Supervisory Control of Discrete Event Systems in the Presence of Sensor and Actuator Attacks

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Abstract— **This work focuses on the design of secure and resilient supervisors for plants modeled as discrete event systems (DES), in the presence of attacks that tamper with their inputs and sensors. We propose to model such attacks as nondeterministic finite state transducers (FSTs) and show how FSTs can be used to capture a very wide class of attacks including all previously considered attacks on DES, as well as additional attacks and attack features reported in recent security incidents. We study the supervisory control problem is in three cases: when attacks occur (i) only on the sensors, (ii) only on the actuators, and (iii) both on the actuators and sensors of the plant. For each case, we present new sets of controllability theorems and synthesizing algorithms for supervisors. We show that for (i), the sensor attacker can be entirely countered by a supervisor, implemented as an FST and derived by the serial composition of the inversion of the attacker and a model of the desired language. For (ii), the actuator attacker can be partly countered by a supervisor derived by the serial composition of a model of the desired language and the inversion of the attacker; and the condition for exact controllability is derived. For (iii), we show that a supervisor can be derived by serially composing the supervisors designed for the cases (i) and (ii). On a series of examples, we illustrate the use of our approach for modeling and design of security-aware supervisory control.**

I. Introduction

Control systems operate in a range of security-critical domains where communication between the controller and the plant, or the physical environment of the plant, may be susceptible to adversarial attacks both in the cyber and physical domains. Consequently, it is critical to provide techniques to analyze the behavior of control systems under attack, as well as synthesize attack-resilient control systems [1], [2], [3]. Such systems should be able to provide strong control guarantees under different types of intelligent and coordinated attacks (e.g., [3], [4]); such malicious behaviors are more complicated than random failures, which is well studied in the fields of reliability and fault tolerant control.

In this work, we adopt the framework of the supervisory control of the discrete event systems [5], in which a supervisor controls the behavior of a plant modeled as a discrete event system (DES) within a desired language in a close-loop. Recently, there is a growing work focused on securing discrete event system (DESs), considering possible attacks on communication between the supervisor and plant [6], [7], [8], [9]. In those works, the attackers have the ability to insert, delete, and replace events/symbols in communication between the plant according to certain prespecified rules, and the supervisor, generally realized by a finite state automaton, regulates the words passing-by to counter the attacks.

One contribution of this paper is to show that all previously studied attacks on DES including injection, deletion, and replacing events/symbols according to certain prespecified rules, fall into a more general class of regularly-rewriting attacks, which are considered in this work. In these attacks, attackers can revise the symbols communicated between the supervisor and the plant ***nondeterministically*** to a word (possibly empty) in a regular language. Mathematically, the regularly-rewriting attacks define a regular relation between the input and output languages of the attackers [10], [11]. We show how they can be suitably realized by finite state transducers (FST) or nondeterministic Mealy machines. Furthermore, to counter the attacks and improve system resiliency, we also consider supervisors that can be modeled as FSTs, instead of automata as done in existing work — this gives the supervisor the ability to rewrite, in addition to monitoring.

FSTs, especially deterministic ones, have found applications in a wide-range of application domains, such as applications in speech recognition [12], [13], [14], [15]. In this work, nondeterministic FSTs are more preferable, as in the context of security, all possible malicious behaviors of the attackers have to be taken into account, and thus nondeterminism is essential to capturing the attacker's behavior. Unlike finite state automata, only the FSTs that have the twins property are determinizable [16]. Specifically, the twins property requires that the possible executions induced by the same input word should generate identical output words.

Another advantage of using FSTs to model attacks is having a library of mathematically rigorous and computationally feasible operations. The class of FSTs is closed under inversion and composition — these operations are mathematically well-defined and easily computable. Consequently, the attack-resilience problem in supervisory control with complex system configuration and multiple attackers modeled by FSTs can usually be simplified to a few basic configurations. Furthermore, as we show in this work, modeling the attackers as FSTs facilitates implementation of platform-based constraints imposed on the attacker by the system design, such as how frequently attacks are disabled due to intermittent use of cryptographic security primitives to protect the communication [17].

Figure 1 presents the considered supervisory control system where FSTs model attacks on the information delivered

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to the controller from the plant's sensors as well as the attacks on the control commands delivered to the actuators. We show how this configurations captures the basic controllability problems in attack-resilient supervisory control. Specifically, in this paper, we focus on three configurations: (i) attacks on sensors, (ii) attacks on actuators, and (iii) attacks on both actuators and sensors of the plant. This allows for the capturing malicious activity that may occur as a result of network-based attacks that corrupt the data communicated between the plant and controller (e.g., as in [18], [1]), as well as non-invasive attacks that affect the environment of the plant (e.g., GPS spoofing attacks [19]).

In this work, we attack-resiliency as controllability under attack, and introduce a new set of controllability theorems and synthesizing algorithms for attack-resilient supervisors used for the supervisory control of discrete event systems where attacks are modeled by FSTs. We show that for the case (i), attacks on sensing information delivered to the controller can be completely countered by an FST-based supervisor derived by the serial composition of the inversion of the (very-general) attack model and a model of the desired language. This is because, modeling the supervisor as an FST gives it the power to generate controls by itself. For the case (ii), the actuator attacks on commands sent to the plant can be partly countered by a supervisor derived by the serial composition of a model of the desired language and the inversion of the attacker. The exact controllability is achieved if the desired language is invariant under the attack. Finally, for the case (iii), we show that an attack-resilient supervisor can be derived by serially composing the supervisors in the cases (i) and (ii). The derived controllability conditions for actuator attacks generalizes the standard controllability conditions for DESs under partial controllable and observable sets [4]. Our controllability conditions for attacks distinguish from existing works on the attack-resilient supervisory control of DESs [6], [7], [8], [9], as a more general model for attacks and supervisors is adopted.

The rest of this paper is organized as follows. After introducing preliminaries in Section II, we show how attack behaviors can be modeled by FSTs (Section III) and formally specify the problem (Section IV). In Section V, a controllability theorem and an algorithm to design an attack-resilient supervisor is presented, when only plant sensors are corrupted. In Section VI, the same problem is studied for the case with attacks only on the actuators of the plant. Finally, these results are generalized in Section VII for the case with attacks on both the actuators and sensors of the plant, before we provide concluding remarks in Section VIII.

