A Collaborative Work-Cell Testbed for Industrial Wireless Communications — The Baseline Design

***Abstract*—TO-DO: 1) author list; 2) blind review process?**
Being the atomic service unit in a plant, the work-cell is a promising use case for testing industrial wireless communication techniques used for reliable and deterministic data transmissions in factory automation processes. To facilitate such studies, a testbed is proposed which replicates essential work-cell elements under generic production scenario settings. Communications between the supervisory controller, machining tools, and robotic operators are characterized in production operations and made accessible for performance evaluation.

***Index Terms*—industrial wireless communications, industrial wireless networks, factory automation processes, testbed design.**

I. Introduction

Industrial plants are the interconnected cyber-physical systems (CPS) that utilize evolving information technologies (IT) to leverage operational technology (OT) insights into production processes. As an integral part of CPS, industrial communication networks connect various field instruments to their control units and transport mission-critical process variables in between [1]. Compared with wired connections, wireless links have their unique advantages in connecting field sensors and actuators with the reduced cabling cost and natural support of mobility [2]. They have gained an increasing attention in the Industry 4.0 and Smart Manufacturing initiatives which are recruiting more real-time data in the field for factory automation applications [3], [4].

Timely and reliable wireless transmissions are the key to agile plant operations responding to both in-process and ambient variations for the improved production efficiency, asset health, and workplace safety [2]. Variable and diverse networking strategies and wireless techniques have been developed to ensure the quality of service (QoS) in industrial wireless communications. Evaluating wireless technologies in terms of their eligibility and performance with diverse industrial use cases have proven to be challenging but essential to industrial wireless implementations [5], [6].

Evaluation platforms play an important role in verifying the wireless network design and comparing the performance different wireless technologies. They provide modeling details of performance requirements and operation specifications on data transmissions in typical industrial wireless use cases, e.g., the plant layout, process workflow, wireless channel model, and data traffic pattern. Modeling efforts have been taken at both the macro level, e.g., spatial statistics of the node density and traffic load on the factory floor, and the micro level, e.g., the latency and interference level in a single transceiver pair. Based on these models, system verification methods using co-simulation platforms [7], [8], [9], [10], hardware-in-the-loop (HIL) experiments [11], and testbeds [12] become popular in studying the unique industrial environment and service characteristics. However, existing solutions on modeling plant factors cannot unfold the whole picture regarding the evaluation purposes. First, most of current discussions are one-way, i.e., mainly describing the impact from industrial operations and environments onto wireless transmissions. Since industrial CPS are featured with the interplay between industrial processes and data networks, the CPS model is expect to represent such a mutual impact. Second, the network design and optimization are usually based on static system settings. The model is expected to indicate the evolving system performance under iterative collaborations between production processes and wireless networks in both short-term and long-haul operations. Last but not least, machine-to-machine (M2M) communications generate and consume data in a vast different way compared to the conventional human-centric Internet data. The model also needs to characterize and verify various traffic models, both empirical and statistic.

To facilitate wireless network researches and showcase the power of wireless technologies in industrial practises, a new testbed is being developed at the National Institute of Standards and Technology (NIST). This paper elaborates the testbed's baseline design which identifies various data needs in the emulated industrial operations and calibrates the performance under hardwired connections before wireless extensions. Generally, there are three innovative features in the testbed.

First, the testbed provides a new perspective on modeling data activities and networking needs in industrial CPS. The work-cell is at the "right" size to captures essential data communications between industrial devices in a manufacturing cycle covering the exchange of production orders and job assignments, coordination between robots and machines, and process visualization through human-machine interfaces (HMI). Meanwhile, as the basic production unit of plants, the work-cell also serves in the other industrial information systems, such as supervisory control and data acquisition systems (SCADA) and manufacturing execution systems (MES), where it communicates with upper-level management systems in various occurrences. Therefore, the proposed work-cell testbed serves as a good reference to test various industrial wireless networks in support of efficient manufacturing activities.

