

Attacks on Distributed Sequential Control in Manufacturing Automation

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Abstract—Industrial Internet of Things (IIoT) represents a backbone of modern Reconfigurable Manufacturing Systems (RMS), which enable manufacturing of a high product variety through rapid and easy reconfiguration of manufacturing equipment. In IIoT-enabled RMS, modular equipment is built from smart devices, each performing its own tasks, while the global functioning is achieved through their networking and intensive communication. Although device communication contributes to the system reconfigurability, it also opens up new security challenges due to potential vulnerability of communication links. In this paper, we present security analysis for a major part of RMS in which manufacturing equipment is sequentially controlled and can be modeled as Discrete Event Systems (DES). Control distribution within DES implies communication of certain events between smart modules. Specifically, in this work we focus on attacks on communication of these events. In particular, we develop a method for modeling such attacks, including event insertion and removal attacks, in distributed sequential control; the method is based on the *supervisory control theory* framework. We show how the modeled attacks can be detected and we provide a method for identification of communication links that require protection to avoid catastrophic damage of the system. Finally, we illustrate and experimentally validate applicability of our methodology on a real-world industrial case study with reconfigurable manufacturing equipment.

I. INTRODUCTION

INDUSTRIAL implementation of Internet of Things (IoT) and Cyber Physical Systems (CPS) significantly changes the way we manufacture, leading to the evolution of manufacturing systems to a new level known as Industry 4.0 [1]. Industry 4.0 factory is a smart factory able to meet the requirements of each individual customer through implementation of Reconfigurable Manufacturing Systems (RMS) [2]. RMS are based on modular equipment that is physically and functionally reconfigurable and can be rapidly and easily adapted to manufacturing of different products [3], [4]; Fig. 1 presents an example of a reconfigurable pneumatic device. To facilitate reconfigurability, the modularity should be achieved not only in terms of mechanical elements, but also in equipment/tool

control, where each mechanical module is augmented by its own Local Controller (LC) with communication and computation capability, representing a smart IoT device.

Control system modularity leads to a shift from the classical IEC 62264 hierarchical industrial automation pyramid to distributed control systems [1], where control is realized through peer-to-peer communication of networked devices that create Industrial IoT (IIoT) [5]. In distributed control of manufacturing systems, each control task is realized through coordinated operations of a number of smart devices that comprise the considered reconfigurable equipment, with the corresponding LCs communicating relevant information to each other in order to achieve the desired system behavior. On the other hand, (usually wireless) communication between LCs introduces new security challenges [6] since communication link may be prone to attacks by adversaries.

In IIoT systems, end-to-end (including communication) security guarantees are of crucial importance [7]. There are different ways to protect communication between devices, such as the use of cryptographic mechanisms to provide continuous or intermittent authentication or adding watermarking/random noise signals (e.g., [8], [9], [10]). Yet, all such methods introduce additional computation/communication overhead, increase communication latency [11], and should be applied only when necessary in resource constrained IIoT-enabled RMS.

Different types of cyberattacks have been reported (e.g., in [12]), including replay attacks where attacker records sensor/actuator signals in one period of time and replays them in another, or covert attacks where adversary secretly takes over control from the supervisor, with the goal to remain undetected. For all attacks it is common that they are not random (opposite to failures) and that adversaries are deceptive and insidious in their goals – e.g., intention to remain stealthy and to achieve negative effect on the system performance. Usually the attackers have some *a priori* knowledge about the system obtained through different cyber-physical intelligence attacks [13], such as eavesdropping.

Whereas the attacks in continuous-time control systems [12], [13] have gained significant attention, attacks in Discrete Event Systems (DES) were only recently explored [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]. Supervisory Control Theory (SCT) models DES as generators of formal languages whose behavior can be captured by Finite State Machines (FSM) [25]. Since SCT and FSM were successfully employed for fault detection in DES, their application in studying DES attacks, as done in this paper, represents a natural extension. An approach for modeling and detection of actuator enablement/disablement and sensor removal/insertion

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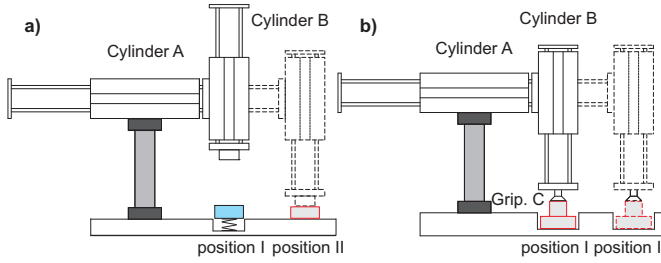


Fig. 1. Examples of reconfigurable manufacturing equipment: a) Running example: Configuration of the system for parts marking; b) Case study: Configuration of the system for parts manipulation.

attacks in remotely supervised plants is presented in [14]. System under attacks is modeled using FSM and SCT framework, while attacks detection and prevention of system from reaching unsafe state is based on DES fault diagnosis. Similar approach for man-in-the-middle sensor attacks is presented in [15], whereas the defense strategy for attacks from [14], [15] is given in [26]. Furthermore, [22] provides the mechanisms for implementation of security modules for the attacks from [15].

Intelligent adversary with *a priori* knowledge about supervisor's performance that arbitrarily alters sensors' readings is modeled in [16], as well as a supervisor robust to these attacks. The work from [17] models event insertion/removal attacks as SCT-based projections that map observed into corrupted events strings through events replacing or inserting, while [18] studies replay and covert attacks in DES and proposes detection method based on permutation of controller inputs and outputs on the plant and supervisor side. In addition, [23] considers the attacks that completely take over the control over plant for a certain time period. Furthermore, [19], [20] propose methods for design of stealthy attacks in such systems. Recent review of the state of the art in application of SCT and FSM in DES attacks modeling and detection is given in [24].

Existing work in modeling and analysis of attacks on DES consider attacks on sensor and actuator signals in the case of a remote plant and a supervisor that carries out *centralized* control (e.g., [17], [21], [24]). On the other hand, distribution of control tasks to smart devices within RMS and intensive communication between them bring about new security challenges. For example, each cylinder from Fig. 1a is a smart cylinder (with integrated limit switches and control valve) that is augmented by its own LC; the control of the system for parts marking is distributed over two LCs that intensively communicate, enabling control of the desired system behavior. In distributed sequential control for RMS, control can be captured as a DES [25]. In such systems every IIoT-enabled LC is closely connected to the corresponding plant module, whereas signals (events) that are communicated between remote LCs (i.e., smart devices) may be vulnerable to attack.

Consequently, in this paper we focus on security-analysis of *distributed* control systems for industrial automation, specifically addressing network-based attacks on event communication. To the best of our knowledge, these kinds of attacks have not been considered in the past. Attacks on communicated events in such systems could lead to an undesirable sequence of system actions, and the system should be prevented from

generating unsafe sequence of events that can lead to catastrophic damage. We present an SCT-based modeling approach to capture common attacks – event insertion and removal in *distributed* sequential control. Furthermore, we introduce a method for attack-detection and identification, focusing on safety-critical attacks that could violate safety requirements of system operation. To minimize computation and communication cost, we show how to determine a set of events whose communication should be protected to ensure safe system operation while minimizing security related overhead.