II. Preliminaries

The empty string is denoted by ε. A finite-length sequence of symbols taken from a given finite set is called a *word*. A set of words is called a *language* of the symbols. The cardinality and the power set of a set $\mathbf{I}$ are denoted by $|\mathbf{I}|$ and $2^{\mathbf{I}}$, respectively. For two sets $\mathbf{I}$ and $\mathbf{O}$, let $\mathbf{I}\backslash\mathbf{O} = \{\mathsf{i} \in \mathbf{I} \mid \mathsf{i} \notin \mathbf{O}\}$. For $n \in \mathbb{N}$, where $\mathbb{N}$ is the set of natural numbers, let $[n] = \{1, .., n\}$. For a word $I = \mathsf{i}_1\mathsf{i}_2 \dots \mathsf{i}_n$, we call $\mathsf{i}_1\mathsf{i}_2 \dots \mathsf{i}_k$, with $k \leq n$, a prefix of I. For a language L, its prefix-closure is defined by $\overline{L} = \{I \mid I \text{ is a prefix of } J, J \in L\}$. The language L is *prefix-closed* if $L = \overline{L}$. Also, we adopt the following convention on generating regular expressions: a superscript * means repeating a symbol or a set of symbols finitely many times, and a comma means "or".

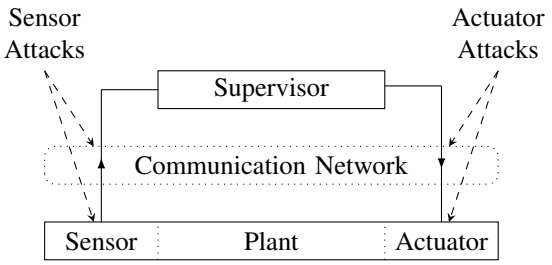


Fig. 1: Supervisory control under attacks on sensors, actuators as well as the communication between the sensors, controller and actuators; in this work, we use finite-state transducers to capture a very general class such attacks.

A *relation* $\mathcal{R}$ between two sets $\mathbf{I}$ and $\mathbf{O}$ is a set $\mathcal{R} \subseteq \mathbf{I} \times \mathbf{O}$. For $\mathsf{i} \in \mathbf{I}$, let $\mathcal{R}(\mathsf{i}) = \mathcal{R}(\mathsf{i}, \cdot) = \{\mathsf{o} \in \mathbf{O} \mid (\mathsf{i}, \mathsf{o}) \in \mathcal{R}\}$. The relation $\mathcal{R}(\mathsf{i})$ is a *partial function* for the input a if $|\mathcal{R}(\mathsf{i})| \leq 1$, for any $\mathsf{i} \in \mathbf{I}$. More generally, for $\mathbf{I}' \subseteq \mathbf{I}$, while slightly abusing the notation we define $\mathcal{R}(\mathbf{I}') = \mathcal{R}(\mathbf{I}', \cdot) = \{\mathsf{o} \in \mathbf{O} \mid (\mathsf{i}', \mathsf{o}) \in \mathcal{R}, \mathsf{i}' \in \mathbf{I}'\}$. Thus, $\mathcal{R}(\cdot)$ defines a function $2^{\mathbf{I}} \to 2^{\mathbf{O}}$. For relation $\mathcal{R} \subseteq \mathbf{I} \times \mathbf{O}$, its inversion is defined by $\mathcal{R}^{-1} = \{(\mathsf{o}, \mathsf{i}) \in \mathbf{O} \times \mathbf{I} \mid (\mathsf{i}, \mathsf{o}) \in \mathcal{R}\}$. Finally, for two relations $\mathcal{R} \subseteq \mathbf{I} \times \mathbf{O}$ and $\mathcal{R}' \subseteq \mathbf{I}' \times \mathbf{O}'$, their (serial) composition is defined by $\mathcal{R} \circ \mathcal{R}' = \{(\mathsf{i}, \mathsf{o}') \in \mathbf{I} \times \mathbf{O}' \mid \exists \mathsf{o} \in \mathbf{O} \cap \mathbf{I}' : (\mathsf{i}, \mathsf{o}) \in \mathcal{R} \wedge (\mathsf{i}', \mathsf{o}') \in \mathcal{R}'\}$.

Finite State Transducers (FSTs) extend Finite State Automata (FSA) by generating a sequence of outputs nondeterministically during execution, by augmenting each transition with a regular output language.

Definition 1 (Finite State Transducer)**.** *A finite state transducer is a tuple* $\mathcal{A} = (\mathsf{S}, \mathsf{s}_{\text{init}}, \mathbf{I}, \mathbf{O}, \mathsf{Trans}, \mathsf{S}_{\text{final}})$ *where*

- S *is a finite set of* states*;*
- $\mathsf{s}_{\text{init}} \in \mathsf{S}$ *is the* initial state*;*
- $\mathbf{I}$ *is a finite set of* inputs*;*
- $\mathbf{O}$ *is a finite set of* outputs*;*
- $\mathsf{Trans} : \mathsf{S} \times \mathbf{I} \cup \{\varepsilon\} \to \mathbf{O} \cup \{\varepsilon\} \times \mathsf{S}$ *is a partial* transition *relation;*
- $\mathsf{S}_{\text{final}} \subseteq \mathsf{S}$ *is a finite set of* final states*.*

The FST is deterministic if Trans is a partial function. The sequence $(\mathsf{s}_{\text{init}}, \mathsf{i}_0, \mathsf{o}_0, \mathsf{s}_0)(\mathsf{s}_0, \mathsf{i}_1, \mathsf{o}_1, \mathsf{s}_1) \dots (\mathsf{s}_{n-2}, \mathsf{i}_{n-1}, \mathsf{o}_{n-1}, \mathsf{s}_{n-1})$ is called an *execution*, if $(\mathsf{o}_i\mathsf{s}_i) \subseteq \mathsf{Trans}(\mathsf{s}_{i-1}, \mathsf{i}_i)$ for $i \in [n]$ with $\mathsf{s}_{-1} = \mathsf{s}_{\text{init}}$. The state s_{n-1} is called reachable upon receiving the input word $I = \mathsf{i}_0\mathsf{i}_1 \dots \mathsf{i}_n$. An input/output word is *accepted* by $\mathcal{P}$, if there exists such an execution ending at $\mathsf{S}_{\text{final}}$. The set of accepted input/output words is called the *input/output languages* of $\mathcal{A}$, denoted by $L_I(\mathcal{A})$ and $L_O(\mathcal{A})$, respectively.

We refer to [14] for common operations on FSTs, such as inversion and composition. Obviously, a finite state trans-

ducer $\mathcal{A}$ defines a regular relation $\mathcal{R}_{\mathcal{A}}$ between the input and output languages. On the other hand, a relation $\mathcal{R} \subseteq \mathbf{I}^* \times \mathbf{O}^*$ is *regular*, only if it is realized by a finite state transducer.

