

Secure Estimation and Control for Cyber-Physical Systems Under Adversarial Attacks

Hamza Fawzi, Paulo Tabuada, *Senior Member, IEEE*, and Suhas Diggavi, *Fellow, IEEE*

Abstract—The vast majority of today's critical infrastructure is supported by numerous feedback control loops and an attack on these control loops can have disastrous consequences. This is a major concern since modern control systems are becoming large and decentralized and thus more vulnerable to attacks. This paper is concerned with the estimation and control of linear systems when some of the sensors or actuators are corrupted by an attacker. We give a new simple characterization of the maximum number of attacks that can be detected and corrected as a function of the pair (A, C) of the system and we show in particular that it is impossible to accurately reconstruct the state of a system if more than half the sensors are attacked. In addition, we show how the design of a secure local control loop can improve the resilience of the system. When the number of attacks is smaller than a threshold, we propose an efficient algorithm inspired from techniques in compressed sensing to estimate the state of the plant despite attacks. We give a theoretical characterization of the performance of this algorithm and we show on numerical simulations that the method is promising and allows to reconstruct the state accurately despite attacks. Finally, we consider the problem of designing output-feedback controllers that stabilize the system despite sensor attacks. We show that a principle of separation between estimation and control holds and that the design of resilient output feedback controllers can be reduced to the design of resilient state estimators.

Index Terms— Algorithm, feedback controller.

I. INTRODUCTION

TODAY'S large-scale control systems are present everywhere in order to sustain the normal operation of many of the critical processes that we rely on. Example of such systems include chemical processes, the power grid, water distribution networks and many more.

In a typical control system one can identify different components including the actuators, the sensors and the controllers. These different components need to communicate with each other: for example the sensors communicate their measurements to the controllers, the controllers use this information to

compute the control input, and the control input is then sent to the actuators so that it can be physically implemented. In order for this communication to take place, a communication network is usually deployed across the plant to be controlled. Although wired networks have been traditionally used for this purpose, an increasing number of control systems now use wireless networks since they are easier to deploy and to maintain. In addition, these networks are sometimes connected to the corporate intranet, and in some cases even to the Internet. Consequently, modern control systems are becoming more open to the *cyber*-world, and as such, are more vulnerable to attacks that can cause faults and failures in the *physical* process even though launched in the *cyber*-domain. This realization led to the emergence of new security challenges that are distinct from traditional cyber security as highlighted in [1], [2].

Real-world attacks on control systems have in fact occurred in the past decade and have in some cases caused significant damage to the targeted physical processes. Perhaps one of the most popular examples is the attack on Maroochy Shire Council's sewage control system in Queensland, Australia that happened in January 2000 [3], [4]. In this incident, an attacker managed to hack into some controllers that activate and deactivate valves and, by doing so, caused flooding of the grounds of a hotel, a park, and a river with a million liters of sewage [3]. Another well publicized example of an attack launched on physical systems is the very recent StuxNet virus that targeted Siemens' supervisory control and data acquisition systems which are used in many industrial processes [5]. Other cases of attacks have been reported in the past years, and we refer the reader to [3] for more real-world examples.

These examples indicate the clear need for strategies and mechanisms to identify and deal with attacks on control systems.

Previous Work Related to Security for Control Systems: The design of control and estimation algorithms that are resilient against faults and failures is certainly not a new problem. In fault-detection and identification [6], [7] the objective is to detect if one or more of the components of a system has failed. Traditionally, this is done by comparing the measurements of the sensors with an analytical model of the system and by forming the so-called residual signal (in some cases, the residual signal actually corresponds to the output of some specifically designed LTI system whose inputs are the sensor measurements [6]). This residual signal is then analyzed (e.g., using signal processing techniques) in order to determine if a fault has occurred. In such algorithms however, there is in general one residual signal *per failure mode*. As we will see later, in our problem formulation the number of failure modes

Manuscript received May 22, 2012; revised February 14, 2013, June 29, 2013, and January 06, 2014; accepted January 12, 2014. Date of publication January 28, 2014; date of current version May 20, 2014. This work was supported by the National Science Foundation 1136174. Recommended by Associate Editor C. Hadjicostis.

H. Fawzi is with the Laboratory for Information and Decision Systems, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: hfawzi@mit.edu).

P. Tabuada and S. Diggavi are with the Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, CA 90095 USA (e-mail: tabuada@ee.ucla.edu; suhas@ee.ucla.edu).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TAC.2014.2303233

can be very large and one cannot afford to generate and analyze a residual signal for each possible failure mode. In another area, namely robust control [8], one seeks to design control methods that are robust against disturbances in the model. In general however, these disturbances are treated as *natural* disturbances to the system and are assumed to be *bounded*. This does not apply in the context of security since the disturbances will typically be adversarial and therefore cannot be assumed bounded. This is the case also in the area of stochastic control and estimation, where the disturbances are assumed to follow a certain probabilistic model, which we cannot adopt for our problem.

Since these assumptions are not justifiable in the context of adversarial attacks, there has been a recent increase in control systems security research [9]–[15]. In [9], the authors consider the problem of control and estimation in a networked system when the communication links are subject to disturbances. The disturbances (corresponding to packet losses) are however assumed to follow a certain stochastic process (typically a Bernoulli process) which does not necessarily capture the behavior of an attacker. In [10] the authors consider a more intelligent jammer who plans his attacks in order to maximize a certain cost, while the objective of the controller is to minimize this same cost. The authors showed the existence of saddle-point equilibrium for this dynamic zero-sum game and derived the optimal jamming strategy for a particular instance of the problem. The results are however derived in the case of one-dimensional systems only, which is a main limitation of this work. In [11], [12] the authors study the fundamental limitations of attack detection and identification methods for linear systems, and for the particular case of power networks. They provide graph-theoretic characterization of the vulnerability of such systems to attacks, and furthermore they propose centralized and decentralized filters to detect and identify attacks when possible. These filters are however computationally expensive and are in general difficult to implement. Another related problem that received attention recently is the problem of reaching consensus in the presence of malicious agents [14]. The authors characterize the number of infected nodes that can be tolerated and propose a way to overcome the effect of the malicious agents when possible. However one particularity of these works is that the dynamics is part of the algorithm and can be specifically designed, rather than being given as in a physical system.

Finally, there has also been recent work in the area of real error-correction over adversarial channels, e.g., [16], where adversarial noise could be unbounded. However the dynamics of the system does not generally play a role and the correction capability is studied in a static setting that does not take advantage of the dynamics of the system. Furthermore, in these works, the error protection mechanism can be designed by suitably choosing the coding matrix, whereas in our case, the plant dynamics is given to us.

Contributions and Organization of the Paper: This paper deals with theoretical as well as algorithmic aspects of estimation and control of linear plants subject to attacks. On the theoretical side we give a new characterization of the maximum resilience of a system to attacks and we prove new results

concerning the separation of estimation and control, and the possibility of increasing the resilience of a system by secure local feedback. On the algorithmic side we adopt a novel point of view inspired from error-correction over the reals [16] which allows us to propose a new estimation algorithm that is robust against the attacks and that is also computationally efficient, unlike most of the previously proposed approaches which suffer from combinatorial explosion [10], [14], [17].

The paper is organized into two main parts:

- 1) The first part (Section III) deals with the *estimation* problem in the presence of attacks. We focus on sensor attacks where the results are especially nice and simple to state and we identify some of the fundamental limitations to estimate the state under attacks. We give in Proposition 2 a new simple characterization of the maximum number of sensor attacks that can be corrected as a function of the pair (A, C) . This proposition shows in particular that it is impossible to reconstruct the state whenever more than half of the sensors are attacked.

We then characterize how secure feedback can be used to improve resilience against attacks. Proposition 4, shows that we can design controllers that improve the resiliency against attacks provided that these controllers are not subject to attacks.

Lastly, on the algorithmic side, we propose a specific state reconstructor resilient to attacks that is inspired from techniques used in compressed sensing and error correction over the reals [16]. We analyze this algorithm rigorously and we characterize the maximum number of attacks it can correct for a given system (Proposition 6). We demonstrate on numerical examples that the proposed algorithm is promising and could potentially be used in real-world applications.

- 2) In the second part of the paper (Section IV), we deal with the problem of *control with output feedback* in the presence of attacks on sensors. Our main result in this part is to show that a principle of separation of estimation and control holds and that the design of resilient output feedback controllers can be reduced to the design of resilient state estimators. More precisely, we show that if one can design an output-feedback law that stabilizes the system despite attacks on sensors, then the state can also be *estimated* in the presence of these attacks.

Preliminary versions of the results appeared in the conference papers [18], [19] as well as in the Master's thesis of the first author [20].