Since our focus is on network-based attacks on sequential controllers in industrial automation systems, we are mainly considering impact on the automation due to false-data injection attacks as well as Denial-of-Service attacks, which prevent some of the messages from being delivered to the controllers.¹ Such attacks have been previously investigated in the other CPS domains where continuous control is applied, as in [27], [28], [29] where e.g., attacks on power-grid infrastructure as well as on continuous control via SCADA systems were considered. On the other hand, we do not consider the origin of the attacks – e.g., the type of software/hardware vulnerability exploited by the attacker to launch the attack. The security-aware framework for industrial automation, which we introduce in this work, enables system designers to provide a formal proof about the attack-detectability and performance for the wide class of attacks, by employing a wide-range of tools for analysis of SCTs, such as [30].

The reminder of the paper is organized as follows. Section II briefly presents a method that is used for distribution of sequential controllers for RMS into LCs, while Section III maps such LCs into the SCT formalism. In Section IV we present a method for attack-modeling, which allows for the identification of events whose communication should be protected (elaborated in Section V). The application of our security-aware methodology is presented on a simple running example, as well as a real-world industrial case study in Section VI. Finally, Section VII provides concluding remarks and avenues for future work.

II. DISTRIBUTING SEQUENTIAL CONTROL TASKS TO SMART DEVICES

Before considering security challenges in distributed sequential control, which are the topic of this paper, we briefly outline the method from [31] that we use for distribution of control tasks to the LCs. We utilize this method since it is strongly related to the IEC 60848 and IEC 61131-3 standards that are commonly employed in practice for control specification. Furthermore, this is a top-down approach, starting from a description of the system functionality as a whole and then distributing control tasks to LCs; thus, the representation of the LCs' functionalities and their relation to the overall control system is transparent and easily understandable. However, the results of this paper (which considers attacks in distributed DES control) are not limited to the utilized method for distribution of control tasks and they can be applied to any

¹On the other hand, since DES do not consider timing information, there is no need to address attacks that result in information only being delayed.

TABLE I
RUNNING EXAMPLE: SIGNALS MAPPING TO LCS

Cyl.	LC	Home sensor	End sensor	Cyl. adv. signal	Cyl. retr. signal	Other signals
A	LC ₁	a0	a1	ap	am	-
B	LC ₂	b0	b1	bp	bm	st

distributed DES control regardless the way LCs are generated (using another approach, such as e.g., [32], or manually).

The method from [31] is based on Control Interpreted Petri Nets (CIPNs) [33] that are captured as bipartite graphs with vertices referred to as places (denoted by P and graphically presented by circles) and transitions (denoted by T and graphically presented by bars), as illustrated in Fig. 2. The state of a CIPN is represented by a marking, which assigns one token to some of the places and which is dynamically changed by transitions firing. In CIPNs, transitions firings are synchronized with sensing events, while actuator outputs (commands) are issued from marked places.

The sequential control distribution starts from a CIPN-based high-level description of the desired system behavior when all sensors and actuators are connected to a centralized controller (referred to as *global-CIPN*). Once a global CIPN is defined, and input and output signals are mapped into LCs with physical access to corresponding sensors and actuators, the method automatically generates local CIPN_{*i*}s, $i = 1, \dots, N$ describing local controllers (LCs) executed on IIoT-enabled smart devices that communicate between each other to achieve coordination – e.g., Send commands in Fig. 2. We describe this in more detail using our running example, introduced below.

Example 1. We consider a system for parts marking shown in Fig. 1a², which consists of two double-acting cylinders (A and B) controlled by bistable dual control valves 5/2 (2 positions, 5 ports); the valves are activated/deactivated by signals introduced in Table I. Cylinders are also equipped with proximity sensors for detecting limit positions. System operation starts when the start switch (*st* in Table I) is pressed. The system's work cycle is described by the following sequence

$$B + B - A + B + B - A - \quad (1)$$

where $X +$ denotes advancement, and $X -$ retracting of cylinder X ($X \in \{A, B\}$). Cylinders represent smart devices with integrated LCs where the assignment of dual control valve activating signals and sensor signals to LCs is given in Table I.

From the behavior of system described in (1), we obtain a global CIPN shown in Fig. 2a that captures the functional specification for sequential control of the whole system. Using the procedure from [31], from the global CIPN we obtain each CIPN_{*i*} describing local control behavior for LC_{*i*} (Fig. 2b-c), while ensuring the desired overall system behavior (as with the centralized controller). To achieve this, the LCs coordinate by communicating certain events. For example, LC₂ (Fig. 2c), while at place P_4^2 (P_4) sends information about rising edge at $b0$ to LC₁ (Fig. 2b) which receives this information at

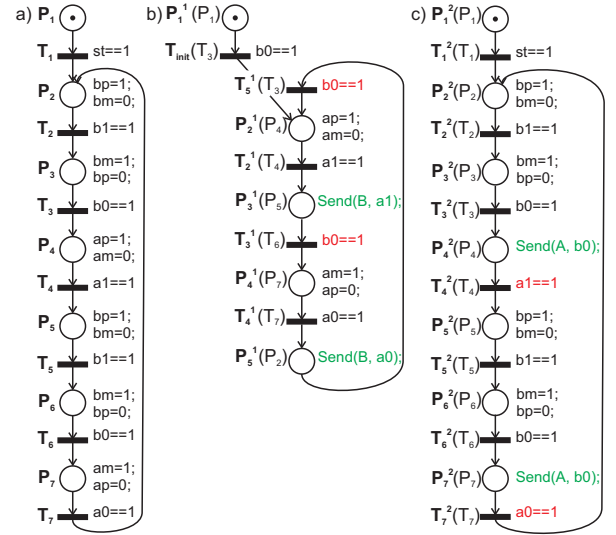


Fig. 2. Running example: a) global CIPN, b) CIPN₁ representing the behavior of LC₁, c) CIPN₂ representing the behavior of LC₂ (notation of places and transitions from CIPN are given in parentheses); $x == 1$ represents input reading allocated to the transition, while $x = 0/1$ denotes output assignment allocated to the place; Send commands are marked green, and receptive transition conditions red.

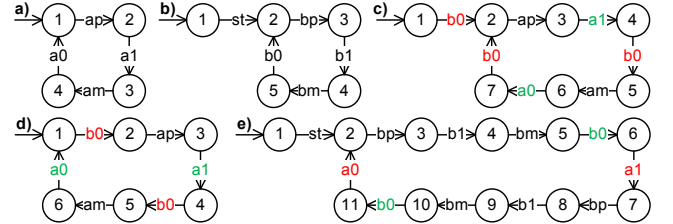


Fig. 3. Running example: a) Automaton G^1 modeling behavior of cylinder A, b) Automaton G^2 representing cylinder B, c) Automaton S^1 obtained from controller CIPN₁ (Fig. 2b), d) Automaton S^1' equivalent to S^1 representing LC₁, e) Automaton S^2 representing LC₂ obtained from CIPN₂ (Fig. 2c). Events that supervisors send are marked green and the events that they receive are marked red.