Remark 1. *In this work, FSA are viewed as FSTs with identical inputs and outputs. On the other hand, FSTs can be viewed as FSA with labels in* $(\mathbf{I} \cup \{\varepsilon\}) \times (\mathbf{O} \cup \{\varepsilon\})$.

III. Modeling Attacks with Finite State Transducers

In this section, we focus on modeling attacks on supervisory control with FSTs and show how such FST-based models generalize all existing attack models. Specifically, we show how FSTs can be used to capture all previously reported attacks on DES, as well as additional attacks and attack features. For example, FSTs can be used to capture constraints imposed by the system design, as well as model finite-memory replay attacks, where the attacker records a finite-length of symbols and replays it repeatedly [20], [2].

Thus, we start by showing that attack models proposed in previous works [6], [9] can be also represented by FSTs as shown in the following examples.

Example 1 (Projection/Deletion/Injection Attacks)**.** *Consider* $\mathbf{I}'$ *where* $\mathbf{I}' \subseteq \mathbf{I}$*. The projection attack defined as*

$$\mathrm{Project}_{\mathbf{I}'}(\mathsf{i}) = \begin{cases} \mathsf{i}, & \text{if} \quad \mathsf{i} \in \mathbf{I}' \\ \varepsilon, & \text{otherwise,} \end{cases} \tag{1}$$

captures attacks that remove all symbols from $\mathbf{I} \setminus \mathbf{I}'$*. On the other hand, the (nondeterministic) deletion attack defined as*

$$\mathrm{Delete}_{\mathbf{I}'}(\mathsf{i}) = \begin{cases} \mathsf{i}, & \text{if} \quad \mathsf{i} \in \mathbf{I}' \\ \varepsilon \text{ or } i, & \text{otherwise,} \end{cases} \tag{2}$$

extends the $\mathrm{Project}_{\mathbf{I}'}$ *attack as it captures that the attacker may (or may not) remove symbols from* $\mathbf{I} \setminus \mathbf{I}'$*; e.g., if* $\mathbf{I}' = \mathbf{I}$ *this model can be used to capture Denial-of-Service attacks [21] over the communication network.*

Finally, the (nondeterministic) injection attack defined as

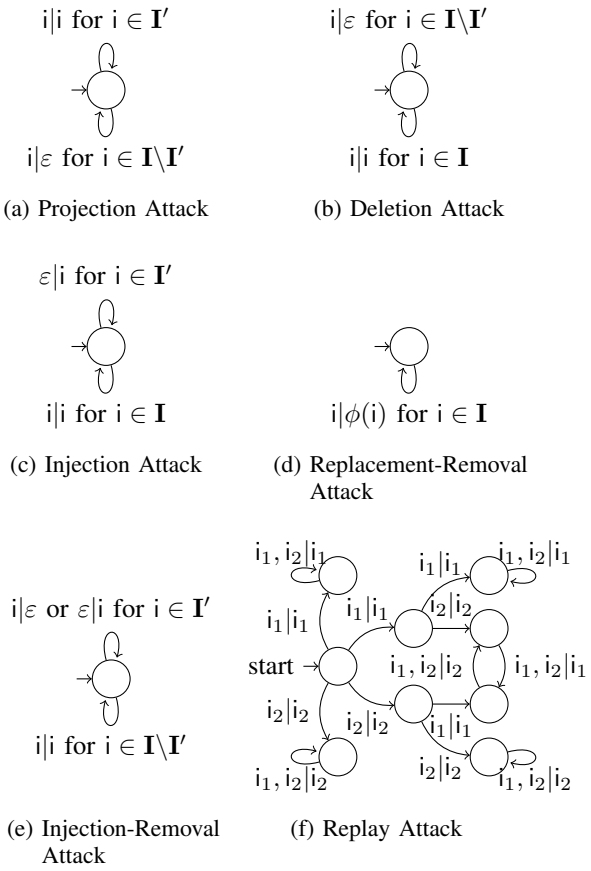
$$\mathrm{Insert}_{\mathbf{I}'}(\mathsf{i}) = (\mathbf{I}')^* \mathsf{i} (\mathbf{I}')^* \tag{3}$$

captures that a finite number of symbols from $\mathbf{I}'$ *can be added before and/or after the symbols. These attacks can be represented by FSTs as shown in Figure 2a, Figure 2b and Figure 2c, respectively.* ◁

Example 2 (Replacement-removal Attack)**.** *This attack is defined by the replacing-removing rule* $\phi : \mathbf{I} \to 2^{\mathbf{I} \cup \{\varepsilon\}}$*, and can be represented by an FST as shown in Figure 2d.* ◁

Example 3 (Injection-removal Attack)**.** *Let* $\mathbf{I}' \subseteq \mathbf{I}$*. An injection-removal attack nondeterministically inserts or removes symbols in* $\mathbf{I}'$ *from a word. This is modeled by the FST in Figure 2e.* ◁

Example 4 (Finite-Memory Replay Attack)**.** *For systems with continuous-state dynamics, replay attacks have been modeled and studied in the context of control systems (e.g., [20], [2]). On the other hand, for DES no such models currently exit. In DES, a replay attack records a prefix of a word and replaces the rest with the repetitions of the recorded prefix. In DES, a replay attack records a prefix of a word and replaces the rest with the repetitions of the recorded prefix, with the prefix size being bounded by the finite-memory capacity (i.e., size)* N*. For example, a replay attack recording a prefix of length up to* $N = 2$ *for any word of symbols* $\mathbf{I} = \{\mathsf{i}_1, \mathsf{i}_2\}$ *can be modeled by an FST as shown in Figure 2f.* ◁



(a) Projection Attack (b) Deletion Attack

(c) Injection Attack (d) Replacement-Removal Attack

(e) Injection-Removal Attack (f) Replay Attack

Fig. 2: FST realizations of different attack models.

Remark 2. *Using FSTs to model attacks naturally supports the composition of multiple attacks that are captured with the corresponding FST models. With the general architecture from Figure 1, the system may be under a coordinated attack from multiple deployed attackers, capturing different 'point-of-entries' for the attack vectors on sensors/actuators and communication network; for example, false data injection via sensor spoofing on a subset of plant sensors (e.g., [19]) in coordination with Denial-of-Service attacks on transmitted measurements from other sensors.*

IV. Resiliency under Attack: Modeling and Problem Formulation

In this section, we introduce a general mathematical framework for the supervisory control of discrete event systems (DESs) subject to attacks on both the plant's actuators and sensors. As illustrated in Figure 3, the supervisor $\mathcal{S}$ controls the behavior of the plant $\mathcal{P}$ by observing the symbols

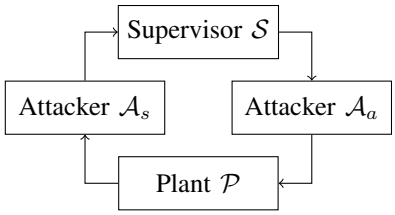
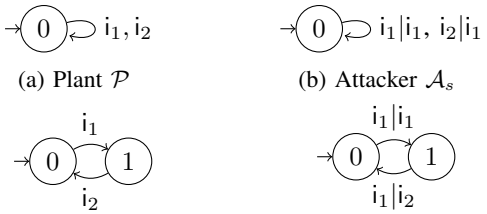


Fig. 3: Controllability under actuator and sensor attack.