Second, the testbed is specialized in emulating collaborative operation scenarios. In Industry 4.0/smart manufacturing paradigms where industrial robots are widely used, the data exchange between robots and with various field appliances is ever increasing. The testbed employs the programmable logic controllers (PLC) to emulate various machining tools working with industrial robots in the integrated production processes. PLC emulators exchange data with their robotic

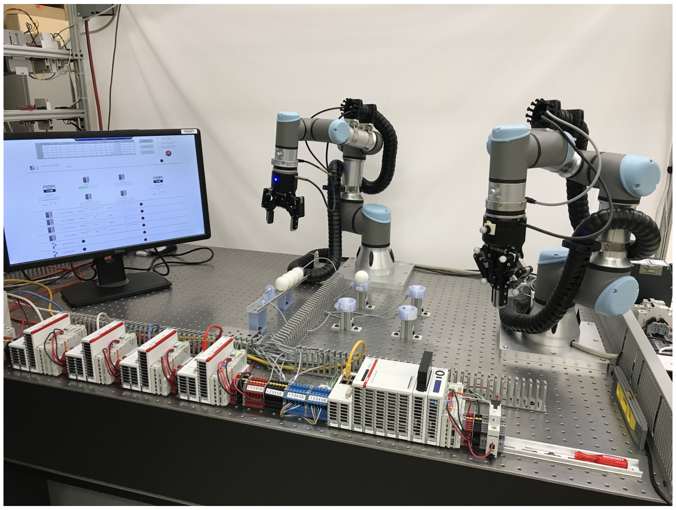

Fig. 1: Collaborative work-cell testbed

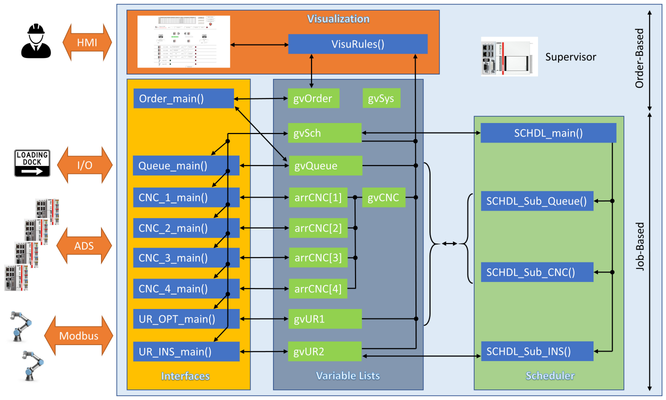

Fig. 2: Architecture of the work-cell supervisor

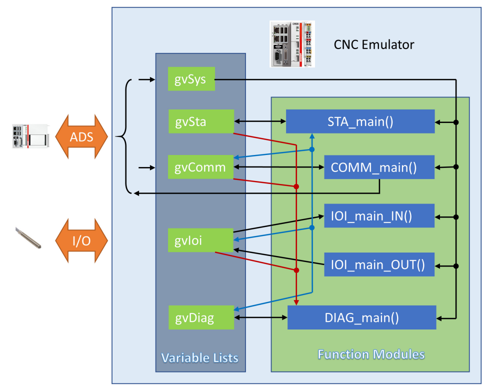

Fig. 3: Architecture of the CNC emulator

partners following customized communication specifications, e.g., the context information, size, and frequency. With repeatable experiments, this test environment can mimic various collaborative manufacturing scenarios and regenerate particular system and network bottlenecks that allow the study of the real-time monitoring and manipulation.

Third, the testbed provides rich work-cell footprints in production operations which facilitate network measurements and evaluation. Previous CPS modeling efforts usually simplified the models of individual work-cells treating them as buffers, and neglected many details of communications. Such simplified models cannot fully represent complex industrial scenarios in either OT or IT domains. The testbed characterizes data flows within and beyond work-cells; and it allows future extensions , e.g., studying multiple work-cells in an assembly line, or adding new factory functions, e.g., safety.

The remainder of the paper is organized as follows. The system architecture is introduced along with brief discussions on the emulated production processes in Section II. Details about the design of machine emulators are presented in Section III. The network synchronization issues and safety-related operations are discussed in Section IV and Section V, respectively. The ongoing measurement and wireless extensions are introduced in Section VI. Concluding remarks are given in Section VII.

