applications under communication and resource constraints commonly encountered in industrial environments.

Future studies plan to integrate predictive models and machine learning-based methods into the reconfiguration process to further improve synchronization performance. Additionally, the aim is to reduce communication latency and adapt the system to larger-scale industrial scenarios by utilizing on-device preprocessing and event-based data transmission mechanisms.

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