(a) Plant $\mathcal{P}$ (b) Attacker $\mathcal{A}_s$

(c) Model of the desired language K (d) Supervisor $\mathcal{S}$

Fig. 4: Sensor attacks that can only be countered by FSTs.

that the plant generates and then sending the possible control symbols back to it. In reality, However, the information about the sensed symbols can be compromised by malicious attacks with the ability of inject, delete or replace symbols in both the control and the observation. These attacks are modeled by two attacker $\mathcal{A}_a$ and $\mathcal{A}_s$ on the actuators and sensors of the plant respectively. The details are as follows.

Specifically, we consider the setup where the plant is modeled by a DES $\mathcal{P}$ driven by a finite set of symbols $\mathbf{I}$. Its state transits upon receiving an acceptable word $i \in \mathbf{I}^*$. Attacks on the plant's actuators and sensors respectively are modeled by FSTs $\mathcal{A}_a$ and $\mathcal{A}_s$ with the same sets of input and output symbols $\mathbf{I} = \mathbf{O}$. They can *regularly rewrite* an acceptable input word, i.e., replace a symbol *nondeterministically* with an arbitrary word taken from some predefined regular language. This includes, for example, injection, replacement and deletion. Note that *we do not assume to know what actions the attacker may perform*. Rather, the FST models use nondeterminism to capture all possible actions of the attacker for a specific set of compromised resources (e.g., sensors, actuators), as well as all potential limitations imposed on the attacker's actions by the system design (e.g., the use of cryptographic primitives on some communication messages to prevent false-data inserting attacks over the network).

Furthermore, in our setup the supervisor is also modeled by an FST $\mathcal{S}$. Using FSTs instead of automata to model supervisors provides them the ability to revise symbols that are required to counter attacks on the plant's sensors; Example 5 presents an attack $\mathcal{A}_s$ that can only be handled by FSTs.

Example 5. *Following the architecture from Figure 3, consider a set of symbols* $\mathbf{I} = \{\mathsf{i}_1, \mathsf{i}_2\}$ *and a plant* $\mathcal{P}$ *accepting the language* $(\mathsf{i}_1, \mathsf{i}_2)^*$ *– see Figure 4a. The (prefix-closed) desired language is* $K = \overline{(\mathsf{i}_1\mathsf{i}_2)^*}$*, represented by a discrete event system* $\mathcal{M}_K$ *as shown in Figure 4c. The sensor attacks* $\mathcal{A}_s$ *are modeled by an FST as shown in Figure 4b.*

Supervising the plant to the desired language K *without the ability to revise symbols is not feasible. The reason is that the supervisor output should be the desired language* $(\mathsf{i}_1, \mathsf{i}_2)^*$*, but the input is always* i_1^**, since the plant only generates* i_2^* *and the attacker rewrites it to* i_1^**. However, for such attack model there exists an FST-based attack-resilient supervisor* $\mathcal{S}$ *for the plant, presented in Figure 4d. It counters the attacks by revising* i_1 *back to* i_2 *every other step.* $\lhd$

In this work, we assume that the attack FSTs $\mathcal{A}_a$, $\mathcal{A}_s$, the supervisor $\mathcal{S}$ and the plant $\mathcal{P}$ only receive acceptable inputs (see Assumptions 1 and 2 for details). This is generally achievable with the proper use of FST models for the attackers $\mathcal{A}_a$, $\mathcal{A}_s$, and the supervisor $\mathcal{S}$.

For the described system, we consider the problem of attack-resilient supervisory control of the plant $\mathcal{P}$ by the supervisor $\mathcal{S}$ in the presence of sensor and actuator attacks modeled by $\mathcal{A}_a$ and $\mathcal{A}_s$. Specifically, let $L(\mathcal{P})$ be the language generated by the plant without supervisor and $K \subseteq L(\mathcal{P})$ be the desired language. We consider the existential and, more importantly, the synthesis problem of a supervisor $\mathcal{S}$ supervising the language received by the plant to be exactly or as close as possible to some desired language K when under attack. This is formally specified in Definition 2. We note that the supervisor is not trying to completely recover a corrupted control; instead, it constrains the control sent to the plant to be within K.

For simplicity, we make the following assumptions for the rest of the work. For the plant $\mathcal{P}$, the supervisor $\mathcal{S}$ and the actuator and sensor attackers $\mathcal{A}_a, \mathcal{A}_s$, all states are final $\mathsf{S}_{\text{final}} = \mathsf{S}$, i.e. both the sets of their inputs and outputs are prefix-closed. In addition, the desired language is also prefix-closed $K = \bar{K}$ and regular. The regularity of K is to ensure that it is controllable by supervisors modeled by FSTs. The prefix-closeness requires that the supervision can be implemented step-by-step.

Definition 2. *Let* K *be the desired language of the plant* $\mathcal{P}$*, and* $\mathcal{A}_a$ *and* $\mathcal{A}_s$ *be the actuator and sensor attack models.*
(1) Controllability Under Actuator/Sensor/Both Attacks*: if there exists a supervisor* $\mathcal{S}$ *such that the restricted language of the plant is equal to the desired language* K*,*

$$\begin{aligned} &\textit{Actuator Attack:} && L(\mathcal{P}|\mathcal{S}, \mathcal{A}_a) = K \\ &\textit{Sensor Attack:} && L(\mathcal{P}|\mathcal{S}, \mathcal{A}_s) = K \\ &\textit{Both:} && L(\mathcal{P}|\mathcal{S}, \mathcal{A}_a, \mathcal{A}_s) = K \end{aligned}$$

(2) Weak Controllability Under Actuator/Sensor/Both Attacks*: if there exists a supervisor* $\mathcal{S}$ *such that the restricted language of the plant is the minimal controllable language contains the desired language* K*,*

$$\begin{aligned} &\textit{Actuator Attack:} && L(\mathcal{P}|\mathcal{S}, \mathcal{A}_a) \supseteq_{\min} K \\ &\textit{Sensor Attack:} && L(\mathcal{P}|\mathcal{S}, \mathcal{A}_s) \supseteq_{\min} K \\ &\textit{Both:} && L(\mathcal{P}|\mathcal{S}, \mathcal{A}_a, \mathcal{A}_s) \supseteq_{\min} K. \end{aligned}$$