II. Testbed Overview

A. Work-Cell Components

As shown in Fig. 1, the testbed emulates a generic work-cell in the manufacturing factory which consists of multiple components including a supervisory control unit, machines, interstage buffers, robots, and human workers.

1) Supervisor: The supervisory control unit, or supervisor, manages its work-cell by monitoring the whole production process, scheduling production flows, and coordinating inter-node actions. Meanwhile, it also serves as the agent on behalf of the entire work-cell to communicate with the upper-level managing systems in the factory, such as SCADA and MES.

As shown in Fig. 2, management functions at the supervisor can be divided into two planes: order-based and job-based. Order-based functions handle incoming orders, update the status based on real-time production results, and maintain the inventory. Job-based functions mainly work on the associated work-cell components and coordinate their production activities following the schedule. The testbed uses a Beckhoff CX2020 PLC as the work-cell supervisor which is equipped with various communication interfaces for internal and external information exchanges [13].

2) Machines: Four computer numeric control (CNC) machines are considered in the testbed whose behaviors in the machine tooling and communications are characterized by emulation models. Each CNC machine consists of a PLC, a 3D-printed part holder, and a proximity sensor. As shown in Fig. 3, the PLC mimics state transitions of the CNC machine in its tooling cycle and exchanges the machine status and job information with the supervisor. The part holder represents the machine's working zone where the proximity sensor is used to monitor the part arrival/departure. The PLC connects the sensor to its digital input/output (I/O) module and samples the input signal. Four Beckhoff CX9020 PLC are used as the emulators along with the propriety I/O modules [14]. Details of the emulator design are discussed in Section III.

3) Robotic Labors: Two UR3 robots are used in the testbed [15]. Each robot has six degrees of freedom (6 DoF)