$T_{init}^1(T_3)$ or at $T_5^1(T_3)$, depending on the CIPN₁ marking and marks $P_2^1(P_4)$. In this way the sequence T_3P_4 captured in the global CIPN (Fig. 2a) is achieved in the distributed setup. \square

III. MODELING DISTRIBUTED SEQUENTIAL CONTROL

CIPNs are commonly used to model DES since they provide easily understandable graphical representation, especially in case of parallel processes. On the other hand, DES can also be represented as Finite State Automata (FSA). Since FSA provide convenient formalisms for modeling attacks on DES [34], in this work we transform each CIPN_{*i*} to FSA, utilizing procedures from [35], [36], within the SCT framework [25].

In SCT, all possible behaviors of a to-be-controlled-physical modules, which we will refer to as *plants*, (e.g., cylinders in Fig. 1) can be represented as an FSA denoted by $G^i = (Q^i, E^i, f^i, q_0^i)$, where Q^i is the finite set of states, E^i is the finite set of events, $f^i : Q^i \times E^{i*} \rightarrow Q^i$ is the transition function (here, $*$ denotes Kleene star), and q_0^i denotes the initial state of G^i . Such plant can be regarded as a generator

²This system is similar to one of the systems used for illustration of control tasks distribution in [31].

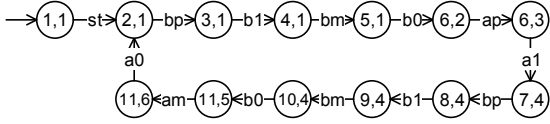


Fig. 4. Running example: Supervisor $S = S^1 || S^2$; in state notation x, y : x, y refer to states from S^2 and S^1 , respectively. In parallel composition, a transition on shared event can occur only if both automata are in a state where such transitions are enabled – e.g., transition on $b0$ (shared for S^1 and S^2) from (1,1) cannot occur as S^2 has no transition from (1) on $b0$

of a language $L^i(G^i)$ that contains strings w^i such that $L^i(G^i) := \{w^i \in E^{i*} : f^i(q_0^i, w^i)!\}$, where $!$ denotes that the $f^i(q^i, w^i)$ is defined. Behavior of N plants within the system can be captured as the FSA G obtained by parallel composition of $G^i, i = 1, \dots, N$, denoted by $G = ||_i G^i$.

For each plant, events in E^i can be partitioned as $E^i = E_o^i \cup E_{uo}^i$, where E_o^i and E_{uo}^i are the sets of observable and unobservable events, respectively. Similarly, the set E^i can be partitioned into the sets of controllable (E_c^i) and uncontrollable events (E_{uc}^i) such that $E^i = E_c^i \cup E_{uc}^i$. Since each physical plant modeled as G^i is locally controlled by a LC specified by $CIPN_i$, sensor signals assigned to $CIPN_i$ transitions belong to E_{uc}^i , while actuator signals assigned to the places are in E_c^i .

With distributed sequential control, LC_i provides controlled behavior of the plant G^i through a feedback control loop by imposing supervisor S^i that restricts the language $L^i(G^i)$ by disabling certain events. Supervisor is only aware of observable events E_o^i obtained from the set E^i by the natural projection $P_o^i : E^{i*} \rightarrow E_o^{i*}$ where (i) $P_o^i(\epsilon) = \epsilon$, with ϵ denoting the empty string; and (ii) $P_o^i(w^i t^i) = P_o^i(w^i) t^i$ if $t^i \in E_o^i$, and $P_o^i(w^i t^i) = P_o^i(w^i)$ if $t^i \notin E_o^i$. Such supervisor can be realized using automaton $S^i = (Q_s^i, E_s^i, f_s^i, q_0^i)$. Here, in addition to observable events from E^i , S^i contains events that are received (communicated) from other supervisors $S^j, j = 1, \dots, i - 1, i + 1, \dots, N$; we denote these events as $c_{j,k}^i$, where k denotes different events if more than one event is communicated from supervisor S^j to S^i . Thus, $E_s^i = E_o^i \cup \{\cup_j \cup_k c_{j,k}^i\}$. S^j transmits $c_{j,k}^i$ to S^i on the transition from state q_c^j for which $f^j(q_c^j, c_{j,k}^i)!$ to the state $f^j(q_c^j, c_{j,k}^i)$.

Finally, the coordinated operation of all supervisors S^i (i.e., all controllers) in the system is captured by $S = ||_i S^i$, while the controlled loop behavior of the system as a whole can be represented as $S \times G$, where \times denotes the product operator.

Running example continued. All possible failure free behaviors of cylinders A and B are captured by automata G^1 and G^2 (Fig. 3a-b), respectively. Here, $E^1 = E_o^1 = \{ap, a1, am, a0\}$, with $E_c^1 = \{ap, am\}$, and $E^2 = E_o^2 = \{bp, b1, bm, b0, st\}$, with $E_c^2 = \{bp, bm\}$. LC_1 and LC_2 implement supervisor controllers S^1 and S^2 , respectively, as shown in Fig. 3c and Fig. 3e; these supervisors are obtained from $CIPN_i$ in Fig. 2b and Fig. 2c. To simplify the presentation, automaton $S^{1'}$ is replaced by equivalent automaton S^1 (Fig. 3d)³. To capture event communication between controllers LC_1 and LC_2 , S^1 and S^2 have the follow-

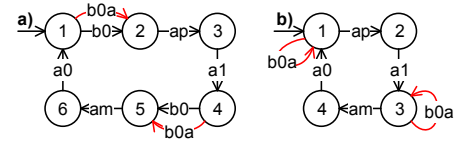


Fig. 5. Running example under $b0$ insertion attack on LC_1 : a) Automaton $S_a^1 - LC_1$ under attack, b) Automaton $G_a^1 -$ cylinder A under attack.

ing events sets: $E_s^1 = \{ap, a1, am, a0, b0\}$ where $b0 = c_{2,1}^1$, and $E_s^2 = \{bp, b1, bm, b0, st, a1, a0\}$ where $a0 = c_{1,1}^2$, and $a1 = c_{1,2}^2$. Communicated events are marked green in transmitting and red in receiving supervisor in Fig. 3c-e; these events model Send commands from Fig. 2. The conjoint operation of S^1 and S^2 – i.e., $S = S^1 || S^2$ – is graphically presented in Fig. 4. \square

IV. MODELING IMPACTS OF ATTACKS IN DISTRIBUTED SEQUENTIAL CONTROL

In this work, we assume that the attacker may compromise events communicated between LCs. Using the LC representation from Sec. III, the compromised events for supervisor S^i are all the events that S^i receives from and transmits to other LCs, captured in sets E_{rx}^i and E_{tx}^i :

$$E_{rx}^i = \bigcup_j \bigcup_k c_{j,k}^i \subseteq E_s^i, \quad E_{tx}^i = \bigcup_i \bigcup_k c_{i,k}^j \subseteq E_s^i \quad (2)$$

Since sequential control does not capture timing-related information, and thus communication delays do not impact correctness of the system operation, in such systems we have to consider two possible types of attacks: (i) *event insertion*, where a controller S^i receives an event $c_{j,k}^i$ before S^j sends it (i.e., without S^j sending it), and (ii) *event removal*, where an event sent to a controller S^i from a controller S^j is not received. These attacks capture standard Denial-of-Service and false-data injection attacks [12], while attacks such as Man-in-the-Middle, which swap one event for another, can be obtained with a combination of these two attacks.