II. FORMAL SETTING AND NOTATIONS

The Formal Setting: Consider the linear control system given by the equations

$$\begin{aligned} x^{(t+1)} &= Ax^{(t)} + B \left(U^{(t)} \left(y^{(0)}, \dots, y^{(t)} \right) + w^{(t)} \right) \\ y^{(t)} &= Cx^{(t)} + e^{(t)}. \end{aligned} \quad (1)$$

Here $x^{(t)} \in \mathbb{R}^n$ represents the state of the system at time $t \in \mathbb{N}$, and $y^{(t)} \in \mathbb{R}^p$ is the output of the sensors at time t . The control input applied at time t depends on the past

measurements $(y^{(\tau)})_{0 \leq \tau \leq t}$ through the output feedback map $U^{(t)}$. The vector $e^{(t)} \in \mathbb{R}^p$ represents the attacks injected by the attacker in the different sensors, and the vector $w^{(t)} \in \mathbb{R}^m$ represents the attacks injected in the actuators. Note that if sensor $i \in \{1, \dots, p\}$ is not attacked then necessarily $e_i^{(t)} = 0$ and the output $y_i^{(t)}$ of sensor i is not corrupted, otherwise $e_i^{(t)}$ (and therefore $y_i^{(t)}$) can take any value. The sparsity pattern of the attack $e^{(t)}$ therefore indicates the set of attacked sensors. The same observation holds for the attacks on actuators $w^{(t)}$.

Note that from a practical point of view, an attack on a sensor could either be interpreted as an attack on the node itself (making it transmit an incorrect signal), or it could also be interpreted as an attack on the *communication link* between the sensor and the receiver device. Similarly an attack on an actuator could either be interpreted as an attack on the actuator itself, or on the communication link from the controller to the actuator. Throughout the paper, we will be talking about “attacked nodes” but we will keep in mind that the second interpretation (attack on the communication link) is also possible. In Section III-B we will actually look at a scenario where it is the communication links that are compromised and not the nodes themselves.

We will assume in this paper that the set of attacked nodes does not change over time. More precisely, if $K \subset \{1, \dots, p\}$ is the set of attacked sensors and $L \subset \{1, \dots, m\}$ the set of attacked actuators, then we have for all t , $\text{supp}(e^{(t)}) \subset K$ and $\text{supp}(w^{(t)}) \subset L$ (where $\text{supp}(x)$ denotes the support of x , i.e., the indices of the nonzero components of x). Note that this is a valid and realistic assumption when the time it takes for the malicious agent to gain control of a node is large compared to the time scale of the estimation algorithm. Furthermore observe that a model where the set of attacked nodes is allowed to change at every time step while having a fixed cardinality would in turn not be very realistic since it would assume that the attacker abandons from t to $t+1$ some of the nodes he had control over. For these reasons, we will assume for our model that the sets K and L of attacked sensors and actuators is constant over time (and, of course, unknown).

Moreover, since we are dealing with a malicious agent, we will not assume the attacks $e_i^{(t)}$ or $w_j^{(t)}$ (for an attacked sensor i or actuator j) to follow any particular model and we will simply take them to be arbitrary real numbers. The only assumption concerning the malicious agent will be about the *number* of nodes that were attacked. Our statements will then typically characterize the number of attacks that can be tolerated in order to correctly estimate/control the plant.

Notations: We use the following notations throughout the paper. If S is a set, we denote by $|S|$ the cardinality of S and by S^c the complement of S . For a vector $x \in \mathbb{R}^n$, the support of x , denoted by $\text{supp}(x)$, is the set of nonzero components of x and the ℓ_0 norm of x is the number of nonzero components of x

$$\begin{aligned} \text{supp}(x) &= \{i \in \{1, \dots, n\} \mid x_i \neq 0\} \\ \|x\|_{\ell_0} &= |\text{supp}(x)|. \end{aligned}$$

Also, if $K \subset \{1, \dots, n\}$, we let \mathcal{P}_K be the projection map onto the components of K ($\mathcal{P}_K x$ is a vector with $|K|$ components, e.g., if $K = \{3, 5\}$ then $\mathcal{P}_K x = (x_3, x_5)$).

For a matrix $M \in \mathbb{R}^{m \times n}$ we denote by $M_i \in \mathbb{R}^n$ the i 'th row of M , for $i \in \{1, \dots, m\}$. We define the *row support* of M to be the set of nonzero rows of M and we denote by $\|M\|_{\ell_0}$ the cardinality of the row support of M

$$\begin{aligned} \text{rowsupp}(M) &= \{i \in \{1, \dots, m\} \mid M_i \neq 0\} \\ \|M\|_{\ell_0} &= |\text{rowsupp}(M)|. \end{aligned}$$

III. ESTIMATION PROBLEM

In this section we deal with the problem of *estimating* the state of a linear dynamical system in the presence of attacks. Throughout the main part of this section we will assume that attacks only occur on the sensors (i.e., no attacks on actuators) for ease of exposition. At the end of the section though we show how to extend the results to the case where there are also attacks on the actuators.

We consider in this section linear dynamical systems of the form

$$\begin{aligned} x^{(t+1)} &= Ax^{(t)} \\ y^{(t)} &= Cx^{(t)} + e^{(t)}. \end{aligned} \quad (2)$$

As mentioned before, $e^{(t)} \in \mathbb{R}^p$ are the attack vectors injected by the malicious agent in the sensors. For simplicity we have also discarded the control input $BU^{(t)}(y^{(0)}, \dots, y^{(t)})$ since it does not affect the results in this section. Indeed the results presented here hold for any linear affine system where the state evolves according to $x^{(t+1)} = Ax^{(t)} + v^{(t)}$ where $v^{(t)}$ is a *known* input (for more details on this, see Section IV-A).

The problem that we consider in this section is to reconstruct the initial state $x^{(0)}$ of the plant from the corrupted observations $(y^{(t)})_{t=0, \dots, T-1}$. Note that since the matrix A is known, the problem of reconstructing the current state $x^{(t)}$ or the initial state $x^{(0)}$ are—at least theoretically, when A is invertible—equivalent. Therefore, there is no loss of generality in focusing on the reconstruction of $x^{(0)}$ instead of the current state $x^{(T-1)}$.

A. Error Correction and Number of Correctable Attacks

Let $x^{(0)} \in \mathbb{R}^n$ be the initial state of the plant and let $y^{(0)}, \dots, y^{(T-1)} \in \mathbb{R}^p$ be the first T measurements that are transmitted from the sensors to the receiver device. The objective of the receiver device is to reconstruct the initial state $x^{(0)}$ from these measurements. These vectors are given by

$$y^{(t)} = CA^t x^{(0)} + e^{(t)}$$

where $e^{(t)}$ represent the error vector (i.e., the attack vector) injected by the attacker (throughout the paper we will use the terms “error vector” and “attack vector” interchangeably to designate the vector $e^{(t)}$ injected by the attacker; the term “error vector” emphasizes the error-correction perspective we adopt in this paper). Recall that $\text{supp}(e^{(t)}) \subset K$ with $K \subset \{1, \dots, p\}$ being the set of sensors that are attacked and whose data is unreliable.

Having received the T vectors $y^{(0)}, \dots, y^{(T-1)}$, the receiver uses a decoder $\mathcal{D} : (\mathbb{R}^p)^T \rightarrow \mathbb{R}^n$ in order to estimate the initial

state $x^{(0)}$ of the plant. The decoder correctly estimates the initial state if $\mathcal{D}(y^{(0)}, \dots, y^{(T-1)}) = x^{(0)}$.

We say that the decoder \mathcal{D} corrects q errors if it correctly recovers the initial state $x^{(0)}$ for any set K of attacked sensors of cardinality less than or equal to q . More formally we introduce the following definition:

Definition 1: We say that q errors are correctable after T steps by the decoder $\mathcal{D} : (\mathbb{R}^p)^T \rightarrow \mathbb{R}^n$ if for any $x^{(0)} \in \mathbb{R}^n$, any $K \subset \{1, \dots, p\}$ with $|K| \leq q$, and any sequence of vectors $e^{(0)}, \dots, e^{(T-1)}$ in \mathbb{R}^p such that $\text{supp}(e^{(t)}) \subset K$, we have $\mathcal{D}(y^{(0)}, \dots, y^{(T-1)}) = x^{(0)}$ where $y^{(t)} = CA^t x^{(0)} + e^{(t)}$ for $t = 0, \dots, T-1$.

Furthermore, we say that q errors are correctable after T steps (or, equivalently, that the system is *resilient* against q attacks after T steps) if there exists a decoder that can correct q errors after T steps.

The definition above can be related to the notion of *strong observability* for linear systems [14], [21]. Indeed, our definition can be formulated in terms of strong observability of the systems $(A, B=0, C, D_K)$ where $D = I_p$ is the identity matrix, and D_K is the restriction of the matrix D to the columns in K . In fact one can verify that: q errors are correctable if and only if the systems $(A, 0, C, D_K)$ are strongly observable for all $K \subset \{1, \dots, p\}$ with $|K| \leq 2q$.