Relationship with existing work: By specifying suitable actuator and sensor attack models, existing DES under attack problem formulations can be derived from the general

problem formulation considered in this work. To show this, let the actuator attack model $\mathcal{A}_a^{(s)} = \text{Insert}_{\mathbf{I}_{uc}} \circ \mathcal{P}$ be the serial composition of the injection attack from (3) and the plant. These inserted symbols are acceptable symbols of the plant, but not uncontrollable by the supervisor. In addition, let the sensor attack model $\mathcal{A}_s^{(s)} = \text{Project}_{\mathbf{I}_o}$ from (1). The removed symbols can be viewed as the unobservable symbols generated by the plant. For such setup, the problem considered in this paper results in the standard (i.e., without taking security/attacks into account) supervisory control formulation [5] with uncontrollable events $\mathbf{I}_{uc}$, and unobservable events $\mathbf{I}_{uo} = \mathbf{I} \backslash \mathbf{I}_o$.

In the second setup, let us assume that actuator and sensor attack modules $\mathcal{A}_a^{(s)}$ and $\mathcal{A}_s^{(s)}$ (defined above) are composed with modules of injection-removal of a set of vulnerable control symbols from Example 3. Our problem for such setup directly captures the problem of supervisory control under the actuator and sensor enablement/disablement attack studied in [9]. Yet, if $\mathcal{A}_s^{(s)}$ is composed with a sensor replacement-removal attack from Example 2, the problem considered in this paper yields the problem of supervisory control under replacement-removal sensor attacks [6]. Similarly, composing $\mathcal{A}_s^{(s)}$ with a sensor injection-deletion attack from Example 3 maps our problem into supervisory control problem under injection-deletion sensor attacks from [6].

V. Controllability Under Attacks on Sensors

We start with the supervisory control problem under only sensor attacks. In the rest of the section, we make the following assumption on the sensor attacker $\mathcal{A}_s$.

Assumption 1. *The attack FST $\mathcal{A}_s$ can (i) accept and (ii) only accept words that are acceptable to the plant $\mathcal{P}$, i.e., $L_I(\mathcal{A}_s) = L(\mathcal{P})$.*

The first part of Assumption 1 means that the attack FST $\mathcal{A}_s$ is well-defined for any acceptable word of the plant $\mathcal{P}$. This can be done by encoding the error behavior of receiving an unacceptable word to the plant model. The second part of Assumption 1 is always achievable by trimming the attacker $\mathcal{A}_s$.

To counter the attack modeled by $\mathcal{A}_s$, we can construct its inversion $\mathcal{A}_s^{-1}$. For any word k passing the plant, the attacker $\mathcal{A}_s$ rewrites it to a word in $\mathcal{R}_{\mathcal{A}_s}(k)$, and the inversion can reverse it back to $\mathcal{R}_{\mathcal{A}_s \circ \mathcal{A}_s^{-1}}(k)$; note that $\mathcal{R}_{\mathcal{A}_s \circ \mathcal{A}_s^{-1}}(k)$ is the set of possible words passing through the plant and yielding the same observation after attack as k. Restricting this set of words to the desired language K guarantees the supervisory control goal. Therefore, the supervisor $\mathcal{S}$ should be designed to be $\mathcal{A}_s^{-1} \circ \mathcal{M}_K$, where $\mathcal{M}_K$ is the automata realizing the desired language K. In this way, it is guaranteed that the supervisor only sends control words within K, even if the sensors are corrupted, as summarized by the theorem below.

Theorem 1 (Controllability under sensor attacks)**.** *The plant $\mathcal{P}$ is controllable to the desired regular language $K \subseteq L(\mathcal{P})$ under attack $\mathcal{A}_s$ on the plant's sensors. This can be achieved by the supervisor $\mathcal{S} = \mathcal{A}_s^{-1} \circ \mathcal{M}_K$.*

Algorithm 1 Design of a Supervisor Resilient to Sensor Attacks

Require: Desire language K, plant $\mathcal{P}$, sensor attacker $\mathcal{A}_s$.
1: Find $\mathcal{M}_K$ realizing $K \subseteq L(\mathcal{P})$.
2: Compute inversion $\mathcal{A}_s^{-1}$.
3: Compute serial composition $\mathcal{S} = \mathcal{A}_s^{-1} \circ \mathcal{M}_K$.
4: **return** Supervisor $\mathcal{S}$.

Proof. It suffices to show the language passing the plant is exactly K under the supervisor $\mathcal{S} = \mathcal{A}_s^{-1} \circ \mathcal{M}_K$. By construction, the supervisor only generates words contained in K. On the other hand, for any $k \in K$, for any $k \in K$, noting that $k \in \mathcal{R}_{\mathcal{A}_s \circ \mathcal{A}_s^{-1}}(k)$, we have $k \in \mathcal{R}_{\mathcal{A}_s \circ \mathcal{S}}(k)$, i.e., the word k is allowed to transmit to the plant. □

Furthermore, Theorem 1 also directly provides a computational method to design such attack-resilient supervisor; the procedure is introduced in Algorithm 1.

Example 6 (Supervisor design under sensor attacks)**.** *From Example 5, the supervisor $\mathcal{S}$ in Figure 4d can be derived by the serial composition of the inversion of the attacker $\mathcal{A}_s$ in Figure 4b and the model of desired language K in Figure 4c by $\mathcal{S} = \mathcal{A}_s^{-1} \circ \mathcal{M}_K$.* ◁

Remark 3. *By Theorem 1, attacks on sensors do not affect controllability, as opposed to previous works [6], [7], [9]. This is because the plant is deterministic, so its state is known from the controls of the supervisor, and the supervisor as an FST can generate controls for the next step by itself without using the sensing information of the plant. These sensing information will become useful to learn the state of the plant when it is nondeterministic, which will be an avenue for future work.*

VI. Controllability Under Attacks on Actuators

In this section, we study the attack-resilient supervisory control problem in systems where only attacks on the actuators of the plant may occur. Specifically, the actuators of the plant $\mathcal{P}$ is under the attack $\mathcal{A}_a$, but the supervisor $\mathcal{S}$ has direct access to the words passing the plant. This problem is more complex then the supervisory control problem with sensor attacks studied in Section V, as the supervisor commands are not directly sent to the plant. Consequently, not all desired language are controllable to the plant. For example, if attack $\mathcal{A}_a$ generates the empty word ε upon all inputs, modeling Denial-of-Service attacks, then the only controllable desired language for the plant is $\{\varepsilon\}$.