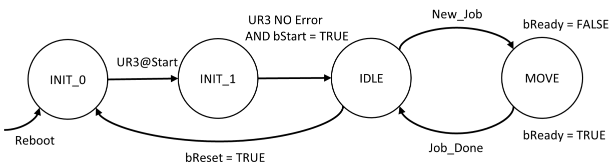

Fig. 4: State machine of robotic manipulators

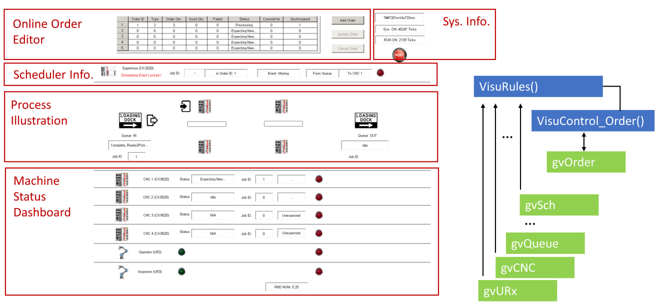

Fig. 5: Snapshot of the testbed human-machine interface

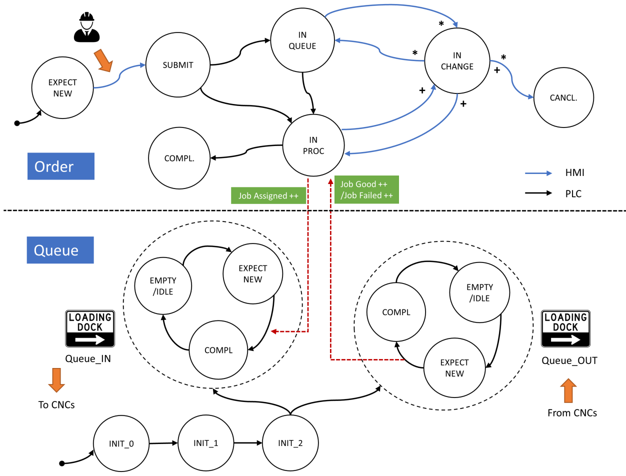

Fig. 6: State machines of the order and queue modules

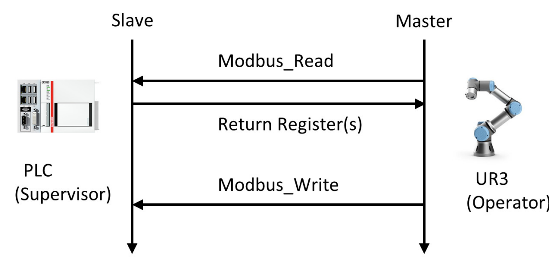

Fig. 7: Modbus communications between the supervisor and the robot

and is equipped with a gripper and a 6 DoF force torque sensor [16]. The robots mainly communicate with the supervisor to receive actuation commands and report their status. The state machine of the robot is shown in Fig. 4. The waypoint information and trajectory planning are programmed in the UR3 scripts based on its role in the work-cell operations.

4) Interstage Queue: The interstage queue is comprised of two loading zones in the work-cell, i.e., the input (Queue_IN) and output (Queue_OUT) buffers, which serve as the start and end points for a single job, respectively. The input buffer accommodates the incoming raw parts into the work-cell and the output buffer collects the finished parts, either good or failed. Each buffer is equipped with a proximity sensor with which the supervisor detects the arrival/departure events and updates the order status accordingly.

5) Human Workers: A collaborative work-cell may be operated by human workers or not. In the testbed, human workers play remotely through HMI to control the work-cell, such as placing orders and stopping/resetting the production. The testbed's HMI as shown in Fig. 5 is updated by the supervisor with the real-time status information collected from distributed components.

B. Baseline Use Case: Machine Tending

The baseline design studies a machine tending use case. Jobs are assigned to the work-cell in batches through HMI as shown in Fig. 6. Each batch, namely an order, contains a number of jobs/parts of the same type with a specific tool path, i.e., a sequence of moves operated at one or more machines. The two robots play different roles in the production: one as the operator and another as the inspector. The operator is in charge of transporting parts between job stops. A job stop refers to the working zone of a machine or the input/output loading zone. Another robot's jobs as the inspector include checking the part quality after each tooling step and reporting the inspection result to the supervisor. Based on the result, the supervisor then tells the operator to either move the part to the next stop along the path (if it passed the check) or drop it to Queue_OUT with a defect mark (if it failed). The inspection result is simulated at the inspector by a random variable associated with the emulated tooling operation.

C. Work-Cell Communications

The topology of the work-cell network is centered around the supervisor which acts as the information hub and gateway for both internal and external data flows. Connections within and beyond the work-cell are managed by different communication protocols. Among them, the inter-PLC links are carrying TCP/IP based TwinCAT Automation Device Specification (ADS) messages [17]. ADS is a medium-independent protocol for the communication between Beckhoff's TwinCAT devices. The supervisor communicates with robots through Modbus which allows the data exchange between heterogeneous industrial appliances in the shared registers at the supervisor as shown in Fig. 7.

Generally, the data exchange in a work-cell is determined by the associated production operations. For process variables (PV) regarding the production efficiency, the supervisor needs to collect the updates from remote machines to estimate the loads of individual stations and ensure the quality. For the ones with the asset health, the supervisor uses them to schedule the