In this section, we focus on capturing impacts of such attacks on system operation. We assume that the attacker's goal is to affect the performance of the system without being immediately revealed; note that there is a number of attacks that can be easily detected, such as inserting events like $b0$ when automaton S^1 is in e.g., state 3 (Fig. 3d). In addition, we assume that the attacker knows the current states of the plants and supervisors, and can use this information to plan his attacks. Finally, the attacker is not able to compromise protected communication links as integrity of these links is ensured with the use of standard cryptographic mechanisms for which the attacker does not possess the shared secret keys.

A. Insertion Attack

Let us consider the insertion attack that inserts event $c_{j,k}^i \in E_{rx}^i$; to simplify our notation, we use s_r^i to denote the 'regular' event ($c_{j,k}^i$) and s_a^i the event inserted by the attacker. To avoid being immediately revealed, the attacker has to insert

³All automata operations throughout the paper are carried out in DESUMA software [30], where the equivalence of automata $S^{1'}$ and S^1 is checked.

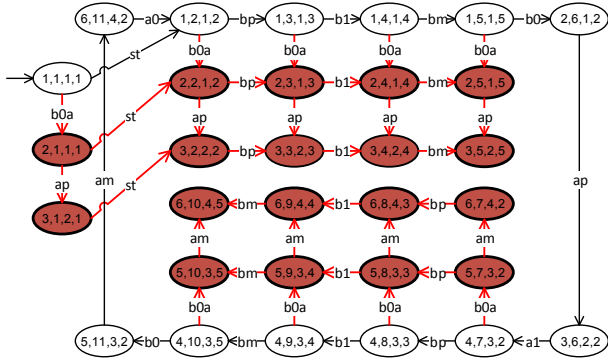


Fig. 6. Running example - b_0 insertion attack on LC_1 : Automaton G_A ; states that G_A can enter after attack are marked red.

event s_a^i only while the supervisor S^i is in a state q_r^i for which $f_s^i(q_r^i, s_r^i)!$. To achieve this, the attacker employs his knowledge of the current state of S^i .

Therefore, we will model the attacks that cannot be immediately revealed and that can affect the system behavior. Here, for every event that can be inserted we need to capture effects of such attack on the supervisor that receives the event, and, as we describe below, modify the corresponding plant model to ensure that adding a new event does not prevent the plant model from evolving (as the plant-generated events are not directly affected by the inserted event). With attack event s_a^i that inserts s_r^i at state $q_r^i \in Q_s^i$ for which $f_s^i(q_r^i, s_r^i)!$, S^i transitions to the state $f_s^i(q_r^i, s_r^i)$ since S^i considers that real s_r^i is received. Thus, the LC_i under attack can be modeled as automaton $S_a^i = (Q_s^i, E_{sa}^i, f_{sa}^i, q_{0s}^i)$ with $E_{sa}^i = E_s^i \cup \{s_a^i\}$ and

$$f_{sa}^i(q^i, s^i) = \begin{cases} f_s^i(q^i, s^i) & \text{if } s^i \in E_s^i \text{ and } f_s^i(q^i, s^i)! \\ f_s^i(q^i, s_a^i) & \text{if } s^i = s_a^i \text{ and } f_s^i(q^i, s_r^i)! \end{cases} \quad (3)$$

Hence, using (3), a transition labeled s_a^i is added in parallel with the transition labeled s_r^i to capture that the inserted event will lead the supervisor to the same state as the real event.

On the other hand, when event s_a^i is inserted by the attacker, the plant modeled by G^i can be at any state q_g^i for which $f^i(q_g^i, s_n^i)!$, where s_n^i is event such that $f_{sa}^i(f_{sa}^i(q_s^i, s_a^i), s_n^i)!$ – i.e., event following s_a^i in S_a^i . To model the receptiveness of the plant to the attack, we add a loop with s_a^i to every state q_g^i in the G^i and generate the model of the physical plant under attack s_a^i , denoted by G_a^i . Automaton $G_a^i = (Q^i, E_{ga}^i, f_{ga}^i, q_0^i)$ where $E_{ga}^i = E^i \cup \{s_a^i\}$ and f_{ga}^i is defined as:

$$f_{ga}^i(q^i, s^i) = \begin{cases} f_s^i(q^i, s^i) & \text{if } s^i \in E^i \text{ and } f^i(q^i, s^i)! \\ q^i & \text{if } s^i = s_a^i \text{ and } f^i(q^i, s_n^i)! \\ & \text{and } f_{sa}^i(f_{sa}^i(q_s^i, s^i), s_n^i)! \end{cases} \quad (4)$$

The second part of relation (4) models that the plant does not change the state on the attack event, but on the following event as imposed by the supervisor. Finally, the overall system behavior under attack G_A is captured by $G_A = (\|S_a^i \times \|G_a^i)$, where $S_a^i = S^i$ and $G_a^i = G^i$ if LC_i is not under attack.

Running example continued. We illustrate the modeling of the insertion attack on communicating b_0 between LC_2 and LC_1 in the running example – i.e., S^1 from Fig. 3d is attacked

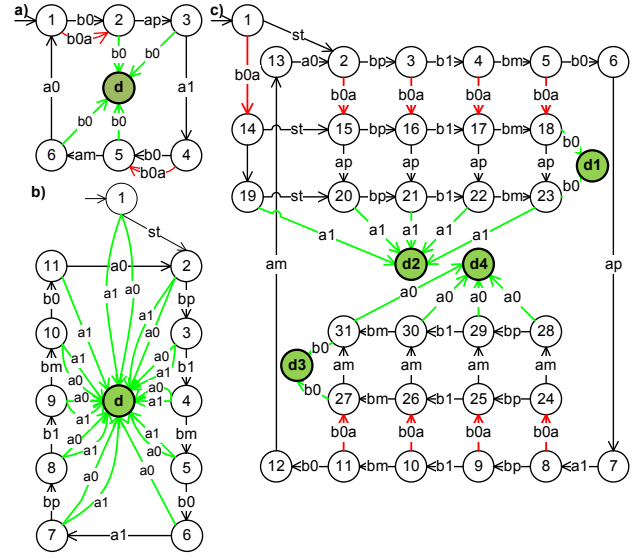


Fig. 7. Running example - b_0 insertion attack on LC_1 : a) Automaton S_{adet}^1 representing LC_1 under attack with integrated attack detection state d , b) Automaton S_{adet}^2 representing LC_2 with integrated attack detection state d , c) $S_{adet} = S_{adet}^1 || S_{adet}^2$.

by inserting 'fake' b_0a . Using our approach, models of $LC_1 - S_a^1$ and cylinder $A - G_a^1$ under attack are derived (Fig. 5).