Let $E_{q,T}$ denote the set of error vectors $(e^{(0)}, \dots, e^{(T-1)}) \in (\mathbb{R}^p)^T$ that satisfy $\forall t \in \{0, \dots, T-1\}$, $\text{supp}(e^{(t)}) \subset K$ for some $K \subset \{1, \dots, p\}$ with $|K| \leq q$. Note that $E_{q,T}$ is a union of $\binom{p}{q}$ subspaces in $(\mathbb{R}^p)^T$.

1) Characterization of the Number of Correctable Errors: Observe that, by definition 1, the existence of a decoder that can correct q errors is equivalent to saying that the following map:

$$\begin{aligned} \mathbb{R}^n \times E_{q,T} &\rightarrow (\mathbb{R}^p)^T \\ (x^{(0)}, e^{(0)}, \dots, e^{(T-1)}) &\mapsto (y^{(0)}, \dots, y^{(T-1)}) \\ &= (Cx^{(0)} + e^{(0)}, \dots, \\ &\quad CA^{T-1}x^{(0)} + e^{(T-1)}) \end{aligned} \quad (3)$$

is invertible, or, more precisely, that it has an inverse for the first n components of its domain (we are only interested in the state $x^{(0)}$, and not necessarily the error vectors).¹ Thus expressing injectivity of this map is equivalent to saying that q errors are correctable. This gives the following proposition:

Proposition 1: Let $T \in \mathbb{N} \setminus \{0\}$. The following are equivalent:

- (i) There is *no* decoder that can correct q errors after T steps;
- (ii) There exists $x_a, x_b \in \mathbb{R}^n$ with $x_a \neq x_b$, and error vectors $(e_a^{(0)}, \dots, e_a^{(T-1)}) \in E_{q,T}$ and $(e_b^{(0)}, \dots, e_b^{(T-1)}) \in E_{q,T}$ such that $A^t x_a + e_a^{(t)} = A^t x_b + e_b^{(t)}$ for all $t \in \{0, \dots, T-1\}$.

¹These two conditions—the existence of an inverse and the existence of an inverse to recover just the first n components—are actually equivalent since the attack vectors are uniquely determined by $x^{(0)}$ and the $y^{(t)}$'s and are given by $e^{(t)} = y^{(t)} - CA^t x^{(0)}$.

The proposition above simply says that it is not possible to unambiguously recover the state $x^{(0)}$ if there are two distinct values x_a and x_b with $x_a \neq x_b$ that can, with less than q corrupted sensors, explain the received data.

Note that the domain of the map defined in (3) is the Cartesian product of the whole \mathbb{R}^n with the error set $E_{q,T}$ which is unbounded. This means that we require the decoder to recover *any* initial state $x^{(0)}$ for *any* sequence of error vectors from $E_{q,T}$. In practice however one could consider only vectors $x^{(0)}$ in some set $\Omega \subset \mathbb{R}^n$ if one has prior knowledge on the initial state (for example, if the states are all nonnegative, say for physical reasons, then one could take $\Omega = \mathbb{R}_+^n$). Similarly, if the attacker has a finite amount of energy then we could envisage considering only elements of $E_{q,T}$ in a certain ball of finite radius. We do not however pursue this here, and we assume in particular that the initial state of the plant can be anywhere in \mathbb{R}^n and that the magnitude of the errors can be arbitrary.

We now give a necessary and sufficient condition for q errors to be correctable that is simpler than the one in proposition 1.

Proposition 2: Let $T \in \mathbb{N} \setminus \{0\}$. The following are equivalent:

- (i) There is a decoder that can correct q errors after T steps;
- (ii) For all $z \in \mathbb{R}^n \setminus \{0\}$, $|\text{supp}(Cz) \cup \text{supp}(CAz) \cup \dots \cup \text{supp}(CA^{T-1}z)| > 2q$.

Proof: (i) \Rightarrow (ii): Suppose for the sake of contradiction that there exists $z \in \mathbb{R}^n \setminus \{0\}$ such that $|\text{supp}(Cz) \cup \text{supp}(CAz) \cup \dots \cup \text{supp}(CA^{T-1}z)| \leq 2q$. Let L_a and L_b be two disjoint subsets of $\{1, \dots, p\}$ with $|L_a| \leq q$ and $|L_b| \leq q$ such that $L_a \cup L_b = \text{supp}(Cz) \cup \dots \cup \text{supp}(CA^{T-1}z)$ (such L_a and L_b exist since $|\text{supp}(Cz) \cup \text{supp}(CAz) \cup \dots \cup \text{supp}(CA^{T-1}z)| \leq 2q$). Let $e_a^{(t)} = CA^t z|_{L_a}$ be the vector obtained from $CA^t z$ by setting all the components outside of L_a to 0, and similarly let $e_b^{(t)} = -CA^t z|_{L_b}$. Then we have $CA^t z = e_a^{(t)} - e_b^{(t)}$ with $\text{supp}(e_a^{(t)}) \subset L_a$ and $\text{supp}(e_b^{(t)}) \subset L_b$ with $|L_a| \leq q$ and $|L_b| \leq q$. Now let, for $t \in \{0, \dots, T-1\}$, $y^{(t)} = CA^t z + e_b^{(t)} = CA^t \cdot 0 + e_a^{(t)}$. If q errors were correctable after T steps by some decoder \mathcal{D} then we would have $\mathcal{D}(y^{(0)}, \dots, y^{(T-1)}) = z$ and also $\mathcal{D}(y^{(0)}, \dots, y^{(T-1)}) = 0$ which is impossible since $z \neq 0$.

(ii) \Rightarrow (i): We again resort to contradiction. Suppose that q errors are *not* correctable after T steps: this means there exists $x_a \neq x_b$, and error vectors $e_a^{(0)}, \dots, e_a^{(T-1)}$ (supported on L_a with $|L_a| \leq q$) and $e_b^{(0)}, \dots, e_b^{(T-1)}$ (supported on L_b , with $|L_b| \leq q$) such that $CA^t x_a + e_a^{(t)} = CA^t x_b + e_b^{(t)}$ for all $t \in \{0, \dots, T-1\}$. Now let $z = x_a - x_b \neq 0$. If we let $L = L_a \cup L_b$, then we have $|L| \leq 2q$, and we have for all $t \in \{0, \dots, T-1\}$, $\text{supp}(CA^t z) \subset L$ which shows that (ii) does not hold. ■

It is interesting to note the connection of the proposition above with the definition of a q -error-correcting linear code in the context of coding over the real numbers. A matrix $C \in \mathbb{R}^{p \times n}$ (with $p > n$) defines a q -error-correcting linear code if for any $z \neq 0$, $|\text{supp}(Cz)| > 2q$ (see for example [22, §3]). This is precisely the condition we obtain from the previous proposition when $T = 1$ or when there is no dynamics.

It is also interesting to observe that the proposition above shows that one cannot recover the initial state $x^{(0)}$ until the observability matrix given by

$$\begin{bmatrix} C \\ CA \\ \vdots \\ CA^{T-1} \end{bmatrix}$$

has rank n . Indeed, if the observability matrix has rank smaller than n then it has a nontrivial kernel and there exists $z \neq 0$ such that $Cz = CAz = \dots = CA^{T-1}z = 0$. This shows, by the above proposition, that “0 errors cannot be corrected”, or in other words, that one cannot reconstruct $x^{(0)}$ even if there are no errors in the $y^{(0)}, \dots, y^{(T-1)}$.

Observe also that the characterization of proposition 2 shows that the maximum number of correctable errors cannot increase beyond $T = n$ measurements. Indeed, this is a direct consequence of the Cayley-Hamilton theorem since we have for any z and for $t \geq n$, $\text{supp}(CA^t z) \subset \text{supp}(Cz) \cup \text{supp}(CAz) \cup \dots \cup \text{supp}(CA^{n-1}z)$.

Finally, one can also directly see from the same proposition that the number of correctable errors is always less than $p/2$, for any T . It turns out that *generically*, i.e., for “almost all” systems (A, C) , the number of correctable errors is maximal and equal to $\lceil p/2 - 1 \rceil$.

Proposition 3: For almost all² pairs $(A, C) \in \mathbb{R}^{n \times n} \times \mathbb{R}^{p \times n}$ the number of correctable errors after $T = n$ steps is maximal and equal to $\lceil p/2 - 1 \rceil$.