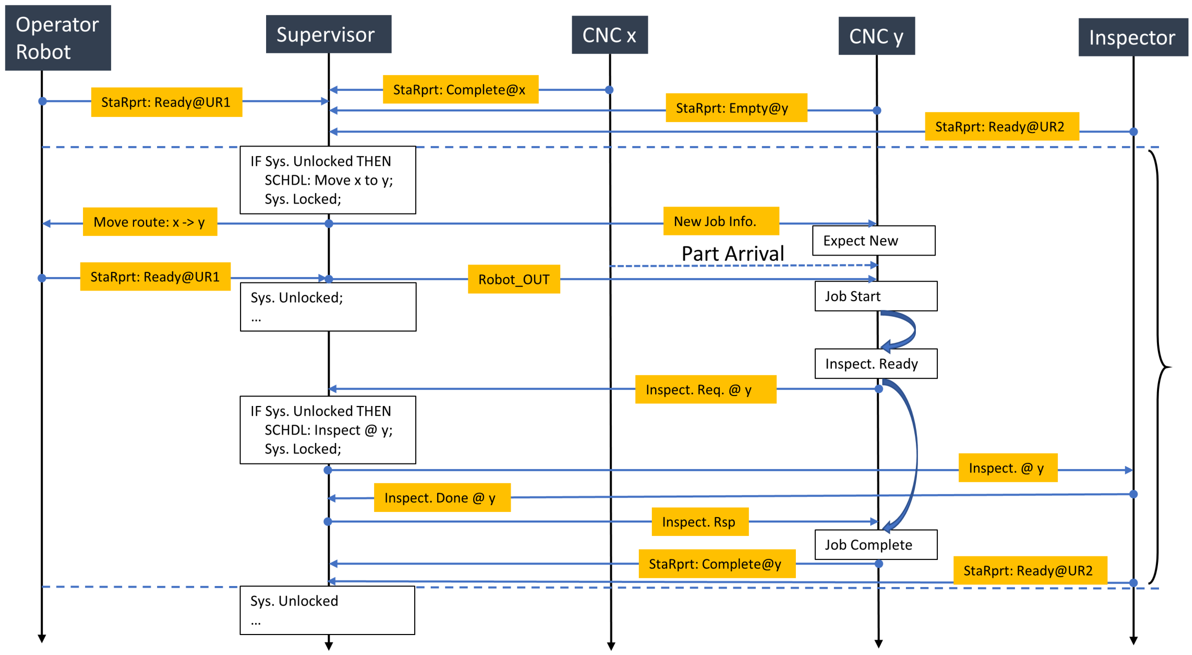

Fig. 8: Timeline illustration of communication messages in an intermediate tooling procedure

TABLE I: Specifications of work-cell data flows

Link	Data	Update Rate	Size (Bytes)	Protocol
Supervisor -CNC	Status report	1 Hz - 100 Hz	10s	ADS
	Safety	100+ Hz	10s	ADS
	Inspection request/response	On-demand	10s	ADS
CNC-CNC	Motion control	1000 Hz	A few	ADS
Supervisor -Robot	Actuation	1 Hz - 50 Hz	A few	Modbus
	Safety	125 Hz	A few	Modbus
Robot -Peripheral	6 axis force and torque sensor	100 Hz - 500 Hz	100s	TCP/IP
Supervisor -External	HMI	10 Hz - 50 Hz	100s	ADS
	IoT	>1 Hz	10s - 100s	MQTT

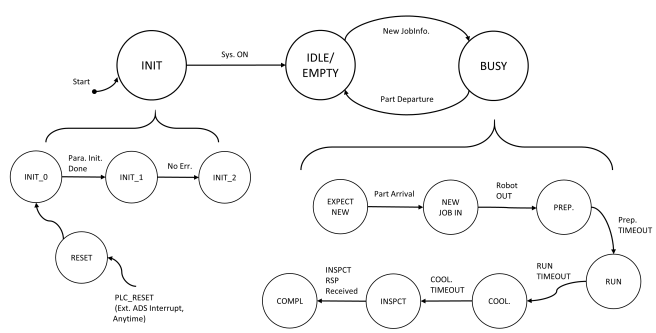

Fig. 9: CNC state machine

maintenance downtime and estimate the cost. To coordinate the collaborative operations in the work-cell, the real-time status of the machine should be made known to its partners so that the synchronous operation can mitigate errors and improve the quality. Besides routine exchanges, part of the CNC machine data is state-related, i.e., data are transmitted according to the current state the machine stays. Fig. 8 illustrates messages that are transported between work-cell components in a job move. Table I summarizes the emulated data flows in the testbed.

III. Tooling Machine Emulation

The testbed is aimed to evaluate the mutual impact between data transmissions and the work-cell performance. Therefore, the CNC emulator is mainly focused on mimicking the machine's behaviors with time dependent and statistical performance features, such as the production efficiency, error and downtime distributions, and part defects. Meanwhile, the emulators also help shape the work-cell data traffic with their periodic status updates and on-demand messages during the production. To fully capture the operational and communication activities of a tooling machine, the CNC emulator conducts state-dependent operations and communications following the state machine as shown in Fig. 9.

