Smart Manufacturing Testbed for the Advancement of Wireless Adoption in the Factory

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Abstract. Wireless communication is a key enabling technology central to the advancement of the goals of the Industry 4.0 smart manufacturing concept. Researchers at the National Institute of Standards and Technology are constructing a testbed to aid in the adoption of wireless technology within the factory workcell and other harsh industrial radio environments. In this paper the authors present a new industrial wireless testbed design that motivates academic research and is relevant to the needs of industry. The testbed is designed to serve as both a demonstration and research platform for the wireless workcell. The work leverages lessons learned from past testbed incarnations that included a dual robot machine tending scenario and a force-torque seeking robot arm apparatus. This version of the testbed includes computational and communication elements such that the operation of the physical system is noticeably degraded under the influence of radio interference, competing network traffic, and radio propagation effects applied within the lab. The testbed includes two collaborative grade robot arms, programmable logical controllers, and high-performance computing devices for situational tracking, alerting, and control. The paper is aimed to provide our contribution to the exploration of industrial wireless testbed design while soliciting feedback from fellow researchers.

Keywords: factory communications · wireless · testbed design · smart manufacturing · simulation · IIoT.

1 Introduction

One method for measuring the physical effects of communication loss and information delay within an industrial wireless network (IWN) on manufacturing processes within a workcell is the creation of a testbed for conducting research and demonstrating ideas and technologies using real equipment, control systems, and processes. Testbeds are useful for investigating cyberphysical systems (CPS)

impacts in that physical systems are entirely real or at least partially real. A CPS is a tightly coupled integration of physical, computing, and communications processes. As such, events within the computing and communications processes impact the physical process. Within a testbed, physical processes such as robot dynamics do not have to be simulated because gravity, inertia, and system dynamics are inherently present and measurable. Additionally, within a testbed, the electromagnetic properties are present, and their impacts on the physical networking devices are felt and equally measurable in terms of information loss and delay. These losses and delays influence the performance of the network and lead to abnormalities in the performance of the physical system.

CPS Theoretical Model Consulting the theoretical model of a CPS shown in Fig. 1, the physical process instrumented with sensors produces one or more sensor outputs, Y, which are transmitted through a network such as an industrial wireless network. Interference and multi-path phenomena may cause losses and delay as the received sensor information $\bar{Y}$ arrives at the control system. The control system then uses $\bar{Y}$ to act upon the physical system by sending commands, U which may arrive as delayed or lost, demoted by $\bar{U}$, at the physical process. The differences between $\bar{Y}$ and Y and between $\bar{U}$ and U cause changes in the behavior of the physical process. The severity of those changes will depend on the resilience of the control system and the properties of the physical system, itself.

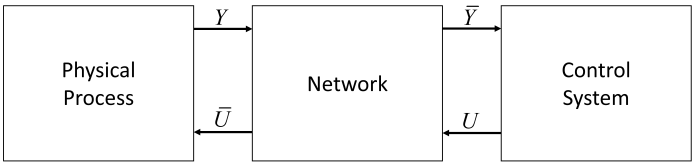

Fig. 1. Theoretical representation of a cyberphysical system.

Motivation While theoretical modeling and simulation are helpful in understanding CPS behaviour, they lack the accuracy of the real-world systems. Therefore, testbeds are used to reproduce larger physical systems on a smaller scale using computing and communication devices and real physical components such as edge devices and robots. The National Institute of Standards and Technology (NIST) has produced a series of industrial wireless testbeds with use cases ranging from chemical production and confined space sensing to robotic machine tending and force controlled actuation. All of these incarnations of the testbed addressed real needs with use cases of low-rate time considerations on the order of 100 ms or more. However, with the emerging requirement of robotic mobility and remote joint actuation in semi-autonomous robotic systems, a new use case

is necessary to conduct future research within the testbed. This use case must be selected such that perturbations within the IWN are rapidly reflected within the physical system. The testbed itself should be implemented to measure in real-time both informational and operational performance commensurate with the use case.