Proof: For $i \in \{1, \dots, p\}$, let $e_i \in \mathbb{R}^p$ be the i ’th unit vector that has a 1 in the i th component and zeros elsewhere. Let f_i be the map defined by

$$f_i : (A, C) \in \mathbb{R}^{n \times n} \times \mathbb{R}^{p \times n} \mapsto \det \begin{bmatrix} e_i^T C \\ e_i^T CA \\ \vdots \\ e_i^T CA^{n-1} \end{bmatrix} \in \mathbb{R}.$$

where the matrix in the argument of the determinant is an $n \times n$ matrix. Note that f_i is a polynomial in the entries of A and C that is not identically zero [to see this take for example $C = \mathcal{P}_{\{1, \dots, p\}}$ to be the projection on the first p components and A to be a circular permutation matrix; then if z is such that $e_i^T Cz = 0, \dots, e_i^T CA^{n-1}z = 0$ then necessarily $z = 0$, and so the $n \times n$ matrix in the definition of f_i has trivial kernel and so has nonzero determinant]. Hence the zero set Z_i of f_i , $Z_i = \{(A, C) \in \mathbb{R}^{n \times n} \times \mathbb{R}^{p \times n} \mid f_i(A, C) = 0\}$ has (Lebesgue) measure zero in $\mathbb{R}^{n \times n} \times \mathbb{R}^{p \times n}$ [23]. Hence $\bigcup_{i=1}^p Z_i$ has also measure zero. Now to conclude, note that for any $(A, C) \in (\bigcup_{i=1}^p Z_i)^c$, the number of correctable errors after $T = n$ is maximal. Indeed if $z \neq 0$, we have that for all i , $(e_i^T Cz, \dots, e_i^T CA^{n-1}z) \neq 0_{\mathbb{R}^n}$ since $(A, C) \notin Z_i$, and so $|\text{supp}(Cz) \cup \text{supp}(CAz) \cup \dots \cup \text{supp}(CA^{n-1}z)|$ is maximal and equal to p . ■

²That is, except on a set of Lebesgue measure zero in $\mathbb{R}^{n \times n} \times \mathbb{R}^{p \times n}$. Note that the Proposition does not apply if we are only interested in matrices (A, C) that have a particular structure (e.g., lie in a certain subspace of $\mathbb{R}^{n \times n} \times \mathbb{R}^{p \times n}$) since the set of pairs with such structure can itself have a zero Lebesgue measure in $\mathbb{R}^{n \times n} \times \mathbb{R}^{p \times n}$.

2) *Computing the Number of Correctable Errors:* Even though for *almost all* pairs (A, C) the number of errors that can be corrected is maximal (equal to $\lceil p/2 - 1 \rceil$ for $T = n$), the problem of actually *computing* the number of errors that can be corrected for a given pair (A, C) after a given number of steps T is a hard problem in general. Actually one simple yet expensive algorithm is to look for the smallest $|K|$ where $K \subset \{1, \dots, p\}$ for which the following matrix has a nontrivial kernel:

$$\begin{bmatrix} \mathcal{P}_{K^c} C \\ \mathcal{P}_{K^c} CA \\ \vdots \\ \mathcal{P}_{K^c} CA^{T-1} \end{bmatrix}.$$

If s is the cardinality of the smallest K for which this matrix has nontrivial kernel, then by proposition 2 the maximum number of correctable errors is $\lceil s/2 - 1 \rceil$. This algorithm is however computationally expensive and requires computing the rank of 2^p matrices in the worst-case. A recent result [24] shows that it is very unlikely that there is a more efficient way to perform the computation.³

B. Increasing the Number of Correctable Errors by State Feedback

In this section we consider the question of whether it is possible to make a given system (A, C) more resilient against attacks by modifying the parameters of the system. More specifically, if B is some given matrix, we look at the problem of designing a matrix G so that the pair $(A + BG, C)$ is resilient against a large number of attacks, while it satisfies at the same time other design constraints.

From a practical point of view, this question can be motivated by the following scenario depicted in Fig. 1: we first assume that the physical system possesses a local control loop that has direct access to the state of the plant and that can control the evolution of the physical system. This is possible for example if the sensors are connected to the local controller through a wired link that is not subject to external attacks. If the local control loop implements a feedback law of the form $u = Gx$ then the evolution of the physical system is governed by the matrix $A + BG$. Also, and as part of the overall plant, a high-level supervisory and monitoring system receives measurements from the sensors through wireless and vulnerable communication links that are subject to attacks. Observe that the choice G of the local controller will affect the resilience of the system to attacks, i.e., how many errors are correctable by the supervisory system. The objective here is therefore to design G in order to make the number of correctable errors of the pair $(A + BG, C)$ as large as possible.

Note that there are other design constraints that come into play in the choice of the local feedback law. Typically G is

³In the special case $T = 1$ of error correction without dynamics, the number of errors that can be corrected is directly related to the *spark* of a matrix F that annihilates C , i.e., such that $FC = 0$ (see [16, §I.G]). The spark of a matrix F is the smallest number of columns that are linearly dependent. According to the recent paper [24], computing the spark of a matrix is NP-hard.

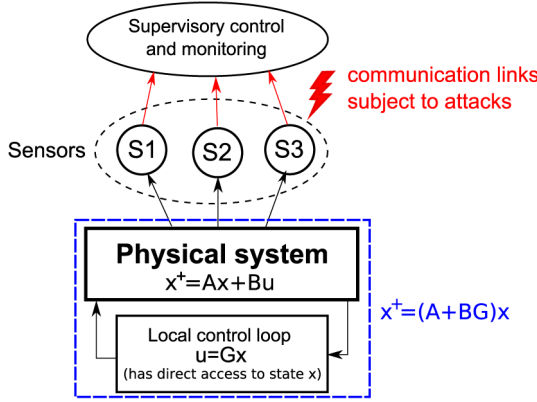


Fig. 1. Scenario where a local control loop has direct access to uncorrupted sensor information. Using this local control loop, the evolution of the physical system will be governed by the matrix $A + BG$ where A is the open-loop matrix, B is the control matrix, and G can be chosen arbitrarily. The objective is to find G such that the pair $(A + BG, C)$ is resilient against a large number of attacks. Choosing such a G will allow the higher level supervisory control and monitoring system to recover the correct state despite attacks in the communication links between the sensors and the supervisory system.

chosen so that the eigenvalues of $A + BG$ are inside the unit disc so that the resulting closed-loop system is stable. It is known by the pole placement theorem that this is possible if the pair (A, B) is controllable [25].

In this section we ask if one can also enforce the requirement that the number of correctable errors of the new pair $(A + BG, C)$ is large, without losing the freedom of choosing the eigenvalues of $A + BG$. We show in this section that the answer is yes, and that if the pair (A, B) is controllable, then it is possible to choose G such that $\lceil p/2 - 1 \rceil$ errors are correctable for $(A + BG, C)$ and such that the eigenvalues of $A + BG$ are in any arbitrary (or almost arbitrary) prescribed locations in the complex plane. In other words, by an adequate choice of the local control law, one can make the system *more resilient to attacks* (the number of correctable errors $\lceil p/2 - 1 \rceil$ is the maximum possible), without compromising the control performance.

More specifically, we have the following result:⁴

Proposition 4: Let $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times 1}$ and $C \in \mathbb{R}^{p \times n}$ and assume that the pair (A, B) is controllable and that each row of C is not identically zero. Then there exists a finite set $F \subset \mathbb{C}$ such that for any choice of n numbers $\lambda_1, \dots, \lambda_n \in \mathbb{C} \setminus F$ such that the λ_i 's have distinct magnitudes, there exists $G \in \mathbb{R}^{1 \times n}$ such that:

- The eigenvalues of the closed-loop matrix $A + BG$ are $\lambda_1, \dots, \lambda_n$.
- The number of correctable errors after n steps for the pair $(A + BG, C)$ is maximal (equal to $\lceil p/2 - 1 \rceil$).

In order to prove this result, we make use of the following lemma (a result of the same flavor was obtained in a slightly different setting in [26]):

⁴We deal only with the single-input case here but the multi-input case can be handled using the same arguments. Moreover, the condition for $\{\lambda_i\}$ to have distinct amplitudes is not much of a restriction since one can always choose the λ_i 's to satisfy this condition and the consequences in terms of performance are negligible.

Lemma 1: Let $A \in \mathbb{R}^{n \times n}$ and $C \in \mathbb{R}^{p \times n}$. Assume that A has n eigenvalues all with distinct magnitudes (in particular A is diagonalizable). Then the following are equivalent:

- q errors are correctable for (A, C) after n steps.
- for every eigenvector v of A , $|\text{supp}(Cv)| > 2q$.