From S_a^1 and G_a^1 (Fig. 5), as well as S^2 and G^2 (Fig. 3), we obtain the model of the system under such attack – G_A (Fig. 6); the states that G_A could enter after b_0 insertion attack are marked red. The states in G_A are denoted by (x, y, z, u) , where x, y, z and u denote the state of S^1, S^2, G^1 and G^2 , respectively. It can be observed that, to remain undetected at the moment of attack, the attack occurs when S^1 is at the state 1 or 4 which are receptive to b_0 . If the attack occurs while S^1 is at another state, it will be immediately detected.

To illustrate this, in Fig. 7 we provide the supervisors S_{adet}^1 and S_{adet}^2 with integrated state d that detects the receipt of an event at the state that is not receptive to this event. Namely, S_{adet}^1 (Fig. 7a) is obtained from S_a^1 (Fig. 5a) by adding the detection state d and transitions labeled b_0 from all the states not receptive to event b_0 to d . Thus, automaton S_{adet}^1 will enter the state d if it receives b_0 at states other than 1 and 4. Similarly, automaton S_{adet}^2 (Fig. 7b) will enter state d if it receives a_0 or a_1 while at states not receptive to these events. Parallel operation of the supervisors S_{adet}^1 and S_{adet}^2 (i.e., $S_{adet} = S_{adet}^1 || S_{adet}^2$) is presented in Fig. 7c; in S_{adet} , d_1 - d_4 correspond to the entrance of S_{adet}^1 and/or S_{adet}^2 in the state d . \square

Generally, S_{adet}^i can be derived from S_a^i as follows. $S_{adet}^i = (Q_{s_{adet}}^i, E_{s_{adet}}^i, f_{s_{adet}}^i, q_{0s}^i)$ where $Q_{s_{adet}}^i = Q_s^i \cup \{d\}$ and:

$$f_{s_{adet}}^i(q^i, s^i) = \begin{cases} f_{sa}^i(q^i, s^i) & \text{if } s^i \in E_{sa}^i \text{ and } f_{sa}^i(q^i, s^i)! \\ d & \text{if } s^i \in E_{r_x}^i \\ & \text{and } \neg f_{sa}^i(q^i, s^i)! \end{cases} \quad (5)$$

Implementing S_{adet}^i instead of S^i at LC_i leads to immediate detection of any unexpected event that is received; this includes the insertion attack if it is not carried out while the supervisor is at the state that is receptive to the attack event.

TABLE II
RUNNING EXAMPLE: Ω_c^k DEFINITION

CD ₁	$w_{c,1}^1 = w_{r1}(ama0ap)^*bp$, $w_{c,2}^1 = w_{r1}(amap)^*bp$ where $w_{r1} = w_r b p b1 b m b0 a p (a1 a m a0 a p)^*$
CD ₂	$w_{c,1}^2 = w_{r2} a m$, $w_{c,2}^2 = w_{r2} b1 a m$, $w_{c,3}^2 = w_{r2} b1 b m a m$ where $w_{r2} = w_r b p b1 b m b0 a p a1 b p (b1 b m b0 b p)^*$
CD ₃	$w_{c,1}^3 = w_{r3} b m$, $w_{c,2}^3 = w_{r3} b1 b m b0 a p a1 b p b m$ where $w_{r3} = w_r b p$

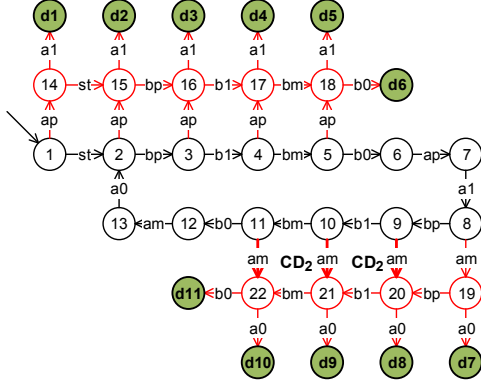


Fig. 10. Running example - b0 insertion attack: Automaton $Obs(G_{Adet})$ that represents all possible system behaviors under b0 insertion attack.

3d-e). Now, let's assume that S^1 is attacked by b0 insertion attack – i.e., inserting event $b0a$ – while at state 1; then, S^2 did not reach state 6. This is represented in Fig. 7c in states 1-5 corresponding to states $(1, y, 1, u)$ in G_A from Fig. 6. If S^2 reaches state 6 (and sends real b0) before S^1 reaches state 4, S^1 will receive real b0 while at state 2 or 3, and attack will be revealed; this is represented by transitions from states 18 and 23 to state d1 in Fig. 7c. As an alternative, if S^1 comes into state 4 before S^2 enters state 6 (i.e., before it sends real b0), it will send a0 to S^2 that is not in the correct state and the attack will be revealed again as illustrated on transitions from states 19-23 to d2 in Fig. 7c. Thus, the attack is detected at one of the states corresponding to G_A states $(3, y, 2, u)$, $(x, 5, z, 5)$ (Fig. 6). To summarize, by implementing S_{adet}^i instead of S^i at LCs, the insertion attacks will be detected at some point for systems in which two-way communication is present.

Note that when LCs have, both, sensor and actuator signals, two-way communication is always present. On the other hand if only actuators or sensors are mapped to LC, two-way communication is introduced with acknowledgment signals used for safety reasons. Thus, the attack will be detected at some point. Nevertheless, between attack occurrence and detection, in general, the system will not behave as desired. The question is whether the system behavior after attack will lead to significant damage, e.g., to the collision of systems' elements or manufactured parts damage.

System behaviors that lead to Catastrophic Damage CD_k , $k \in 1, \dots, M$ can be described by a set of undesired event strings $\Omega_c^k = \{w_{c,1}^k, \dots, w_{c,l_k}^k\}$. The question is, whether the system will exhibit a sequence from Ω_c^k , i.e., will CD_k occur under attack event s_a^i before the attack is revealed. Namely, if s_a^i potentially leads to CD_k , then communication of s_r^i between

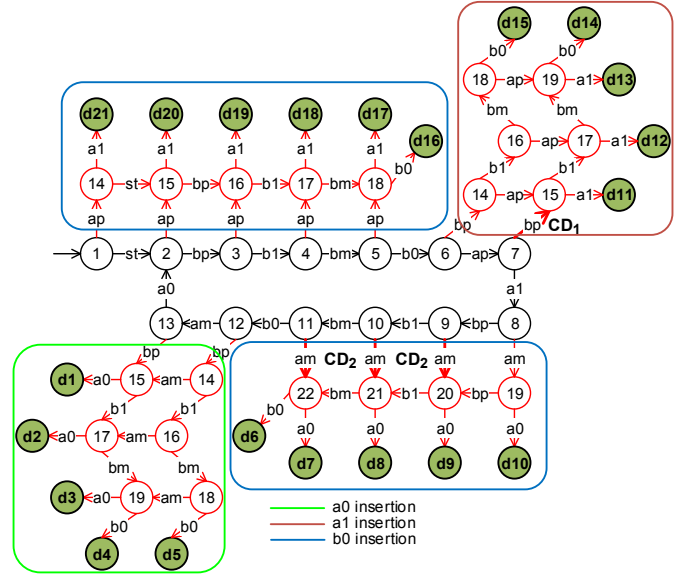


Fig. 11. Running example - $Obs(G_{AUdet})$ that represents all possible system behaviors under a0, a1, and/or b0 insertion attacks.