In the rest of the section, we make the following assumption on the actuator attack model $\mathcal{A}_a$.

Assumption 2. *The attack FST $\mathcal{A}_a$ can (i) generate and (ii) only generate words that are acceptable to the plant $\mathcal{P}$, i.e., $L_O(\mathcal{A}_a) = L(\mathcal{P})$.*

The first part of Assumption 2 means that the actuator attack $\mathcal{A}_a$ will not cause an error by sending an unacceptable

Algorithm 2 Constructing an FST Filter for Desired Language K.

Require: The desire language K, plant $\mathcal{P}$.

1: Find automata $\mathcal{M}$ and $\mathcal{M}'$ with $L(\mathcal{M}) = L(\mathcal{P})$ and $L(\mathcal{M}') = K$.
2: Convert $\mathcal{M}$ and $\mathcal{M}'$ to FSTs by adding ε as output and input symbol for each transition, respectively.
3: $\mathcal{A} = \mathcal{M} \circ \mathcal{M}'$.
4: Trim off transitions with input symbol ε in $\mathcal{A}$.
5: **return** Supervisor $\mathcal{A}$.

Algorithm 3 Design of Supervisor under Actuator Attacks

Require: Desire language K, plant $\mathcal{P}$, actuator attacker $\mathcal{A}_a$.

1: Find FST filter $\mathcal{M}_K$ for K .
2: Compute inversion $\mathcal{A}_a^{-1}$.
3: Compute serial composition $\mathcal{S} = \mathcal{M}_K \circ \mathcal{A}_a^{-1}$.
4: **if** the output language $L_O(\mathcal{S} \circ \mathcal{A}_a) \subseteq K$ **then**
5: **return** K is controllable
6: **else**
7: **return** K is not controllable
8: **end if**
9: **return** Supervisor $\mathcal{S}$.

input of the plant $\mathcal{P}$ (such attacks are easy to detect); instead, the attack will try to affect the plant and violate the control goal by sending a word in $L(\mathcal{P})\backslash K$ to the plant. The second part ensures that every word in $L(\mathcal{P})$ may possibly be sent to the plant $\mathcal{P}$ – otherwise, we can only discuss controllability with respect to $L_O(\mathcal{A}_a)$ (see Remark 5).

For attack-resilient supervision of the plant under actuator attacks, the supervisor $\mathcal{S}$ needs to (i) constrain (i.e., filter) the words passing the plant $\mathcal{P}$, and (ii) rewrite these words to counter the effects of the actuator attacks $\mathcal{A}_a$.

Filter: Unlike our approach presented in Section V, for the first requirement, we construct an FST filter $\mathcal{M}_K$ of the desired language $K \in L(\mathcal{P})$. This is because an automaton of K cannot handle input words in $L(\mathcal{P})\backslash K$. The filter takes a word $k \in L(\mathcal{P})$ and sends the same word if $k \in K$, and ε otherwise. Algorithm 2 gives the procedure to achieve this.

For the second requirement, we construct the inversion $\mathcal{A}_a^{-1}$ of the actuator attacker. Consequently, the supervisor is $\mathcal{S} = \mathcal{M}_K \circ \mathcal{A}_a^{-1}$. For any word k passing $\mathcal{M}_K$, we know $k \in K$. The inversion $\mathcal{A}_a^{-1}$ rewrites it to a word in $\mathcal{R}_{\mathcal{A}_a^{-1}}(k)$, and the actuator attack $\mathcal{A}_a$ rewrites it to $\mathcal{R}_{\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(k)$ and passes to the plant. This is the set of possible words that can be derived by attacking the input words yielding k. Consequently, we have $k \in \mathcal{R}_{\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(k)$ and $K \subseteq \mathcal{R}_{\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(K)$.

Since $\mathcal{R}_{\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(K)$ is not necessarily contained in K, the supervisor $\mathcal{S} = \mathcal{M}_K \circ \mathcal{A}_a^{-1}$ only restricts the language passing the plant to a minimal superset of K. The desired language K is controllable, when the containment holds. This is equivalent to checking if K is contained in the output language of $\mathcal{M}_k \circ \mathcal{A}_a^{-1} \circ \mathcal{A}_a$. In this way, it is guaranteed that the plant only receives control words from K, even if the actuators are corrupted. This is summarized below.

Theorem 2 (Controllability under actuator attack)**.** *The plant $\mathcal{P}$ is weakly controllable to the desired regular language $K \subseteq L(\mathcal{P})$ under the attacks $\mathcal{A}_a$ on its actuators by the supervisor $\mathcal{S} = \mathcal{M}_k \circ \mathcal{A}_a^{-1}$. Accordingly, the minimal controllable language containing K is*

$$\tilde{K} = \mathcal{R}_{\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(K). \tag{4}$$

The desired language is controllable if and only if $\tilde{K} = K$, or equivalently the output language of $\mathcal{M}_k \circ \mathcal{A}_a^{-1} \circ \mathcal{A}_a$ satisfies

$$L_O(\mathcal{M}_k \circ \mathcal{A}_a^{-1} \circ \mathcal{A}_a) \subseteq K. \tag{5}$$

Proof. Sufficiency: It suffices to show the language passing the plant is exactly K under the supervisor $\mathcal{S} = \mathcal{M}_k \circ \mathcal{A}_a^{-1}$. By (5), the plant only receives words in K. On the other hand, for any $k \in K$, noting that $k \in \mathcal{R}_{\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(k)$, we have

$$k \in \mathcal{R}_{\mathcal{S}\circ\mathcal{A}_a}(k) = \mathcal{R}_{\mathcal{M}_k\circ\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(k),$$

namely, the word k is allowed to transmit to the plant.

Necessity: It suffices to show the minimality of $\tilde{K}$ in (4). Suppose there exists a supervisor $\mathcal{S}$ that can weakly control the plant to K' such that

$$K \subseteq K' \subseteq \tilde{K}. \tag{6}$$

Then for any $k' \in K'$, there exists supervisor's output word k such that $k \in \mathcal{R}_{\mathcal{A}_a}^{-1}(k')$. Hence, any word in $\mathcal{A}_a(k)$ can be transmitted to the plant, i.e., $\mathcal{A}_a(k) \subseteq K'$. Namely,

$$\mathcal{A}_a^{-1} \circ \mathcal{A}_a(K') \subseteq K' \tag{7}$$

Combining (4),(6), and (7), it follows that

$$\tilde{K} = \mathcal{A}_a^{-1} \circ \mathcal{A}_a(K) \subseteq \mathcal{A}_a^{-1} \circ \mathcal{A}_a(K') \subseteq K'.$$

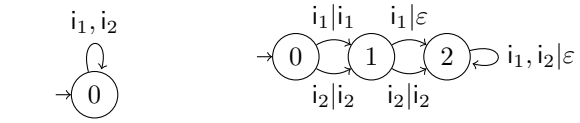
This implies that $K' = \tilde{K}$. □

Theorem 2 provides a computational method to design such supervisor, as provided in Algorithm 3.