Contributions The contributions of this work are as follows: 1) We present our lessons learned conducting experimental studies with past incarnations of the NIST industrial wireless testbed; 2) we present our use case requirements and testbed considerations for a general industrial wireless testbed that readily demonstrates cyberphysical effects rapidly in humanly detectable fashion when information loss and delay are introduced; 3) we present the functional design of the testbed which implements our proposed use case.

Paper Organization The paper is organized as follows: In Section 2, previous relevant academic works are presented. Then in Section 3, lessons learned from past incarnations of software-based and hardware-in-the-loop testbed simulations are reviewed. Next, in Section 4, requirements for the new use case motivated primarily by robotic mobility is addressed along with the requirements for the testbed platform itself. In Sections 5 and 6, the proposed use case and testbed are elaborated in detail. Concluding remarks are given in the final section.

2 Related Work

Wireless communication technologies have been proactively extending their footprints onto the factory floor from non-critical process monitoring services to more deterministic transmission of mission-critical application data [6]. Standardization bodies have released their own visions of service requirements on industrial wireless communications [5, 1]. The European Telecommunications Standards Institute (ETSI) has classified a series of use cases in industrial sectors, mainly as machine-typed communications, and identified corresponding radio transmission requirements on individual classes [5]. The Third Generation Partnership Project (3GPP) has also identied service requirements for industrial wireless use cases and address them in their 5G cellular use scenarios, e.g., massive machine-type communications (mMTC) and ultrareliable and low-latency communications (URLLC) [1]. However, justification of specific values regarding key performance metrics is barely disclosed in these efforts. Recently, there is an ongoing discussion on calibrating wireless service requirements to truly reflect system needs in typical industrial communications scenarios, e.g., factory workcells [12].

Validating industrial wireless requirements and further evaluating candidate solutions have proven challenging. Existing validation approaches can be classified into three main categories: theoretical analysis, software simulation, and hardware testbed. Theoretical analysis has been widely used to showcase performance trend by statistically modelling traffic load and link quality [14]. However, it is very difficult to model complex industrial use cases where factors for

both network performance and manufacturing productivity need to be captured thoroughly, especially when transmissions are closely associated with process precision and plant safety. Being widely used to verify theoretical analysis and project system performance, simulation techniques have the flexibility of scaling up and finely tuning the studied use case under different conditions. However, experts in their own domains (e.g., industrial engineers and communications engineers) often find it difficult to select/develop appropriate simulation modules for components that fall out of their expertise, who tend to make over-simplified or erroneous modeling assumptions that deviates the delivery of trustworthy results. Recently co-simulation tools have been developed to jointly mimic behaviors of component systems/networks of CPS in a hierarchical High-Level Architecture (HLA) [13]. Jeng *et al.* introduced a factory co-simulator that jointly considers the production pipeline across multiple workstations and information interaction between them through the network [9]. Such work can also be further extended to the hardware-in-the-loop (HIL) experiments to render more accurate estimation on the performance with tested equipment [3]. Being built upon mathematical models, simulation methods also encounter similar design issues to keep a balance between depiction accuracy and computation efficiency. Besides software-based evaluation, testbeds have been developed to test existing wireless techniques and prototypes in the emulated industrial use cases. Lucas-Estan *et al.* designed experiments to test wireless link redundancy schemes in a multi-robot testbed which is focused on improving reliability of wireless transmissions [11]. Given vast diversity and variability of industrial use cases, the design of effective testbed for individual use cases becomes a key to the success of wireless deployment. NIST engineers have examined the impact of wireless links on industrial system performance through a series of testbeds [3, 7, 8, 4, 2]. Based on lessons learned in these practices, we will examine design principles to highlight industrial wireless requirements in this paper.

3 Lessons Learned from Past Testbed Incarnations

In this section, we discuss the lessons learned from various previous tesbeds that have been used in the NIST industrial wireless systems (IWS) lab. These previously developed testbeds and experimental studies can be found in [3, 7, 8, 4, 2].