Proof:

- (i) \Rightarrow (ii): This direction simply corresponds to taking x to be an eigenvector of A in the condition $|\text{supp}(Cx) \cup \dots \cup \text{supp}(CA^{n-1}x)| > 2q$ of Proposition 2.
- (ii) \Rightarrow (i): We assume that all eigenvectors v of A satisfy $|\text{supp}(Cv)| > 2q$ and we will show that for any $x \neq 0$, we have $|\text{supp}(Cx) \cup \text{supp}(CAx) \cup \dots \cup \text{supp}(CA^{n-1}x)| > 2q$. The idea here is that if $x \neq 0$ then for t large enough the vector $A^t x$ will be very close to an eigenvector w of A , and hence the support of $CA^t x$ will have more than $2q$ elements since $|\text{supp}(Cw)| > 2q$. More formally, let $x \in \mathbb{R}^n \setminus \{0\}$ and consider the decomposition of x in the eigenbasis of A : $x = \sum_{i=1}^s \alpha_i v_i$ with $\alpha_i \neq 0$ for at least one i , and where v_1, \dots, v_s are eigenvectors of A associated with eigenvalues $\lambda_1, \dots, \lambda_s$. Since the eigenvalues of A have distinct magnitudes we can assume that $|\lambda_1| > |\lambda_2| > \dots > |\lambda_s|$. We isolate the largest eigenvalue in this decomposition and we denote $\lambda = \lambda_1$ and $w = v_1$. Now we have $(A^t x - \alpha_1 \lambda^t w) / \lambda^t \rightarrow 0$ when $t \rightarrow +\infty$. Let $S = \text{supp}(Cw)$. Note that since w is an eigenvector of A we have $|S| > 2q$ (by assumption). We'll now show that for t large enough, the support of $CA^t x$ contains S : let $\beta = \min_{i \in S} |(Cw)_i|$ and observe that clearly $\beta > 0$. Let t be large enough so that $|C(A^t x - \alpha_1 \lambda^t w)_i| / |\lambda|^t < \beta/2$ for all $i \in S$. Now we have, for $i \in S$

$$\begin{aligned} \frac{1}{|\lambda|^t} |CA^t x|_i &\geq \frac{1}{|\lambda|^t} (|\lambda^t Cw|_i - |CA^t x - \lambda^t Cw|_i) \\ &> \beta - \beta/2 = \beta/2 > 0. \end{aligned}$$

Hence $S \subset \text{supp}(CA^t x)$ for large enough t . But since we have $\text{supp}(CA^t x) \subset \text{supp}(Cx) \cup \text{supp}(CAx) \cup \dots \cup \text{supp}(CA^{n-1}x)$ by the Cayley-Hamilton theorem, we have $S \subset \text{supp}(Cx) \cup \text{supp}(CAx) \cup \dots \cup \text{supp}(CA^{n-1}x)$. Finally since this is true for any $x \neq 0$, and since $|S| > 2q$, we conclude by 2 that q errors are correctable after n steps. ■

We now use this lemma to prove Proposition 4:

Proof: (Proposition 4): To prove the result, we will show that if the chosen poles $\lambda_1, \dots, \lambda_n$ have distinct magnitudes and do not fall in some finite set F , then there is a choice of G such that the eigenvalues of $A + BG$ are exactly the $\lambda_1, \dots, \lambda_n$, and the corresponding eigenvectors v_i are such that $|\text{supp}(Cv_i)| = p$. Thus, by the previous lemma, this will show that the number of correctable errors for $(A + BG, C)$ is $\lceil p/2 - 1 \rceil$.

First note that if λ is an eigenvalue of $A + BG$ and x is a corresponding eigenvector, then we have $Ax + BGx = \lambda x$, or, if $(\lambda I - A)^{-1}$ is well defined, $x = (\lambda I - A)^{-1} BGx$, i.e., x is proportional to the vector $(\lambda I - A)^{-1} B$ (since Gx is a real number). This means that if λ is an eigenvalue of $A + BG$, then necessarily the corresponding eigenvector is $(\lambda I - A)^{-1} B$.

We will therefore look for values of λ for which $C(\lambda I - A)^{-1} B$ has full support.

Let $i \in \{1, \dots, p\}$ be fixed and denote by e_i the vector in \mathbb{R}^p that has a 1 in the i th component and zeros elsewhere. Note that since (A, B) is controllable and since $C^T e_i \neq 0$, there exists λ such that $e_i^T C(\lambda I - A)^{-1} B \neq 0$ (see [25, Chapter 3, Theorem 2.17(ii)]), and in fact the set $F_i = \{\lambda \in \mathbb{C} \mid e_i^T C(\lambda I - A)^{-1} B = 0\} \subseteq \mathbb{C}$ is finite (zeros of a non-identically-zero rational fraction).

Now consider $F = (\cup_{i=1}^n F_i)$, and let $\lambda_1, \dots, \lambda_n$ be any choice of n numbers in $\mathbb{C} \setminus F$ with distinct magnitudes. We will show that there exists G such that the eigenvalues of $A + BG$ are the λ_j 's and the eigenvectors v_j are such that Cv_j has full support.

By controllability of (A, B) there is a G such that the eigenvalues of $A + BG$ are the λ_j 's. We know that the eigenvectors of $A + BG$ are the $v_j = (\lambda_j I - A)^{-1} B$. Now by the choice of the λ_j 's and by the definition of F we know that for all j and for any i , $e_i^T C(\lambda_j I - A)^{-1} B \neq 0$. In other words, for any j , the vector Cv_j has full support. Hence, by lemma 1, the number of correctable errors of $(A + BG, C)$ is maximal. ■

C. Optimization Formulation of the Optimal Decoder

In the previous sections we have discussed and quantified the resilience of a given system (A, C) by characterizing the maximum number of attacks that are tolerable so that the initial state of the system could still be exactly recovered. We saw that if the system (A, C) satisfies the condition

$$|\text{supp}(Cz) \cup \dots \cup \text{supp}(CA^{T-1}z)| > 2q, \quad \forall z \neq 0 \quad (4)$$

then it is possible to correct any attacks on q sensors using the T observations $y^{(0)}, \dots, y^{(T-1)}$. We did not discuss however how to actually *recover* the state $x^{(0)}$ from the observations. In this section we focus on the problem of *constructing* a decoder that can correct any number q of errors as long as q satisfies the condition (4) above.

Consider the decoder $\mathcal{D}_0 : (\mathbb{R}^p)^T \rightarrow \mathbb{R}^n$ defined such that $\mathcal{D}_0(y^{(0)}, \dots, y^{(T-1)})$ is the optimal \hat{x} solution of the following optimization problem:

$$\begin{aligned} & \underset{\hat{x} \in \mathbb{R}^n, \hat{K} \subset \{1, \dots, p\}}{\text{minimize}} && |\hat{K}| \\ & \text{subject to} && \text{supp}(y^{(t)} - CA^t \hat{x}) \subset \hat{K} \\ & && \text{for } t \in \{0, \dots, T-1\}. \end{aligned} \quad (5)$$

Observe that the decoder \mathcal{D}_0 looks for the smallest set K of attacked sensors that can explain the received data $y^{(0)}, \dots, y^{(T-1)}$. We show in the next proposition that the decoder \mathcal{D}_0 is optimal in terms of error-correction capabilities.

Proposition 5: Assume that q errors are correctable after T steps, i.e., that (4) holds. Then the decoder \mathcal{D}_0 corrects q errors, i.e., for any $x^{(0)} \in \mathbb{R}^n$, and any $e^{(0)}, \dots, e^{(T-1)}$ in \mathbb{R}^p such that $\text{supp}(e^{(t)}) \subset K$ with $|K| \leq q$, we have $\mathcal{D}_0(y^{(0)}, \dots, y^{(T-1)}) = x^{(0)}$ where $y^{(t)} = CA^t x^{(0)} + e^{(t)}$.

Proof: Let $x^{(0)}$ and the $e^{(t)}$'s satisfy the stated assumptions, with $\text{supp}(e^{(t)}) \subset K$ and $y^{(t)} = CA^t x^{(0)} + e^{(t)}$. Assume for the sake of contradiction that the feasible point $(x^{(0)}, K)$ is not the unique optimal point for (5). Hence there exists $x_a \neq$

$x^{(0)}$, and $e_a^{(0)}, \dots, e_a^{(T-1)}$ with $\text{supp}(e_a^{(t)}) \subset K_a$ that generate the same sequence $y^{(0)}, \dots, y^{(T-1)}$ of observed values, with in addition, $|K_a| \leq |K| \leq q$. We therefore have two different initial conditions $x^{(0)} \neq x_a$ and two different error vectors corresponding to less than q attacked sensors that generate exactly the same sequence of observed values. This exactly means that q errors are *not* correctable after T steps which contradicts the assumption. ■

The proposition above therefore shows that the decoder \mathcal{D}_0 is the best decoder in terms of error-correction capabilities, since if any decoder can correct q errors, then \mathcal{D}_0 can as well. One issue however is that the optimization problem (5) is not practical since it is NP-hard in general. Indeed for the special case $T = 1$ (corresponding to the case of “static” error-correction over the reals mentioned earlier) the decoder becomes

$$\underset{\hat{x} \in \mathbb{R}^n}{\text{minimize}} \quad \|y - C\hat{x}\|_{\ell_0} \quad (6)$$

(where $\|z\|_{\ell_0} = |\text{supp}(z)|$) which is known to be NP-hard (see for example [22]).