Three main states refer to the machine's three working modes: initialization (INIT), idle, and busy. Each main state can be further divided into a set of substates which characterize further details of operations. For example, the INIT mode has three stages to facilitate the site synchronization among distributed nodes which will be discussed in Section IV. The dwelling time in each state can be either timed according to the machine's specification, e.g., the approximate G-code execution time and material removal rate, or determined by

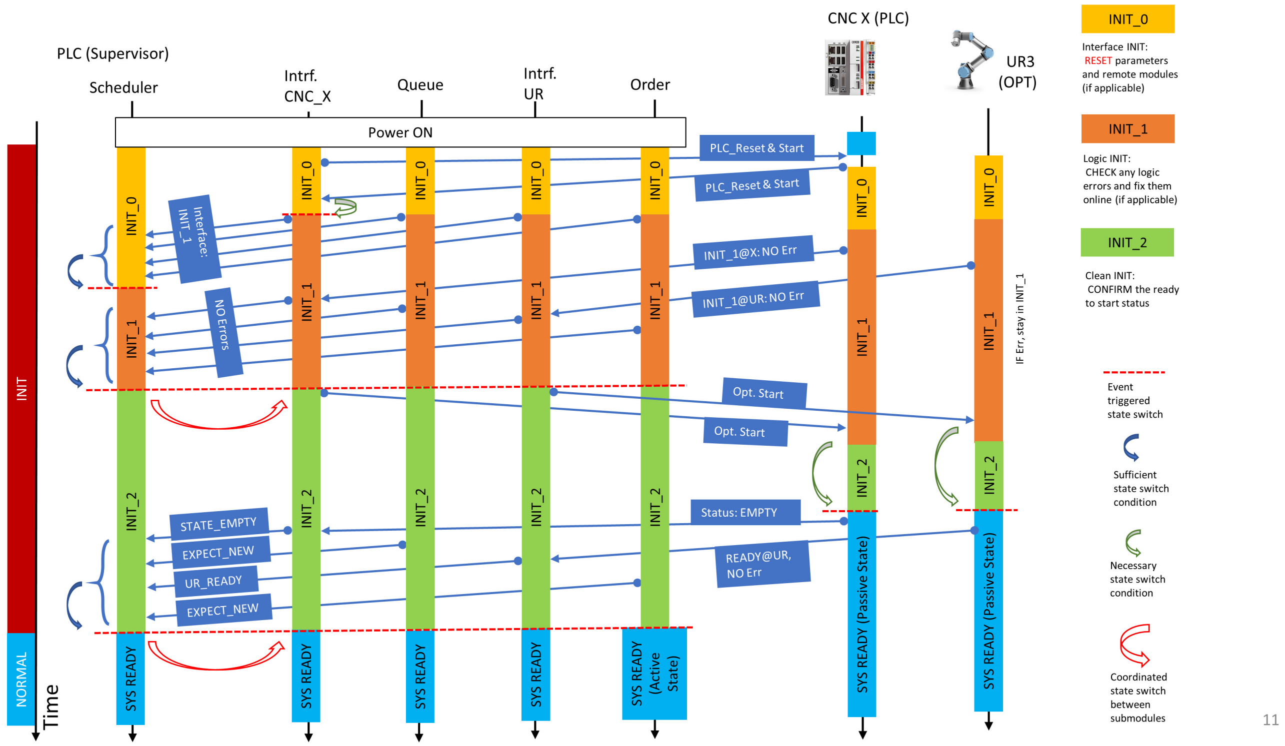

Fig. 10: Timeline illustration of initialization phases

external events that trigger state transitions, e.g., a notification message. The randomness can also be introduced based on statistical machine/production models. Examples of randomness components in the models include: 1) the time of a tooling procedure; 2) time varying energy consumption in different states, e.g., power variations in material-drilling processes; 3) tool life estimation; 4) part defect rate; 5) measurement drift between calibrations; and 6) safety related events, e.g., unexpected interrupts due to object intrusion. Using empirical models and measurement data, we can model the above performance metrics statistically and regenerate the state-related traffic for the studied machine.