3.1 Tennessee Eastman Chemical Factory

In [3], industrial wireless communications devices were deployed for pressure, temperature, and flow sensors data transfer for the control of a simulated chemical factory. IEEE802.15.4-based protocols were deployed such as WirelessHART and ISA100.11a. Both simulations and HIL experiments were performed for this application in [10] and [3], respectively. We found that, generally, process control applications with large time constant can be impacted by communications impairments when the wireless channel is poor for an extended period of time.

The existing WirelessHART and ISA100.11a can perform adequately for these applications while the wireless sensors are connected to the network. However, we found that networks were not robust to events outside the scheme of information transmission such as the loss of a router node, gateway, etc. due to power loss or similar incidents.

Moreover, comparing simulations to HIL experiments, we found that experimental studies are needed to reflect the more realistic impacts of protocol implementation and higher layer protocol impacts such as by Modbus. We have deployed a channel emulator to replicate the impact of electromagnetic propagation in industrial environments on CPS performance. We have also learned that abstract network performance criteria such as packet loss and packet latency may not reflect the communications impact on the production process and hence physical process related criteria should be evaluated in various experimental studies.

3.2 Confined Space Gas Sensing Testbed

In [7], we performed an experimental study on a testbed which is very similar to the chemical factory use case in Section 3.1 such that a similar HIL concept is deployed. The main difference is that different wireless channel models were deployed and different types of information were transferred. In the confined space case, the simulated gas levels at different points of the confined space are transferred over wireless using HIL simulation, and the effectiveness of a safety alerting application is considered. In this setup, we found that the communications protocol implementation could impact the system performance where the implemented Modbus protocol has an update period of 2 seconds which is much slower than the signal and channel variations. We also found that testing can be performed on the signal-level for sensors and actuators signals in case of unavailability of network-level metrics. However, we concluded that the network-level metrics are needed to further understand the reasons behind the measured performance.

3.3 3D Gantry System Testbed

In [8], a commercial 3D gantry system was deployed where the g-code commands to control the gantry system were streamed using a WiFi network. In this experimental study, we found that while converting an originally wired testbed to a wireless one, a ground truth measuring technique has to exist in order to quantify the system performance and hence the wireless impact on performance. Generally, ground truth measurements can be obtained through instrumented feedback from the system, if exists, or through a remote observer where a vision tracking system was deployed in this testbed.

Similar to previously discussed testbeds, the definitions of physical process metrics are needed where these metrics have to be impacted by wireless communications impairments. In this experiment, where g-code command delays made the 3D gantry to halt at a specific location waiting for the following command,

performance metrics, such as dwell time and production rate, were considered. The main lesson learned in this experimental study was that queuing of the control commands can mitigate the impact of rapid changes in the wireless channels i.e., keeping a buffered set of commands at the remote station can help to keep the process running. Buffering is not always a viable solution in latency-sensitive applications.

3.4 Force Seeking Apparatus Testbed

In [4], a force seeking apparatus was built using a robot arm and an attached force-torque sensor (FTS). A single wireless channel is deployed where the FTS transmits the force value to the robot controller which reacts when a specific threshold is reached. A machine learning algorithm is used to estimate the interference level on the wireless channel based on tracking the robot arm movements. In this study, we assessed the impact of interference on the physical performance of a fast process where the direct relation between wireless channel quality and the process is quantified. In single wireless channel scenarios, we study only the impact of external interference while competing traffic scenarios are not considered. Hence, we concluded it would be desirable to have a testbed with multiple deployed wireless nodes allowing us to study channel contention scenarios. We also found that the FTSs are not designed to be used wirelessly where large delays can cause dropping the connection with the robot controller. The dropped connection requires resetting the FTS control box to continue its operation which is not acceptable in industrial processes. We concluded that, in general, the industrial devices should be designed to handle information loss and delay more readily through means of mitigative control system programming or user adjustment of device parameters rather than hard-coding total system failure.