However, in [16], Candes and Tao proposed to replace the ℓ_0 “norm” by an ℓ_1 norm, thereby transforming the problem into a convex program that can be efficiently solved

$$\underset{\hat{x} \in \mathbb{R}^n}{\text{minimize}} \quad \|y - C\hat{x}\|_{\ell_1}.$$

It was then shown in [16] that if the matrix C satisfies certain conditions, then the solution of this convex program is the same as the one given by the ℓ_0 optimal decoder. In the next section we consider this relaxation in the context of our problem.

D. The ℓ_1 Decoder: A Relaxation of the Optimal Decoder

For $T \in \mathbb{N} \setminus \{0\}$, consider the linear map $\Phi^{(T)}$ defined by

$$\Phi^{(T)} : \mathbb{R}^n \rightarrow \mathbb{R}^{p \times T}$$

$$x \mapsto [Cx \mid CAx \mid \dots \mid CA^{T-1}x].$$

Furthermore, if $y^{(0)}, \dots, y^{(T-1)} \in \mathbb{R}^p$, let $Y^{(T)}$ the $p \times T$ matrix formed by concatenating the $y^{(t)}$'s in columns

$$Y^{(T)} = [y^{(0)} \mid y^{(1)} \mid \dots \mid y^{(T-1)}] \in \mathbb{R}^{p \times T}.$$

Recall that for a matrix $M \in \mathbb{R}^{p \times T}$ with rows $M_1, \dots, M_p \in \mathbb{R}^T$ the ℓ_0 “norm” of M is the number of nonzero rows in M

$$\|M\|_{\ell_0} = |\text{rowsupp}(M)| = |\{i \in \{1, \dots, p\} \mid M_i \neq 0\}|.$$

Observe that the optimal decoder \mathcal{D}_0 introduced in the previous section can be written as

$$\mathcal{D}_0(y^{(0)}, \dots, y^{(T-1)}) = \arg \min_{\hat{x} \in \mathbb{R}^n} \|Y^{(T)} - \Phi^{(T)} \hat{x}\|_{\ell_0}.$$

As we saw in the previous section, this decoder finds the minimum number of attacked sensors that can explain the received data $y^{(0)}, \dots, y^{(T-1)}$.

Analogously to [16], we can define an ℓ_1 decoder which, instead of minimizing the number of nonzero rows, minimizes

the sum of the magnitudes of each row. Specifically, if we measure the magnitude of a row by its ℓ_r norm in \mathbb{R}^T (for $r \geq 1$), we obtain the following decoder $\mathcal{D}_{1,r}$:

$$\mathcal{D}_{1,r}(y^{(0)}, \dots, y^{(T-1)}) = \arg \min_{\hat{x} \in \mathbb{R}^n} \|Y^{(T)} - \Phi^{(T)} \hat{x}\|_{\ell_1/\ell_r} \quad (7)$$

where, by definition, $\|M\|_{\ell_1/\ell_r}$ is the sum of the ℓ_r norms of the rows of the matrix M

$$\|M\|_{\ell_1/\ell_r} = \sum_{i=1}^p \|M_i\|_{\ell_r}.$$

Note that the optimization problem in (7) is convex and can be efficiently solved. Also note that such “mixed” ℓ_1/ℓ_r norms were also used in the compressed sensing literature in the context of joint-sparse and block-sparse signal recovery [27].

We saw in Proposition 2 that the number of errors that can be corrected by the optimal ℓ_0 decoder \mathcal{D}_0 is equal to the largest number q such that $|\text{supp}(Cz) \cup \text{supp}(CAz) \cup \dots \cup \text{supp}(CA^{T-1}z)| > 2q$ for all $z \neq 0$.

The next proposition characterizes the maximum number of errors that can be corrected by the ℓ_1/ℓ_r decoder $\mathcal{D}_{1,r}$.

Proposition 6: The following are equivalent:

- (i) The decoder $\mathcal{D}_{1,r}$ can correct q errors after T steps.
- (ii) For all $K \subset \{1, \dots, p\}$ with $|K| = q$ and for all $z \in \mathbb{R}^n \setminus \{0\}$, it holds

$$\sum_{i \in K} \|(\Phi^{(T)} z)_i\|_{\ell_r} < \sum_{i \in K^c} \|(\Phi^{(T)} z)_i\|_{\ell_r}. \quad (8)$$

Proof: (i) \Rightarrow (ii): Suppose for the sake of contradiction that (ii) does not hold. Then there exists $K \subset \{1, \dots, p\}$ with $|K| = q$, and $G = \Phi^{(T)} z \in \mathbb{R}^{p \times T}$ with $z \neq 0$ such that $\sum_{i \in K} \|G_i\|_{\ell_r} \geq \sum_{i \in K^c} \|G_i\|_{\ell_r}$. Let $x^0 = 0$ and define the K -supported error vectors $e^{(t)}$, for $t \in \{0, \dots, T-1\}$ by $e_i^{(t)} = G_{i,t}$ if $i \in K$ and $e_i^{(t)} = 0$ otherwise. Now consider $y^{(t)} = CA^t x^0 + e^{(t)} = e^{(t)}$ and let $Y^{(T)}$ be, as before, the $p \times T$ matrix obtained by concatenating the $y^{(t)}$'s in columns. Note that $\text{rowsupp}(Y^{(T)}) = K$, and that $Y_i^{(T)} = (\Phi^{(T)} z)_i$ for all $i \in K$. We will now show that the objective function for (7) at $z \neq 0$ is smaller than at $x^0 = 0$, which will show that the decoder $\mathcal{D}_{1,r}$ fails to reconstruct $x^{(0)}$ from the $y^{(t)}$'s. This will show that (i) is not true. Indeed we have

$$\begin{aligned} \|Y^{(T)} - \Phi^{(T)} z\|_{\ell_1/\ell_r} &= \sum_{i=1}^n \|(Y^{(T)} - \Phi^{(T)} z)_i\|_{\ell_r} \\ &= \sum_{i \in K^c} \|G_i\|_{\ell_r} \leq \sum_{i \in K} \|G_i\|_{\ell_r} \\ &= \sum_{i=1}^n \|(Y^{(T)} - \Phi^{(T)} x^0)_i\|_{\ell_r} \\ &= \|Y^{(T)} - \Phi^{(T)} x^0\|_{\ell_1/\ell_r}. \end{aligned}$$

(ii) \Rightarrow (i): We again resort to contradiction. Suppose that (i) is not true. This means there exists $x^{(0)}$, and $e^{(0)}, \dots, e^{(T-1)}$ with $\text{supp}(e^{(t)}) \subset K$ with $|K| \leq q$ such that $\mathcal{D}_{1,r}(y^{(0)}, \dots, y^{(T-1)}) \neq x^{(0)}$ where $y^{(t)} = CA^t x^{(0)} + e^{(t)}$ (i.e., the decoder

$\mathcal{D}_{1,r}$ fails to reconstruct $x^{(0)}$ from the $y^{(t)}$'s). By definition of the decoder $\mathcal{D}_{1,r}$, this means that there exists $\tilde{x} \neq x^{(0)}$ that achieves a smaller ℓ_1/ℓ_r objective than $x^{(0)}$

$$\sum_{i=1}^n \|(Y^{(T)} - \Phi^{(T)} \tilde{x})_i\|_{\ell_r} \leq \sum_{i=1}^n \|(Y^{(T)} - \Phi^{(T)} x^{(0)})_i\|_{\ell_r}.$$

Now let $z = \tilde{x} - x^{(0)} \neq 0$, and let $G = \Phi^{(T)} z = U - V$ with $U = Y^{(T)} - \Phi^{(T)} x^{(0)}$ and $V = Y^{(T)} - \Phi^{(T)} \tilde{x}$. We have

$$\sum_{i \in K} \|G_i\|_{\ell_r} = \sum_{i \in K} \|U_i - V_i\|_{\ell_r} \geq \sum_{i \in K} \|U_i\|_{\ell_r} - \|V_i\|_{\ell_r}.$$

Now since $\text{rowsupp}(U) \subset K$, and since \tilde{x} achieves a smaller ℓ_1/ℓ_r objective than x^0 , we have $\sum_{i \in K} \|U_i\|_{\ell_r} = \sum_{i=1}^n \|U_i\|_{\ell_r} \geq \sum_{i=1}^n \|V_i\|_{\ell_r}$. Hence we have

$$\begin{aligned} \sum_{i \in K} \|G_i\|_{\ell_r} &\geq \sum_{i=1}^n \|V_i\|_{\ell_r} - \sum_{i \in K} \|V_i\|_{\ell_r} \\ &= \sum_{i \in K^c} \|V_i\|_{\ell_r} = \sum_{i \in K^c} \|G_i\|_{\ell_r} \end{aligned}$$

where the last equality is because $\text{rowsupp}(U) \subset K$. Hence (ii) is not true. ■

Observe that, as expected, if the ℓ_1/ℓ_r decoder can correct q errors, then the ℓ_0 decoder can correct q errors as well. Indeed, if we assume the opposite, then by Proposition 2 there exists $z \neq 0$ such that $|\text{supp}(Cz) \cup \dots \cup \text{supp}(CA^{T-1}z)| \leq 2q$, which is equivalent to saying that $|\text{rowsupp}(\Phi^{(T)} z)| \leq 2q$. Now let $G = \Phi^{(T)} z$ and let K be the q rows of G with the largest ℓ_r norms, then we clearly have $\sum_{i \in K} \|G_i\|_{\ell_r} \geq \sum_{i \in K^c} \|G_i\|_{\ell_r}$, which contradicts the condition of the previous proposition.