Therefore, the machines emulated in the testbed can be programmed to highlight the details of real practices to study the network impact on the work-cell performance. Process variables can be modeled in the testbed focused on different topics such as 1) the production (task) efficiency, e.g., the execution time, material removal rate, energy consumption, and part defect rate; 2) asset health, e.g., the tool life time, failure probability, and downtime schedules for calibration and maintenance; and 3) work-cell collaboration, e.g., the clock drift, coordination precision, and safety. Besides checking the network support on routine data transmissions as scheduled, the testbed is particularly useful for testing the network performance in extreme cases with rare occurrences. The emulator can produce the traffic in the special use cases, such as the recovery from unexpected overload events or in emergency cases, and repeat it for comparative studies.

The quality of the "product" is also virtually rendered in the testbed. The result of each single part after a tooling process is randomly generated following the statistical model to mimic the defect rate in a real machine. The inspector is in charge of generating the result and return it to the supervisor for scheduling the next move. According to the study of the quality and quantity relationship in production systems [18], [19], part failures have both independent and dependent causes. The independent failure follows a Bernoulli distribution with the uncertainty of temporal independence. On the other hand, the dependent types of failures, which are often referred to as "persistent" or "systematic" ones, are those caused by tool failures, such as the broken drill or clog in the painting tube. In such cases, the failure of product is highly related with the asset failure rate. Since both types of failures are decoupled by their nature, the testbed carries the failures of the product as well as the ones related with assets to emulate the occurrences of various failures across time. The delivery delay or loss in communication links also affect the performance of operations and safety measures.

IV. Synchronization of Networked Components

Since work-cell components are collaboratively working in the production, the testbed implements multiple approaches to coordinate these distributed nodes.

First, we develop a phased initialization process at the beginning of each experiment. As shown in Fig. 10, the testbed initialization includes three steps:

INIT_0: Parameter initialization/reset;
INIT_1: Logic error check and confirmation;
INIT_2: Loading ready-to-go state.

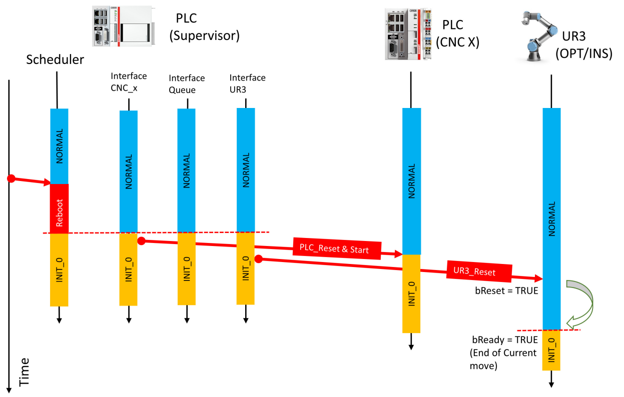

Fig. 11: Synchronized initialization among distributed nodes

The supervisor keeps the pace by triggering the state transition only after all components have met the state-specific conditions.

Meanwhile, the testbed also supports the online reset through HMI as shown in Fig. 5. Once the reset button is clicked, the supervisor will send the reset commands to individual nodes and direct them to restart from INIT_0 as shown in Fig. 11.

Besides the signaling procedures, the testbed also introduces the global clock synchronization throughout the work-cell. In the work-cell, a Meinberg Lantime M900 time server as the grandmaster provides the IEEE 1588 precision time protocol (PTP) synchronization service [20]. The synchronized clocks of industrial equipment facilitate collaborative operations which require the microsecond- or even nanosecond-level accuracy, e.g., in coordinated robot movements. Meanwhile, the synchronization also functions in wireless networks which leverages the management of orthogonal time-frequency radio resources. It improves the wireless performance by mitigating the interference caused by the misalignment of time slots with inaccurate timing.

V. Safety-aware Scheduling and Operations

In the baseline, the testbed considers production activities without physical human contact where human workers stay in the remote safety zone and interact with the process through HMI. Major safety concerns include collision risks between robots and the interruption of tooling when a robot hits the running machine. Therefore, the testbed is designed with multiple safety approaches to eliminate possible risks to protect the asset.