3.5 Dual Robot Machine-Tending Testbed

In [2], a more comprehensive testbed was built where two robot arms, one supervisory PLC, and four machine emulators worked together to perform a pick-and-place task. The supervisory control signals to the robot controllers and the machines were transmitted wirelessly. The data for the network traffic and the status of the machines and robot arms were collected. Although, we were able to show the impact of wireless on the network-level metrics, such as packet latency, the impact of wireless on the physical process was almost negligible because only supervisory commands were transferred wirelessly. The latency of supervisory commands were significantly lower than the scan time of the control loop causing negligible physical impact. We discovered that in-network contention is more impactful than electromagnetic interference. Moreover, we discovered that multiple source of contention impacted the system more compared to a single traffic source.

We have also run experiments using both periodic and event-based Modbus polling for the communications between the supervisor and the robot controllers. We found that periodic Modbus polling is more robust to the channel because

no timeout warnings may occur. However, it is less bandwidth efficient than the event-based counterpart. On the other hand, event-based Modbus polling is preferred in wireless communications scenarios not to interfere with other network activities. Moreover, access to the robot arm middleware would allow more control of Modbus polling properties. As a result, a middleware alternative such as robot operating system (ROS) would be suitable.

4 Requirements for New Use Case

To enable adoption of an effective use case for deployment in the NIST industrial wireless testbed, development of clear requirements is a necessary and an essential first step. Using our lessons learned and experience, it was required that the new use case proposed have noticeable physical impact under degraded communications situations, have industry relevance, and have an accessible software middleware.

Noticeable Physical Impact Learned from Section 3.5, the new use case requires noticeable physical impact from the degradation of communication. Such degradation occurs commonly in wireless communications. In the use case, wireless links are used to carry traffic to control the physical action directly; thus, any significant fluctuation in latency or reliability of the wireless link will be immediately noticeable by measurement or observation. In past incarnations, physical manifestations from communication loss and delay were not immediately noticeable because the physical systems were more immune to information disturbances in the wireless network.

Industry Relevance Constructing a use case that is similar to the types of applications used by industry is required as the findings discovered will be relevant. This requirement suggests that a new use case should perform a similar task or physical operation that is found in industrial applications.

Access to Software Middleware Many current industrial devices do not support wireless communications in their design. Such devices have proven to have difficulties in compatibility with current wireless solutions, e.g., overly strict timeout thresholds, such as with Modbus client configurations, which may trigger system failures as described in Sections 3.4 and 3.5. Therefore, it is asserted that the desired industrial wireless testbed provide access to the software residing between applications and the industrial wireless networking stack on each host.

5 Proposed Use Case

In this section, we explain briefly the proposed dual robot leader-follower use case. We first introduce the design of the use case where the major system components are defined. Then, we validate that the proposed use case satisfies the use case requirements in Section 4.

5.1 Design

In Fig. 2, the physical process is shown where two robot arms equipped with FTSs are collaborating in lifting a semi-rigid object. Dual robot object lifting is a general industrial approach used for heavy lifting and over-sized material handling. Typically, stationary robots used for lifting communicates through wired technologies. However, the need for flexible manufacturing and mobile robots in future factories requires the deployment of wireless technologies for communications between robots. In the leader-follower schemes, one robot is assigned the rule of the leader to achieve a certain control objective. The other robot, the follower, takes specific actions relative to the leader to maintain a desired relation with the leader with respect to the position or forces on the lifted object. As a result, communications between the leader and the follower plays a crucial role in maintaining the integrity of the lifted object and preventing collisions for the mobile robots.

The control of the leader-follower scenario allows the follower to take decisions based on transferred information about the leader activity. The leader information is transferred using a deployed industrial wireless network. Furthermore, the control of the leader-follower scenario could be done in a centralized approach. In the centralized approach, the centralized controller makes decisions about the follower actions based on the joint state information transferred by the both robots. Moreover, we attach an FTS to the lifted object in order to measure the applied forces and study the impact of wireless communications on the lifted object.