As a matter of fact, the condition of the previous proposition (for the ℓ_1/ℓ_r decoder) is in some sense a more quantitative version of the condition of proposition 2 for the ℓ_0 decoder. The two conditions guarantee that the row components of $\Phi^{(T)} z$ are sufficiently spread and are not too concentrated on a small subset of the rows.

As an illustration, consider the simple example where the number of sensors is $p = n$ and $C = I_n$ (i.e., we have one sensor per component of the state $x \in \mathbb{R}^n$) and where A is the cyclic permutation given by

$$A = \begin{bmatrix} 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & & \ddots & 0 \\ 0 & 0 & \dots & 0 & 1 \\ 1 & 0 & 0 & \dots & 0 \end{bmatrix}. \quad (9)$$

It is easy to see that after $T = n$, the rows of the matrix $\Phi^{(n)} z = [z \ Az \ \dots \ A^{n-1}z]$ are identical up to a permutation, and so the ℓ_r norm of any two rows of $\Phi^{(T)} z$ are equal. This shows that for any subset K of rows with $|K| < n/2$, we have $\sum_{i \in K} \|(\Phi^{(n)} z)_i\|_{\ell_r} < \sum_{i \in K^c} \|(\Phi^{(n)} z)_i\|_{\ell_r}$, which shows that the ℓ_1/ℓ_r decoder can correct a maximal number of errors after n steps, namely, $\lceil n/2 - 1 \rceil$.

Finally note that the condition of Proposition 6 for the ℓ_1/ℓ_r decoder corresponds to the well-known “nullspace property” in compressed sensing and sparse signal recovery [28].

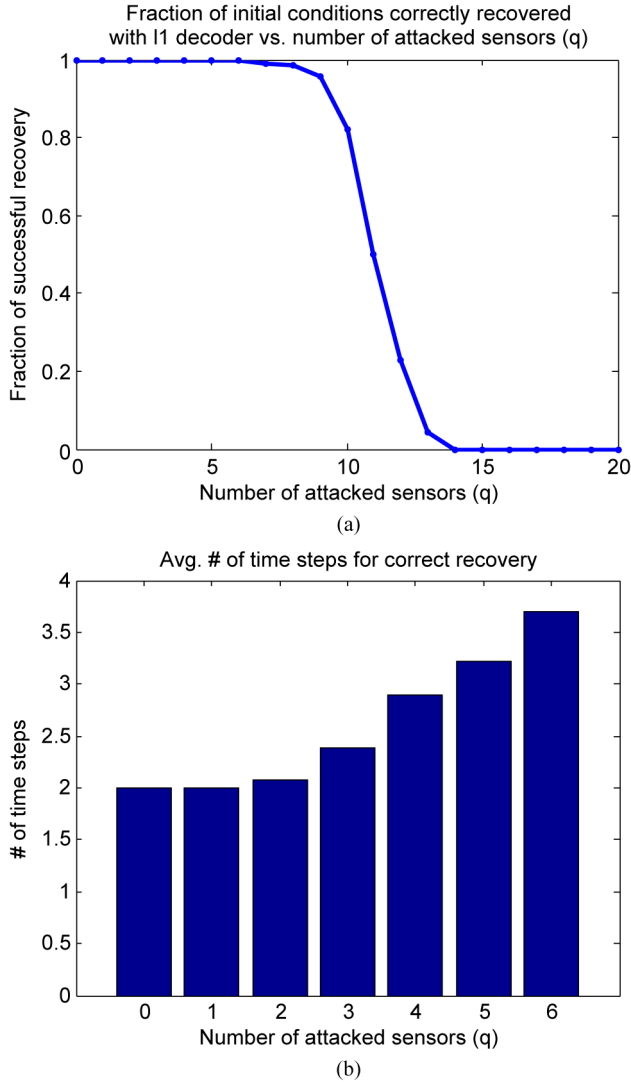


Fig. 2. Performance of ℓ_1/ℓ_2 decoder on a randomly chosen system with $n = 25$ states and $p = 20$ sensors. We see that when the number of attacked sensors is small enough, the ℓ_1/ℓ_2 can still recover the exact state of the system (left). As the number of attacked sensors increases, more measurements are needed to correctly recover the state of the system (right).

E. Numerical Simulations

In this section we show the performance of the proposed decoding algorithm first on a random toy example and then on a more realistic system modeling an electric power network.

1) *Random System*: We first consider the ℓ_1/ℓ_2 decoder on a system of size $n = 25$, $p = 20$ where $A \in \mathbb{R}^{25 \times 25}$ and $C \in \mathbb{R}^{20 \times 25}$ have iid Gaussian entries. For different values q of attacked sensors, we tested the decoder on 200 different initial conditions $x^{(0)}$ and attacked sensors $K \subset \{1, \dots, p\}$ with $|K| = q$. The initial conditions $x^{(0)}$ were randomly generated from the standard Gaussian distribution, and the attack sets were chosen uniformly at random from the set of subsets of $\{1, \dots, p\}$ of size q . Fig. 2(a) shows the fraction of initial conditions that were correctly recovered by the ℓ_1/ℓ_2 decoder [cf. (7)] in less than $T = 15$ time steps for the different values of q . We see that for q less than 6 all the initial conditions were correctly recovered in less than $T = 15$ time steps. Fig. 2(b) shows the number of time steps that it took in average to

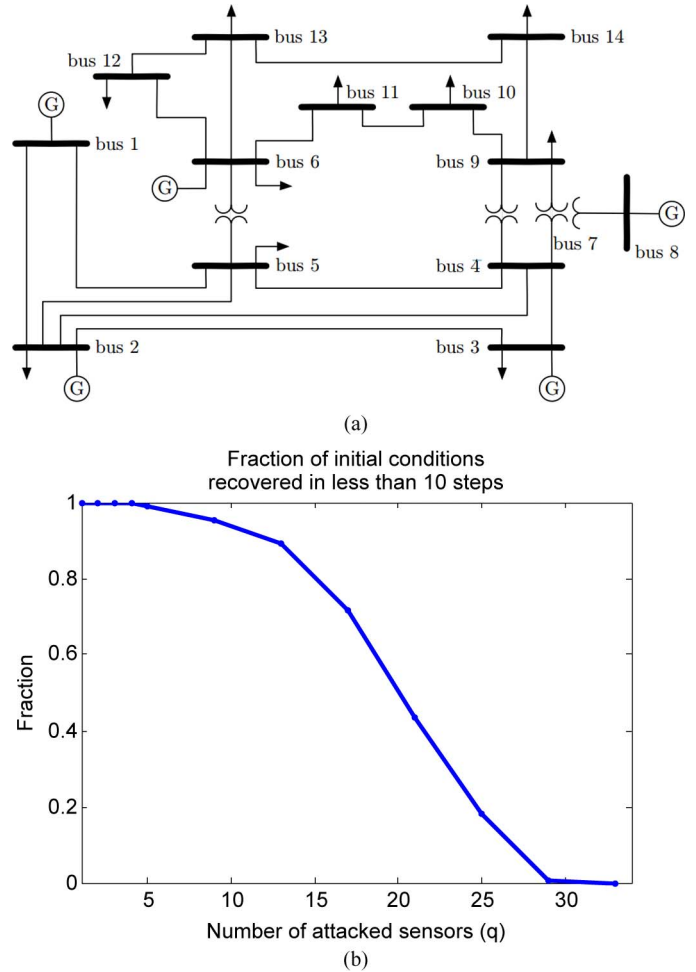


Fig. 3. Performance of the ℓ_1/ℓ_∞ decoder on the IEEE 14-bus power network example (Fig. 3(a) is from [17]). The decoder successfully recovered the state of the system when the number of attacked sensors was less than 4. When the number of attacked sensors was less than 12, the decoder recovered the correct state in more than 90% of the cases.

correctly recover the initial state, as a function of the number of corrupted components q . We see that as q increases, more measurements were needed to correctly recover the state of the system.