LCs has to be protected. To answer the question, we employ the automaton G_{Adet} that represents the system behavior under the attack event s_a^i . This automaton incorporates states for detection of the event being received at a wrong state, and it is obtained from S_{adet} and G_a , as $G_{Adet} = S_{adet} \times G_a$.

Here, G_{Adet} contains the unobservable event⁴ s_a^i that will break the chain of events from Ω_c^k and cannot be directly used for checking whether the system will exhibit the behavior specified by Ω_c^k , since the strings from Ω_c^k do not contain s_a^i . Event s_a^i could be easily eliminated from G_{Adet} by a natural projection. However, this could lead to generation of a nondeterministic automaton; to solve this issue and to preserve language equivalence, observer $Obs(G_{Adet})$ of G_{Adet} should be generated [37]. If $Obs(G_{Adet})$ accepts any string from Ω_c^k , then CD_k could happen during the s_a^i attack, and communication of s_r^i should be protected, as summarized in Procedure 1. It should be noted that $Obs(G_{Adet})$ is used offline, during system design, to model the behavior of the system under attack and to identify communication channels that require protection. The observer that considers all insertion attacks s_{aj} simultaneously, is obtained from G_{AUdet} , and the language $L(Obs(G_{AUdet}))$ represents the union of languages $L(Obs(G_{Ajdet}))$.

We illustrate the use of Procedure 1 on our running example.

Running example continued. In the running example, three insertion and three removal attacks could occur – a0 and a1 on communication from LC₁ to LC₂, and b0 on communication from LC₂ to LC₁. The regular cycle of the system can be presented by string $w_r \in \Sigma_r$, where $\Sigma_r = \{st(bp\ b1\ bm\ b0\ ap\ a1\ bp\ b1\ bm\ b0\ am\ a0)^*, st\}$. Mechanical design of the system (Fig. 1a) is such that marker can come into the position I to take marking liquid and leave it either in

⁴By design, the system is not aware that attack signals are attack; thus these are not observable events.

TABLE III
CASE STUDY: Ω_c^k DEFINITION

CD ₁	$w_{c,1}^1 = w_{r1}ap, w_{c,2}^1 = w_{r1}bmap, w_{c,3}^1 = w_{r1}bmb0bpap$ where $w_{r1} = w_r bpb1cp(bmb0bpb1)^*$
CD ₂	$w_{c,1}^2 = w_{r2}am, w_{c,2}^2 = w_{r2}b1am, w_{c,3}^2 = w_{r2}b1bmam$ where $w_{r2} = w_r bpb1cpbmb0apa1bp(b1bmb0bp)^*$
CD ₃	$w_{c,1}^3 = w_{r3}(ama0ap)bp, w_{c,2}^3 = w_{r3}(amap)^*bp$ where $w_{r3} = w_r bpb1cpbmb0ap(a1ama0ap)^*$
CD ₄	$w_{c,1}^4 = w_{r4}bp$ where $w_{r4} = w_r bpb1cpbmb0apa1(bpb1bmb0)^*am$

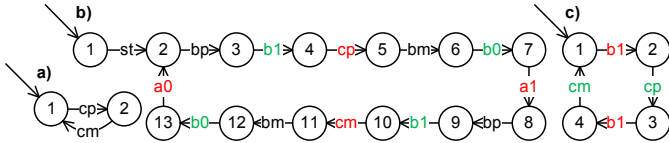


Fig. 12. Case study: a) Automaton G^3 representing gripper C , b) Automaton S^2 representing LC_2 , c) Automaton S^3 representing LC_3 .

horizontal or in vertical direction (note that in regular work-cycle approaching and leaving are in vertical direction). On the other hand, it can enter and leave position II only in vertical direction; otherwise the marking liquid could be diffused over the part thus endangering marking quality. Furthermore, to ensure part marking, it is necessary that cylinder B reaches end position before retracting at both, position I and II. Thus, there exist three situations that endanger the quality of the process: (i) CD_1 - marker enters position II from horizontal direction, (ii) CD_2 - marker leaves position II in horizontal direction, and (iii) CD_3 - cylinder B retracts before reaching end position. For each of these situations, events strings sets Ω_c^k can be identified as presented in Table II.

$Obs(G_{Adet})$ that contains all possible consequences of insertion attacks on $b0$ is presented in Fig. 10. It is obtained from $G_{Adet} = S_{adet} \times G_a$, where $S_{adet} = S_{adet}^1 || S_{adet}^2$ (Fig. 7) and $G_a = G_a^1 || G_a^2$ (Fig. 5b and Fig. 3b); states $d1 - d11$ are derived from states d in S_{adet}^1 and/or S_{adet}^2 . In case of $b0$ insertion attack CD_2 could occur (strings $w_{c,1}^2, w_{c,2}^2$ and $w_{c,3}^2$). Fig. 11 represents $Obs(G_{A_{Udet}})$; it can be observed that in the case of $a1$ insertion attack, the occurrence of CD_1 is possible (string $w_{c,1}^1$). Nevertheless, $a0$ insertion attack will not have catastrophic effect on the system performance. Furthermore, neither of insertion attacks would cause CD_3 . All three removal attacks will lead to deadlock, as presented in Fig. 9 for $b0$ removal attack. System behavior models are similar in the case of $a0$ or $a1$ removal attacks. Thus, removal attacks will lead to none of CD_k . Consequently, the communication of $b0$ and $a1$ should be protected, while for $a0$ encryption is not necessary. \square

VI. INDUSTRIAL CASE STUDY

We consider a case study that refers to the manipulator obtained by reconfiguring the marking device from our running example as presented in Fig. 1b. We also considered a more complex system with concurrent processes (specifically, the case study from [31]), and similar results were obtained. Due

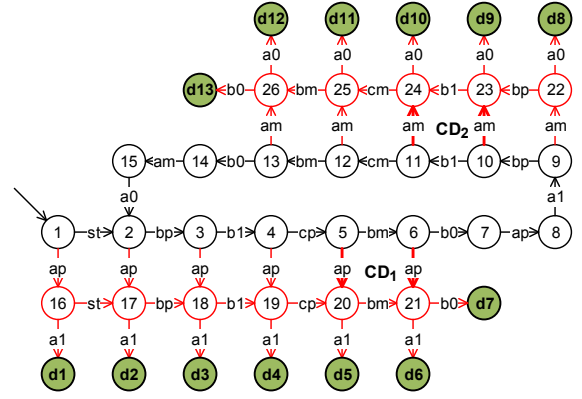


Fig. 13. Case study - $Obs(G_{Adet})$: $b0$ insertion attack on LC_1 .

to the space constraint, the detailed system analysis for the second case study has been omitted from this work.