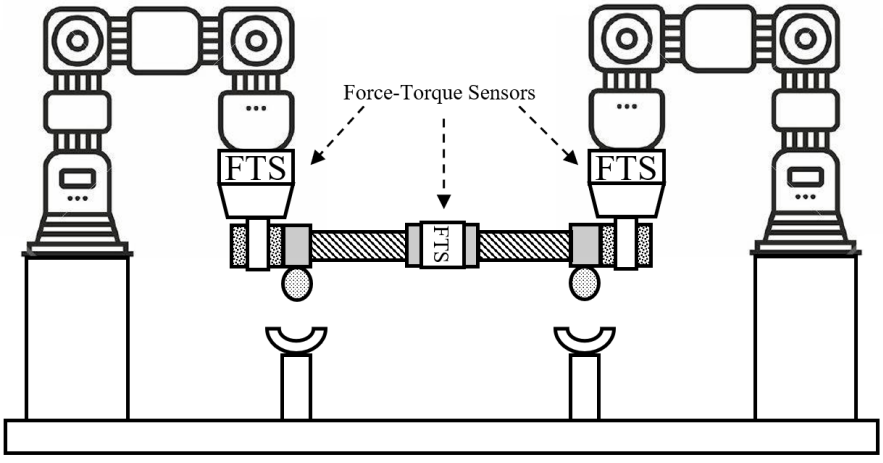

Fig. 2. The leader-follower use case diagram.

5.2 Requirement Coverage

This proposed use case was selected by incorporating the lessons learned from previous use cases in Section 3 and to satisfy the discussed use case requirements in Section 4. In the proposed use case, the goal is to get a direct impact of wireless communications on the physical process through having the leader-follower relation between the robots. Any latency or reliability issues in the information transfer between the leader and the follower is expected to affect the desired relation between them. The impact of wireless communications on the physical process can be measured through the position feedback of the robot arms and the FTSs. Capture of network data is made possible through the use of network probes strategically placed throughout the testbed. Similarly, capture of performance data of the physical system is made possible by instrumenting the testbed with ground truth measurement and recording probes such that variables such as forces, torques, positions, velocities, and accelerations are captured independently of the wireless network. We deploy a master clock to synchronize all the collected physical process and network traffic data. Finally, this proposed use case replicates a realistic scenario which can be found in heavy lifting and over-sized material handling.

6 Proposed Testbed

6.1 Architecture

The testbed serves as an evaluation platform that emulates workcell operations in the proposed use case and measures the impact of node interactions on the production performance. As shown in Fig. 3, it consists of three main subsystems according to their different roles: *workcell modules*, *network components*, and *measurement devices*. In the designed architecture, subsystems are connected with each other through predefined interfaces and integrated as a complete evaluation process. Design details of each one will be elaborated in the following section.

6.2 Components

Workcell modules include testbed components that participate in manufacturing tasks, e.g., robots and their controllers in the leader-follower use case. In the testbed, we deploy two Universal Robots (UR) UR3 CB-series robots that serve as actors in the leader-follower use case. Each UR3 is equipped with a 6 degree-of-freedom (6-DoF) robot arm, one control box, and peripheral devices, known as URCaps, which include a Robotiq gripper and a 6-axis force-torque sensor attached to the end effector. Instead of using proprietary UR programs, the control of robots implements agents atop the robot operating system (ROS) middleware which provides a rich set of options in control functions and peripheral support for UR3. In ROS, robot-oriented processes are identified as separate