First, the supervisor sets a safety flag in its scheduler to indicate if there is an active robot moving in the work-cell. The scheduler only assigns at most one robot to be actively operating. Once the flag is set, the locked scheduler would not assign a new job to another robot so that collisions are avoided.

Second, the active robot will keep notifying the contacted machine(s) in the current job so that the machine would not start to process the part until the robot returns to the safety zone. As shown in Fig. 8, the "Robot_OUT" message indicates the clearance of the contact.

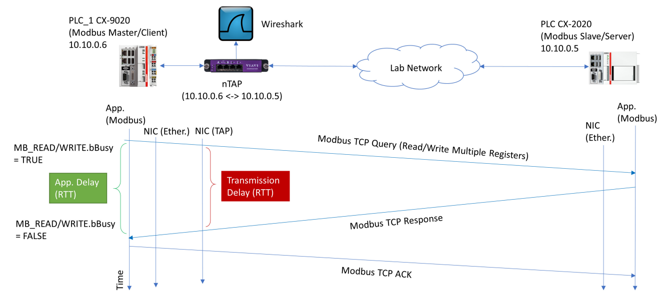

Fig. 12: Illustration of using network TAP devices in the link level delay measurement

Besides, an additional logic check on the waypoint information is performed at the robot to verify the fetched instruction through Modbus. Meanwhile, the supervisor will clear the waypoint information set in the registers right after the robot confirms the reception. In this way, it prevents the robot from repeating the out-of-date operations in case that the new waypoint information is lost in the transmission. Initial experiments confirm that introducing such an approach allows error-free operations through very light supervisor-robot Modbus communications as low as 1 Hz.

VI. Measurements and Wireless Extensions

A. Testbed Measurements

System and network measurements are performed in the testbed which employs various performance metrics regarding the production efficiency, product quality, and network utility in highly discrete manufacturing processes [21].

The main observation point is set at the supervisor as the testbed takes a centralized topology. Table I also indicates that the majority of data flows assumed in the work-cell operations are associated with the supervisor. Therefore, data that are routed from/to the supervisor are collected. Specifically, all work-cell components are connected to an industrial-grade switch whose ports are further separated into operation and measurement uses. Utilizing the switch's "port mirroring" function, we copy and forward the going-through data from the supervisor's operation port to the measurement port where a computer are collecting them with network packet analyzers, e.g., WireShark. The data in individual experiments will be stored for the future analysis and modeling.

To study the impact of link-level transmissions on the work-cell performance, e.g., packet losses of mission-critical PV updates, we introduce the network test access point (TAP) devices in the link-level measurements. It is very useful to capture link failures in the lossy wireless channels. As shown in Fig. 12, we collect data copies at both ends of the link so that the delay as well any packet loss can be detected.

B. Wireless Extensions

Based on the baseline design, wireless extensions are also underway. As each network node is equipped with the Ethernet adapter(s), hardwired connections between work-cell components can be replaced by wireless links if the Ethernet-wireless adapters are used. Currently, we are working with industrial partners to verify the wireless solution using the wireless local area network (WLAN) radios. To reduce the conversion delay between Ethernet packets and WLAN packets, the Ethernet-WLAN conversion takes place in the link layer (Layer 2 forwarding) where both Ethernet packets and wireless packets share the same network address of the node.

Channel emulator is also considered in the testbed evaluation to mimic the channel response in real factory radio environments [22].

VII. Conclusions

In this paper, we have reported an ongoing effort on building a work-cell testbed for studying behaviors of networked appliances in industrial applications. The testbed is aimed to serve as an evaluation platform for verifying the performance of different wireless technologies in support of deterministic and reliable industrial communications. Current version is built as a baseline with hardwired Ethernet connections between individual components. In the future work, we will introduce wireless links and evaluate their performance in harsh industrial radio environments. We will release the future progress and measurement data in the NIST pubic domain repository as a reference for industrial traffic modeling efforts and comparative studies on industrial wireless technologies [23].

Disclaimer

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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