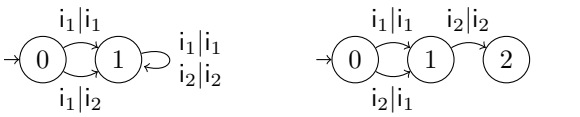
Example 7 (Supervisor design for actuator attacker)**.** *For the setup from Figure 3 without attacks on sensors, let us consider a set of symbols $\mathbf{I} = \{\mathrm{i}_1, \mathrm{i}_2\}$ and a plant $\mathcal{P}$ accepting the language $(\mathrm{i}_1, \mathrm{i}_2)^*$, as shown in Figure 5a. The (prefix-closed) desired language is $K = \overline{(\mathrm{i}_1, \mathrm{i}_2)\mathrm{i}_2}$, associated with the FST filter $\mathcal{M}_K$ (Figure 5b). Now we consider the following two cases.*

Controllable: The model of attacks on the actuators of the plant is represented by an FST $\mathcal{A}_a$ shown in Figure 5c. It rewrites the first i_1 nondeterministically to i_1 or i_2. The output language $L_O(\mathcal{S} \circ \mathcal{A}_a) = \overline{(\mathrm{i}_1, \mathrm{i}_2)\mathrm{i}_2}$ is exactly K. Therefore, the plant is controllable to K by the supervisor $\mathcal{S}$ even under the attack.

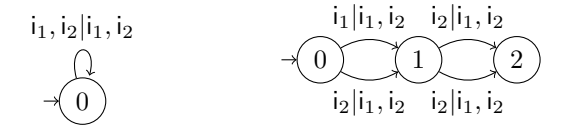
Weakly Controllable: The attacker $\mathcal{A}_a$ on the actuators of the plant is represented by an FST from Figure 5e. It rewrites any i_1 nondeterministically to i_1 or i_2. It sends first i_1 and then i_1 or i_2 upon receiving i_2. The output language $L_O(\mathcal{S} \circ \mathcal{A}_a) = \overline{(\mathrm{i}_1, \mathrm{i}_2)(\mathrm{i}_1, \mathrm{i}_2)}$ is larger than K. Therefore, the



(a) Plant. (b) Filter of Desired Language K.



(c) Actuator Attacker I. (d) Supervisor I.



(e) Actuator Attacker II. (f) Supervisor II.

Fig. 5: Example supervisors for actuator attacks.

plant is uncontrollable to K by the supervisor $\mathcal{S}$. It is easy to see that $\overline{(\mathrm{i}_1,\mathrm{i}_2)(\mathrm{i}_1,\mathrm{i}_2)}$ is a minimal superset of K. $\lhd$

Remark 4. *Note that the supervisor in Figure 5f, derived in Example 7, is nondeterministic — at the state 0, it can either send i_1 or i_2 upon receiving i_1. The controllability theorem guarantees that in the presence of attacks, the union of all possible words received by the plant under all these allowable controls is exactly the desired language K. In implementation, the nondeterminism can be resolved by choosing one of the allowable controls. Accordingly, the possible words received by the plant is contained in K.*

VII. Controllability Under Attacks on Both Actuators and Sensors

In this section, we study the supervisory control problem in which there are attacks on both the actuators and sensors of the plant, as shown in Figure 3. This is a combination of the supervisory control problems studied in Sections V and VI. In the rest of the section, we assume that the actuator attacker $\mathcal{A}_a$ and the sensor attacker $\mathcal{A}_s$ are well-defined as stated in Assumptions 1 and 2.

From Section VI, it follows that the FST $\mathcal{M}_K \circ \mathcal{A}_a^{-1}$ can constrain the words passing the plant $\mathcal{P}$, and revise these words to counter the actuator attacker $\mathcal{A}_a$. This, in combination with the analysis in Section V, implies that the supervisor $\mathcal{A}_s^{-1}\circ\mathcal{M}_K\circ\mathcal{A}_a^{-1}$ can additionally counter the sensor attacker $\mathcal{A}_s$. It is easy to check that $K \subseteq \mathcal{R}_{\mathcal{A}_s\circ\mathcal{S}\circ\mathcal{A}_a}(K)$. However, $\mathcal{R}_{\mathcal{A}_s\circ\mathcal{S}\circ\mathcal{A}_a}(K)$ is not necessarily contained in K. The supervisor $\mathcal{S} = \mathcal{A}_s^{-1} \circ \mathcal{M}_K \circ \mathcal{A}_a^{-1}$ only restricts the language passing the plant to a minimal superset of K. The desired language K is controllable, when the containment holds. This is summarized by the following theorem.

Theorem 3 (Controllability under both attacks)**.** *For the system from Figure 3, the plant $\mathcal{P}$ is weakly controllable to the desired regular language $K \subseteq L(\mathcal{P})$ under the attacks $\mathcal{A}_a$ and $\mathcal{A}_s$ on its actuators and sensors, respectively, by the supervisor $\mathcal{S} = \mathcal{A}_s^{-1} \circ \mathcal{M}_K \circ \mathcal{A}_a^{-1}$. Accordingly, the minimal controllable language containing K is*

$$\tilde{K} = \mathcal{R}_{\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(K). \tag{8}$$

The desired language is controllable if and only if $\tilde{K} = K$, or equivalently the output language of $\mathcal{M}_K \circ \mathcal{A}_a^{-1} \circ \mathcal{A}_a$ satisfies

$$L_O(\mathcal{M}_K \circ \mathcal{A}_a^{-1} \circ \mathcal{A}_a) \subseteq K. \tag{9}$$

Proof. Necessity: Same as the necessity proof for Theorem 2.