The manipulator has two translational degrees of freedom realized by smart cylinders A and B as in running example (Table I). It is also equipped with a smart vacuum gripper C that is controlled by a monostable dual control valve 3/2, and has integrated LC_3 with mapped signal cp for part gripping and cm for part releasing. Manipulator moves elastic part from position I to II and performs the following work cycle:

$$B + C + B - A + B + C - B - A - \quad (9)$$

where cylinder activities are denoted as in (1), whereas $C+$ refers to part gripping and $C-$ to part releasing. Work cycle is started by pressing start switch (st) mapped to LC_2 .

A. Attack Modeling and Identification of Undesired System Behaviors

Following the introduced modeling approach, automata G^1 , G^2 and G^3 , representing all possible legal behaviors of cylinders A and B , and gripper C are generated. G^1 and G^2 are the same as in the running example (Fig. 3a-b), whereas G^3 has the following set of events $E^3 = E_o^3 = E_c^3 = \{cp, cm\}$ and it is shown in Fig. 12a. Local controllers LC_1 , LC_2 and LC_3 impose supervisors S^1 , S^2 , and S^3 , respectively. Supervisor S^1 is the same as in the running example (Fig. 3d) and has event set $E_s^1 = \{ap, a1, am, a0, b0\}$ with the event $b0 = c_{2,1}^1$ that is communicated from LC_2 . Supervisor S^2 (Fig. 12b) is based on the following events set $E_s^2 = \{st, bp, b1, bm, b0, a0, a1, cp, cm\}$ and it has four communicated events: (1) $a0 = c_{2,1}^2$ and $a1 = c_{2,2}^2$ received from LC_1 , and (2) $cp = c_{3,1}^2$ and $cm = c_{3,2}^2$ received from LC_3 . Finally, S^3 (Fig. 12c) contains the events $E_s^3 = \{cp, cm, b1\}$, where $b1 = c_{2,1}^3$ is received from LC_2 . Note that gripper C does not contain sensors and that acknowledgment events cp and cm are sent from S^3 to S^2 for safety reasons to ensure two-way communication in S^3 as elaborated in Section V.

The strings $w_r \in \Sigma_r$, where $\Sigma_r = \{st(bp \ b1 \ cp \ bm \ b0 \ ap \ a1 \ bp \ b1 \ cm \ bm \ b0 \ am \ a0)^*, st\}$ define regular cycles of the system. On the other hand, catastrophic damages could happen in the following scenarios (described by events string sets $w_{c,lk}^k$, $k \in \{1, 2, 3, 4\}$ defined in Table III):

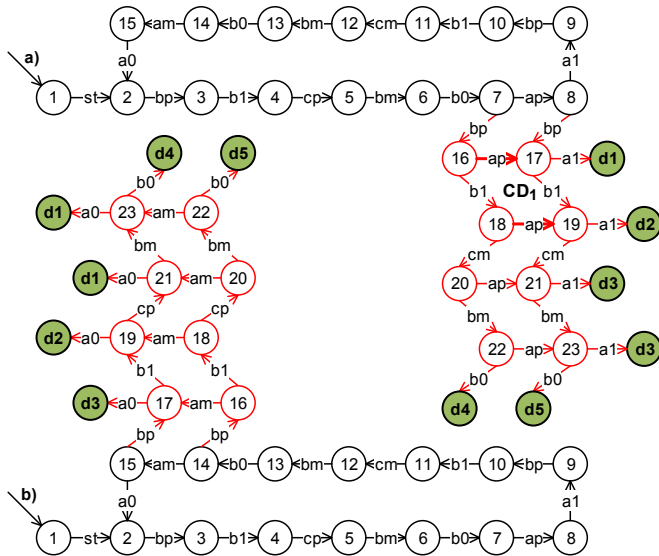


Fig. 14. Case study - $Obs(G_{A_{det}})$: a) $a1$ and b) $a0$ insertion attack on LC_2 .

CD₁ manipulator with gripped part in position I tries to advance cylinder *A* before retracting cylinder *B*,
CD₂ manipulator in position II tries to retract *A* before releasing part and before retracting *B*,
CD₃ manipulator tries to put down the part while moving it from position I to position II,
CD₄ manipulator does not leave the part in position II and tries to put it down while moving it from position II to I.

Observers for insertion attacks: (1) $b0$ and (2) $a1$ and $a0$ are shown in Fig. 13 and Fig. 14, respectively. From these figures, it can be observed that CD_1 can appear during $b0$ insertion attack on LC_1 ($w_{c,1}^1$ and $w_{c,2}^1$ on transitions from 5 to 20 and 6 to 21 - Fig. 13) and during $a1$ insertion attack on LC_2 ($w_{c,3}^1$ and $w_{c,1}^1$ on transitions from 16 to 17 and 18 to 19 - Fig. 14a). Furthermore, CD_2 can occur during $b0$ insertion attack on LC_1 ($w_{c,1}^2$ and $w_{c,2}^2$ on transitions from 10 to 23 and 11 to 24 - Fig. 13). Other insertion attacks (observers are omitted due to space limitation) will not lead to CDs. Furthermore, removal attacks will lead to immediate deadlock and will not cause any damage. Thus, transmissions of $b0$ from LC_2 to LC_1 and of $a1$ from LC_1 to LC_2 should be protected.

B. Experimental Validation

We experimentally evaluated our approach to attack modeling and detection on a real-world industrial case-study – industrial manipulator shown in Fig. 15. Each actuator (two cylinders and gripper) represents a smart device with its own LC, where the mapping of sensors and actuators is captured in Table I for cylinders A and B, while cp and cm are mapped to LC_3 (i.e., the gripper’s LC).

Hence, the control system of the manipulator from Fig. 15 is implemented using three wireless nodes (LCs); we employed ARM Cortex-M3 microcontroller boards that communicate over IEEE 802.15.4-compliant wireless transceivers. LC₁-LC₃ implement S^1_{adet} , S^2_{adet} and S^3_{adet} obtained from S^1 (shown in Fig. 3d), S^2 (Fig. 12b), and S^3 (Fig. 12c) by adding the attack

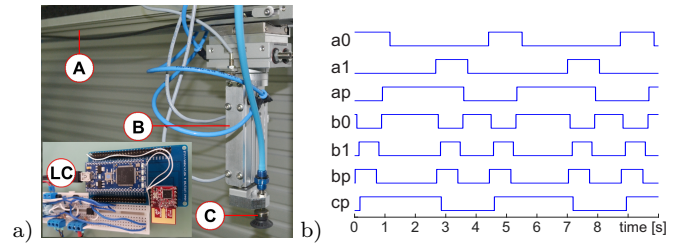


Fig. 15. Industrial case study: a) Experimental installation; b) Timing diagram capturing inputs and outputs of the system in a scenario without attack.

detection state. On the entrance to the state d at any of the LCs, the system stops immediately. Timing diagram capturing the sequence of controllable and uncontrollable events acquired from the real-world manipulator during a regular work-cycle (i.e., without attack) is presented in Fig. 15; due to space constraints, we do not show am , bm , and cm signals, as they are only inverted signals of the ap , bp , and cp , respectively.