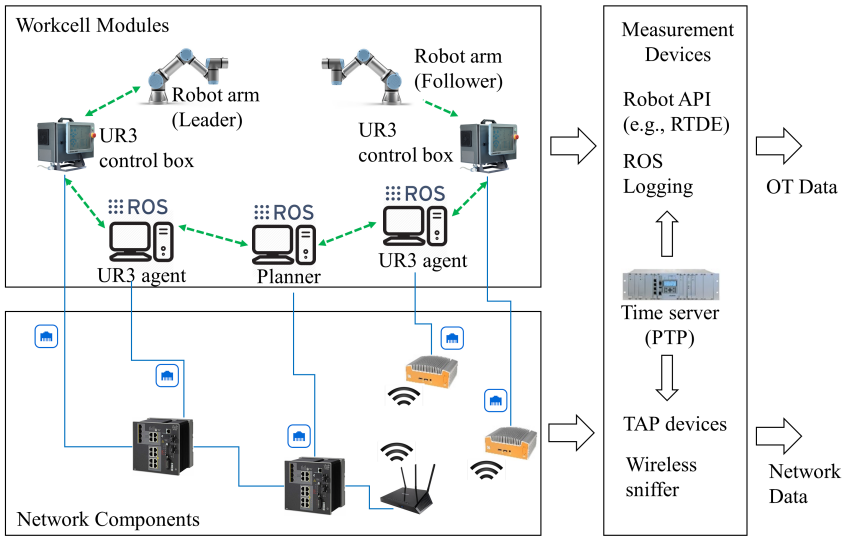

Fig. 3. Workcell testbed architecture

function nodes which can be distributed across multiple physical machines being connected through the network. As shown in Fig. 3, the testbed hosts three computers running Ubuntu 18.04 with the ROS Melodic distribution. Two of them serve as UR3 agents where ROS UR3 drivers are installed to adapt universal ROS functions and commands to UR3 features. The coordination between the leader and the follower can be realized through the peer-to-peer communications between UR3 agents. In this case, the third machine, i.e., the ROS planner, performs motion planning for both robots. There is another feasible approach in which both UR3 agents report to the planner who will resolve their joint trajectory actions and reply to both with respective action commands.

Network components are network devices that enable workcell modules to communicate with each other for job-oriented information exchange and process control. Each workcell module in the testbed contains one or more built-in Ethernet interfaces. Two Cisco IE-4000 industrial gigabit Ethernet switches serve as the wired network backbone. Ethernet-wireless adapters are used to replace wired connections by enabling wireless communications between modules. Fig. 3 illustrates an example of connecting to the follower robot through wireless. The testbed uses IPv4 addresses to manage communication devices. Additional network connections are also planned in the testbed that provide measurement data links and other complimentary features, such as time synchronization services.

Measurement devices collect data including but not limited to manufacturing progress, machine status, link quality, and network health. Table 1 summarizes

Table 1. Testbed measurement data collections

Data	Source	Type	Time Synced	Format
Actual joint status (e.g., position, velocity, and acceleration)	UR3 joints	Workcell	Yes, PTP	CSV
URCap force and torque	FTSs at UR3 end effectors	Workcell	Yes, PTP	CSV
ROS UR3 control (Leader/follower status)	ROS UR3 agents	Workcell	Yes, PTP	CSV
ROS Motion planning output (target joint status)	ROS master	Workcell	Yes, PTP	CSV
Force and torque (ground truth)	FTS at the lifted object	Workcell	Yes, PTP	CSV
Ethernet packet captures	TAP	Network	Yes, PTP	PCAP
Wireless packet captures	Wireleess sniffer	Network	Yes, PTP	PCAP

data to be collected and saved for further analysis. Specifically, production-related workcell data and network data are monitored and captured at different measurement devices. The former ones are usually collected through UR3's API, e.g., the real-time data exchange (RTDE), or saved locally in workcell modules, e.g., the ROS logging at ROS nodes; the latter ones are mainly captured by traffic analysis tools, such as test access point (TAP) devices for real-time traffics in Ethernet links and the wireless sniffer. Note that the testbed uses real-time readings from the FTS at the lifted object as the ground truth for measuring the performance of coordinated operations between the leader and the follower. Besides, timing information is also rendered and embedded into each record so that discrete events can be aligned in time to review the operation logic and network behaviors in future analysis. Therefore, the testbed can implement the precision time protocol (PTP) to provide the sub-microsecond level accuracy across the networked distributed clocks. A Meinberg M900 time server is used as the central PTP master clock that supports the IEEE 1588-2008 (PTPv2) standard.