Sufficiency: It suffices to show that the language passing the plant is exactly K under the supervisor $\mathcal{S} = \mathcal{A}_s^{-1}\circ\mathcal{M}_K\circ\mathcal{A}_a^{-1}$. By (9), we have that

$$L_O(\mathcal{S} \circ \mathcal{A}_a) \subseteq L_O(\mathcal{M}_K \circ \mathcal{A}_a^{-1} \circ \mathcal{A}_a) \subseteq K,$$

namely, the plant only receives words in K. On the other hand, for any $k \in K$, noting that $k \in \mathcal{R}_{\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(k)$ and $k \in \mathcal{R}_{\mathcal{A}_s\circ\mathcal{A}_s^{-1}}(k)$, it follows that

$$k \in \mathcal{R}_{\mathcal{A}_s\circ\mathcal{S}\circ\mathcal{A}_a}(k) = \mathcal{R}_{\mathcal{A}_s\circ\mathcal{A}_s^{-1}\mathcal{M}_K\circ\mathcal{A}_a^{-1}\circ\mathcal{A}_a}(k),$$

namely, the word k is allowed to transmit to the plant. $\square$

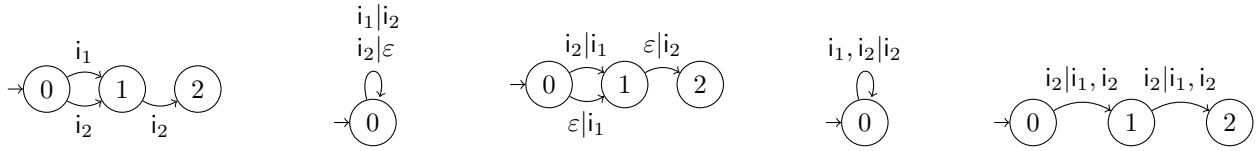
From Theorem 3, the design of an attack-resilient supervisor can be performed by separately taking into accounts the actuator and sensor attacks, and the attacks on sensors $\mathcal{A}_s$ have no influence on the controllability. This result is different from most previous works [9], [5], [6], and is caused by the fact that the supervisor, when modeled by an FST, and not an automaton, has more power in generating control commands (i.e., can generate controls by itself); thus, it depends much less on the input word it receives. By adding a component $\mathcal{A}_s^{-1}$, the effect of the sensor attacker $\mathcal{A}_s$ is totally countered, as is summarized by the following corollary. Theorem 3 also provides a computational method to design such supervisor, as given in Algorithm 4.

Algorithm 4 Design of Supervisors Resilient to Actuator and Sensor Attacks

Require: Plant $\mathcal{P}$, actuator attacker $\mathcal{A}_a$, sensor attacker $\mathcal{A}_s$, Desire language K.

```
Find a model M_K of K .
Compute inversion A_a^{-1} and A_s^{-1} .
Compute serial composition S = A_s^{-1} ∘ M_K ∘ A_a^{-1} .
if the output language L_O(A_s ∘ S ∘ A_a) ⊆ K then
    return K is controllable
else
    return K is not controllable
end if
return Supervisor S.
```

Example 8 (Supervisor design for both attackers)**.** *From Example 7, consider a set of symbols $\mathbf{I} = \{\mathrm{i}_1, \mathrm{i}_2\}$ and a plant $\mathcal{P}$ accepting the language $(\mathrm{i}_1, \mathrm{i}_2)^*$, as shown in Figure 5a. The (prefix-closed) desired language is $K = \overline{(\mathrm{i}_1, \mathrm{i}_2)\mathrm{i}_2}$, represented by an automaton $\mathcal{M}_K$ as shown in Figure 6a. Now, let us consider the following two cases.*



(a) Desired Language K (b) Sensor Attacker I (c) Supervisor I (d) Sensor Attacker II (e) Supervisor II

Fig. 6: Example supervisors for sensor and actuator attacks.

Controllable: The attacks $\mathcal{A}_a$ and $\mathcal{A}_s$ on the sensors and actuators of the plant are modeled by FSTs from Figures 5c and 6b, respectively. The actuator attack rewrites the first i_1 *nondeterministically to* i_1 *or* i_2*. The sensor attack removes* i_2 *and replaces* i_1 *with* i_2*. The supervisor shown in Figure 6c does not contain any transition with input label* i_1*, as it will never appear due to the attack. The output language $L_O(\mathcal{A}_s \circ \mathcal{S} \circ \mathcal{A}_a) = \overline{(\mathsf{i}_1, \mathsf{i}_2)\mathsf{i}_2}$ is equal to K. Thus, the plant is controllable to K by the supervisor $\mathcal{S}$.*

Weakly Controllable: The actuator and sensor attacks $\mathcal{A}_a$ and $\mathcal{A}_s$ are modeled by FSTs from Figures 5e and 6d, respectively. The actuator attack rewrites i_1 *nondeterministically to* i_1 *or* i_2*. The sensor attack replaces* i_1 *with* i_2*. The supervisor does not contain any transition with input label* i_1*, as it will never appear. Obviously, the output language $\overline{(\mathsf{i}_1, \mathsf{i}_2)(\mathsf{i}_1, \mathsf{i}_2)}$ minimally contains K.*

Comparing to Example 7, adding sensor attacks has no influence on controllability. This agrees with Remark 3. $\lhd$

Finally, we note that if the second part of Assumption 2 is violated, i.e., $L_O(\mathcal{A}_a) \subseteq L(\mathcal{P})$, Theorems 2 and 3 still hold on the trimmed plant accepting $L_O(\mathcal{A}_a)$.

Remark 5. *For $L_O(\mathcal{A}_a) \subseteq L(\mathcal{P})$, $\tilde{K} = \mathcal{A}_a^{-1} \circ \mathcal{A}_a(K)$ is the minimal controllable language containing $K \cap L_O(\mathcal{A}_a)$, and K is controllable if $L_O(\mathcal{M}_K \circ \mathcal{A}_a^{-1} \circ \mathcal{A}_a) \subseteq K$ and $K \subseteq L_O(\mathcal{A}_a)$.*

VIII. Conclusions

In this work, we have studied the supervisory control problem of designing supervisors for plants modeled by discrete event systems (DES) such that the system is resilient to attacks on the plant's actuators and sensors. We have considered a very general class of attacks and have proposed to model them by finite state transducers (FSTs), as they support mathematically rigorous and computationally feasible operations, such as inversion and composition, that facilitates modeling complicated attack behaviors. We have shown that FSTs can be used to capture all previously reported attacks on DES, as well as additional attacks and attack features.

We have studied the attack-resilient supervisory control problem in three setups where attacks occur on: (i) sensors, (ii) actuators, and (iii) both actuators and sensors; we have presented new sets of controllability conditions and synthesizing algorithms for supervisors in these scenarios. Specifically, we have shown that for (i), an FST-based supervisor derived by the serial composition of the inversion of the attack model and a model of the desired language should be used; for (ii), the actuator attacks can be partly countered by a supervisor derived by the serial composition of a model of the desired language and the inversion of the attack model; and for (iii), a supervisor can be derived by serially composing the supervisors from (i) and (ii).

Future work include system with nondeterministic plants and methods to optimally resolve controller nondeterminism.

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