In addition to wireless nodes implementing the distributed controllers, the experimental installation also contains the fourth LC, based on the same ARM board, which is used as an attacker. The attacker is completely aware of the system design and performance, as it can eavesdrop all communication between control LCs and has the knowledge of the LCs design. Thus, the attacker is capable of crafting attacks that will not be immediately revealed. To validate the proposed method for attacks modeling and detection, using the attack LC, we have implemented all attacks on the manipulator from the case-study (i.e., previous subsection). The observed executions of the system were completely compliant with the previously described observers (in Figures 13 and 14).

For example, in Fig. 16 we present the timing diagrams experimentally acquired from the system in the presence of attacks; specifically, we illustrate system performance under *b0* and *a1* insertion attacks launched at different time instants; note that the attacks may have different impact based on the timing instance in which they are launched. We first illustrate system execution under the *b0* insertion attack that was activated at time $t = 4.55s$, resulting in the sequence *w_r bp b1 cp ap bm b0*,⁵ as shown in Fig. 16a, which corresponds to transitions through states 5, 20, 21, *d7* from Fig. 13 before attack detection at *d7*; this attack leads to CD_1 .

On the other hand, b_0 insertion attack at time $t = 7.31s$ results in the event sequence, shown in Fig. 16b: $w_r bp b_1 cp bm b_0 ap a_1 bp b_1 cm \mathbf{am} bm b_0$; this reflects transitions through states 12, 25, 26 before detection at $d13$ (Fig. 13) and does not lead to any catastrophic damage.

Similarly, $a1$ insertion attacks at times $t = 5.40s$ and $t = 5.86s$ lead to the event sequences from Fig. 16c-d: (i) $w_r \text{ } bp \text{ } b1 \text{ } cp \text{ } bm \text{ } b0 \text{ } ap \text{ } \mathbf{bp} \text{ } b1 \text{ } a1$ corresponding to transitions 8, 17, 19, d2 in the observer from Fig. 14a, and (ii) $w_r \text{ } bp \text{ } b1 \text{ } cp \text{ } bm \text{ } b0 \text{ } ap \text{ } \mathbf{bp} \text{ } b1 \text{ } cm \text{ } bm \text{ } b0 \text{ } a1$ corresponding to the transitions 8, 17, 19, 21, 23, d5 in the observer from

⁵Under $b0$ insertion attacks, the occurrence of uncontrollable events $a1$ or $a0$ after attack detection is caused by the controllable events ap/am and system inertia.

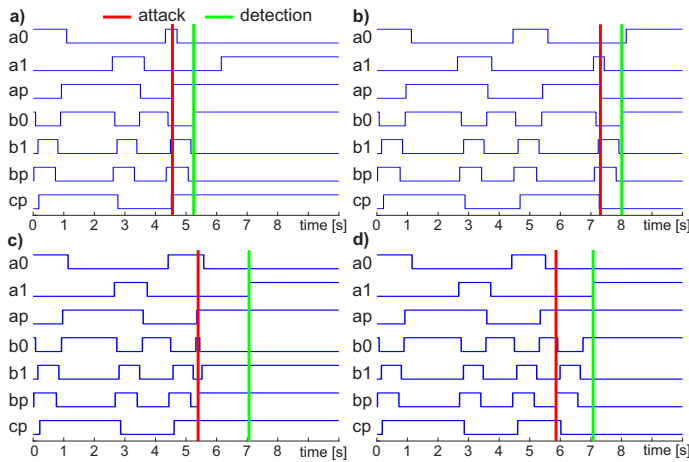


Fig. 16. Case study: experimentally captured timing diagrams of the inputs and outputs of the manipulator in the presence of: (a-b) b_0 insertion attacks, and (c-d) a_1 insertion attacks at different time instants.

Fig. 14a before attack detection. Neither of the illustrated a_1 insertion attacks leads to catastrophic damage of the system.

VII. DISCUSSION AND CONCLUSION

In this paper, we have focused on security challenges in design of sequential control systems for industrial automation, where the control is distributed over IIoT-enabled smart devices. We have presented a method for modeling relevant attacks on communication between such Local Controllers (LCs), which share information about local events to ensure their coordination and the desired overall system operation. We have focused on event-insertion and event-removal attacks that allow us to capture a wide-range of standard attacks on industrial systems, such as Denial-of-Service attacks, false-data injection attacks, as well as Man-in-the-Middle attacks. We have considered attacks that cannot be immediately detected, in order to have significant impact on system operation, and for such attacks we have presented methods to model their impact on the system. To achieve this, we have employed a standard Supervisory-Control Theory (SCT) framework that is widely adopted for modeling of sequential control systems used for industrial automation; this allows for modeling of both physical behavior of smart IIoT-enabled devices as well as cyber behavior of their LCs in the presence of the attacks.

In the considered case studies, we have shown that stealthy event-removal attacks lead to system deadlock; the reason is that the considered systems for safety reasons already employ two-way communication where every command is followed by either a corresponding sensing event or a communication acknowledgment event. The deadlock is immediate for such systems that do not have parallel (concurrent) processes since in these processes there is no branching in input and output sequence, and removing any actuation command or sensing event would prevent continuation of the system execution.

On the other hand, in such systems (i.e., with such two-way communication) that do contain parallel processes, the deadlock is immediate on the attacked branch, whereas the parallel branches continue work-cycle until they converge with

the attacked branch; the deadlock on the whole system occurs at the convergence point.⁶ It should be noted that concurrent processes in sequential control are parallel in their nature and do not impose any time-related, mechanical or other constraints on branch parallelism that could lead to security related issues.

Furthermore, we have shown that due to two-way communication between LCs, event-insertion attack can be eventually revealed using the developed detection mechanism. Nevertheless, between attack occurrence and detection, the system can exhibit undesired behaviors that could result in significant damage. Hence, we have provided a method to identify events whose communication should be protected, to ensure satisfiable system operation in resource-constrained systems, in the presence of attacks.

The proposed method is experimentally verified using a real-world case study with three LCs. For the systems with higher number of LCs and with higher complexity of control tasks where a large number of commands are executed between subsequent communications, the sequence of events can be modeled by higher level of abstraction, such as macro steps in Grafset [38]. In this way a hierarchical structure can be introduced into events. Our future efforts will include timing-based analysis of the system under attacks, and the use of (time) intermittent authentication to protect communication.

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⁶As captured in Section VI, we have also performed security analysis for a system with parallel processes. However, due to the space constraints, a detailed description of the example of such system is omitted from this paper.

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