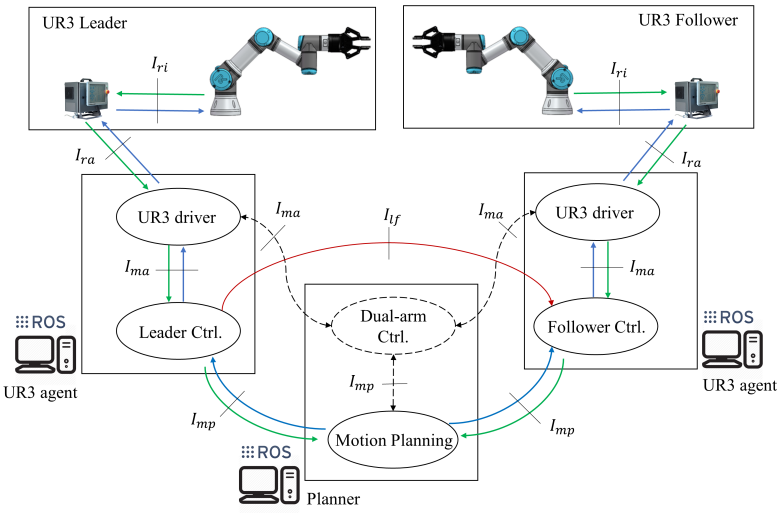

Fig. 4. Testbed interfaces

6.3 Interfaces

Fig. 4 illustrates interfaces between workcell modules that are used to enable the coordination between the two actors in the proposed leader-follower use case. As data communications are directional, we define the *upstream* data flow to be the one from the end node, i.e., the UR3 robot arm, toward the planner which is denoted by green arrows in the figure. The *downstream* data is reversed and denoted in blue. When the leader(follower) has its own controller residing in the agent machine, the leader will routinely share its motion information to the follower, either as geometrical variables or force-torque readings, which allows the follower to track the leader's trajectory and calculate its own route to keep the metrology bar in the desired state. In another case when the ROS planner also takes over the control mission, a new dual-arm control node will replace the separate controllers in UR3 agents. The flows will be updated accordingly which are illustrated as dashed arrows in Fig. 4.

Table 2 summarizes interfaces defined for data exchanges between different nodes. Note that each interface contains data in both upstream and downstream directions. Except I_{ri} for UR3 internal traffics, the other interfaces are built for communications between ROS nodes. ROS provides three communication styles including synchronous request/reply interactions ("services"), asynchronous data streaming ("topics"), and data storage in a parameter server. We will use the testbed to explore the capability of wireless links in support of different communications styles in selected interfaces. For each interface, a set of protocols is listed for which the use case will be tested. Ethernet is used for baseline performance testing, while wireless local area network (WLAN) protocols

Table 2. Testbed interface specifications

Interface	Protocol	Data		Note
		Upstream	Downstream	
UR3 internal, I_{ri}	Serial	UR3 and URCap status	Joint trajectory action	UR3 proprietary
UR3-ROS, I_{ra}	Ethernet WLAN	Robot status	Joint trajectory action	ROS UR3 driver
ROS master-agent, I_{ma}		Robot status	Joint trajectory action	ROS topics/services
ROS motion planning, I_{mp}		Target trajectory	Joint trajectory action	ROS topics/services
Leader-Follower, I_{lf}		Force-torque-based or geometrical trace		ROS topics/services

such as IEEE 802.11 will be used when a wireless protocol is employed. Fifth generation wireless (5G) is envisioned as well when resources come available.

7 Conclusions

In this paper, we have presented the next evolution of an industrial wireless testbed. The testbed is designed with the goal of investigating use cases that will noticeably degrade under the influence of radio interference, competing network traffic, and radio propagation effects applied within the lab. One specific use case is presented in which two robots perform a coordinated lift operation using either a geometric leader follower or a force-torque minimization control scheme. In the control scheme presented, wireless links are used to carry joint state information such that lost or delayed state information immediately impacts physical action. Capture of performance data of the network and physical systems is made possible by the use of probe devices. Our testbed will serve as a research and demonstration platform for reliable industrial wireless deployment and control system strategies. Finally, our work is presented with lessons learned from past incarnations of our wireless testbed such that our work may help others construct better wireless testbeds by learning from our successes and failures. Once completed, results from our testbed will be made available through reports, papers, and publication of data sets.

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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