For each simulation, the attack values (i.e., the values injected by the attacker in the components K) were chosen randomly from a Gaussian distribution. In order to illustrate the fact that the decoder can handle unbounded attacks, the magnitude of the attacks were chosen to be 20 times larger than the magnitude of the state. Furthermore, the matrix A was appropriately scaled so it has a spectral radius of 1. The optimization problems were solved using CVX [29].

2) *Electric Power Network*: In this section we apply the proposed decoding algorithm on a model of an electric power network and more specifically on the IEEE 14-bus power network [30]. The network, depicted in Fig. 3(a) is composed of 5 synchronous generators and a total of 14 buses. The system is represented by $2 \times 5 = 10$ states giving the rotor angles δ_i and the frequencies $\omega_i = d\delta_i/dt$ of each generator. Under some simplifying assumptions the evolution of the system can be captured by a linear difference equation corresponding to the linearized swing equations (see [31] for the derivation of the equations).

We assume, like in [17], that $p = 35$ sensors are deployed and measure at every time step the real power injections at every bus (14 sensors), the real power flows along every branch (20 sensors), and the rotor angle at generator 1 (1 sensor).

For different values of attacked sensors q , we ran 200 simulations with different sets of attacked sensors K of cardinality q , and different initial conditions $x^{(0)}$ that were randomly generated like in the previous example. In the simulations we did not allow the last sensor measuring the rotor angle to be attacked. Indeed if this sensor is attacked then there is no hope of correctly recovering the state since the system becomes unobservable. The ℓ_1 decoder we used however is the one described in Section III-D and did not incorporate the knowledge of the unattacked sensor in any way. Fig. 3(b) shows the number of simulations (out of the 200) where the state $x^{(0)}$ was correctly recovered using the ℓ_1/ℓ_∞ decoder in less than $T = 10$ steps. Observe that for $q \leq 4$ the success rate of the decoder was 100%. Furthermore when $q \leq 12$ the decoder correctly recovers the state in more than 90% of the cases. These simulations show that the ℓ_1/ℓ_r decoder works very well in this example and therefore is a promising practical technique.

F. The Case of Attacks on Actuators

In this section we incorporate into our model attacks on actuators (in addition to attacks on sensors) and we show to extend the decoder of the previous section to this case. Consider a plant that evolves according to the equations

$$\begin{aligned} x^{(t+1)} &= Ax^{(t)} + B \left(U^{(t)} \left(y^{(0)}, \dots, y^{(t)} \right) + w^{(t)} \right) \\ y^{(t)} &= Cx^{(t)} + e^{(t)} \end{aligned} \quad (10)$$

where $A \in \mathbb{R}^{n \times n}$, $B \in \mathbb{R}^{n \times m}$, $C \in \mathbb{R}^{p \times n}$, and $(U^{(t)})_{t=0,1,\dots}$ is an output-feedback control law. As before the vectors $e^{(t)}$ represent attacks on sensors. The vectors $w^{(t)}$ represent attacks on actuators: if actuator $j \in \{1, \dots, m\}$ is not attacked, then $w_j^{(t)} = 0$, otherwise actuator j is attacked and $w_j^{(t)}$ can be arbitrary. The set of attacked actuators will typically be denoted by L . In this section we will use the letter q to denote the total number of attacked nodes (sensors and actuators), $q = |K| + |L|$.

Our objective is to monitor the state of the plant from the observations $y^{(t)}$. More formally if T is some time horizon, we wish to reconstruct the sequence⁵ of states $x^{(0)}, \dots, x^{(T-1)}$ from the observations $y^{(0)}, \dots, y^{(T-1)}$. If such reconstruction is possible when the attack vectors $e^{(t)}$'s and $w^{(t)}$'s are restricted to have less than q nonzero components combined (i.e., $|K| + |L| \leq q$), we say that q attacks are correctable, or equivalently, that the system is resilient against q attacks. More formally we have the following definition:

⁵Observe that in the previous section where we dealt with attacks on sensors only, the objective was to only reconstruct the initial state $x^{(0)}$ since we could then simply use the dynamics to propagate the initial condition and obtain $x^{(1)}, x^{(2)}, \dots, x^{(T-1)}$. When considering attacks on actuators, using the dynamics to propagate the initial state requires the knowledge of the attacks. Hence in this section we explicitly ask for the recovery of the *whole* sequence $x^{(0)}, \dots, x^{(T-1-d)}$ where $d \in \mathbb{N}$ is some delay parameter.

Definition 2: Let a control system of the form (10) be given. We say that q attacks are correctable after T steps (or equivalently, that the system is resilient against q attacks after T steps with a delay δ if there exists a decoder $\mathcal{D} : (\mathbb{R}^p)^T \rightarrow (\mathbb{R}^n)^{T-\delta}$ such that for any $x^{(0)} \in \mathbb{R}^n$, for any $w^{(0)}, \dots, w^{(T-2)}$ with $\text{supp}(w^{(t)}) \subseteq L$ and any $e^{(0)}, \dots, e^{(T-1)}$ with $\text{supp}(e^{(t)}) \subseteq K$ with $|K| + |L| \leq q$ we have $\mathcal{D}(y^{(0)}, \dots, y^{(T-1)}) = (x^{(0)}, x^{(1)}, \dots, x^{(T-1-\delta)})$.

a) *An explicit decoder:* We now consider the problem of designing a decoding algorithm that recovers the sequence of states despite attacks on sensors and actuators. We show that one can formulate the decoding problem as an optimization problem, in the same way we did when there were only sensor attacks. Indeed assume we have received measurements $y^{(0)}, \dots, y^{(T-1)}$ and that we wish to reconstruct the sequence of states $x^{(0)}, \dots, x^{(T-1-\delta)}$. Then this can be done by solving the following optimization problem:

$$\begin{aligned} \text{minimize} \quad & |\hat{K}| + |\hat{L}| \\ \text{subject to} \quad & \text{supp}(\hat{e}^{(t)}) \subseteq \hat{K}, \text{supp}(\hat{w}^{(t)}) \subseteq \hat{L} \\ & y^{(t)} = C\hat{x}^{(t)} + \hat{e}^{(t)} \\ & \hat{x}^{(t+1)} = A\hat{x}^{(t)} + B(u^{(t)} + \hat{w}^{(t)}). \end{aligned} \quad (11)$$

The optimization variables are indicated by a “hat” (e.g., $\hat{x}^{(t)}$, etc.); the other variables (namely, $y^{(t)}$ and $u^{(t)}$) are given. The optimization program above finds the *simplest* possible explanation of the received data $y^{(0)}, \dots, y^{(T-1)}$, i.e., the one with the smallest number of attacked nodes. One can show that if the system is resilient against q attacks (in the sense of definition 2), and if the number of actual attacks is less than q , then the output of the optimization problem above gives the correct sequence of states, i.e., $\hat{x}^{(0)} = x^{(0)}, \dots, \hat{x}^{(T-1-\delta)} = x^{(T-1-\delta)}$.

Unfortunately though, and as we mentioned earlier, solving this optimization problem is hard in general. We can however use the same ideas used previously to relax the decoder by replacing the “ ℓ_0 ” norm (that measures the *cardinality* of the attack set) by an ℓ_1 norm. When considering attacks on actuators in addition to attacks on sensors this relaxation leads to the following tractable decoder:

$$\begin{aligned} \text{minimize} \quad & \sum_{i=1}^p \|\hat{E}_i\|_{\ell_r} + \lambda \sum_{i=1}^m \|\hat{W}_i\|_{\ell_r} \\ \text{subject to} \quad & \hat{E}_i = (\hat{e}_i^{(0)}, \dots, \hat{e}_i^{(T-1)}) \\ & \hat{W}_i = (\hat{w}_i^{(0)}, \dots, \hat{w}_i^{(T-2)}) \\ & y^{(t)} = C\hat{x}^{(t)} + \hat{e}^{(t)} \\ & \hat{x}^{(t+1)} = A\hat{x}^{(t)} + B(u^{(t)} + \hat{w}^{(t)}). \end{aligned} \quad (12)$$

For each i the auxiliary variables $\hat{E}_i \in \mathbb{R}^T$ and $\hat{W}_i \in \mathbb{R}^T$ carry the i 'th components of the attack vectors over the time horizon $t = 0, \dots, T-1$. Thus if $\|\hat{E}_i\|_{\ell_r} = 0$ then $\hat{e}_i^{(t)} = 0$ for all $t = 0, \dots, T-1$ and the i 'th sensor is not attacked, and similarly if $\|\hat{W}_i\|_{\ell_r} = 0$ then the i 'th actuator is not attacked. Now observe

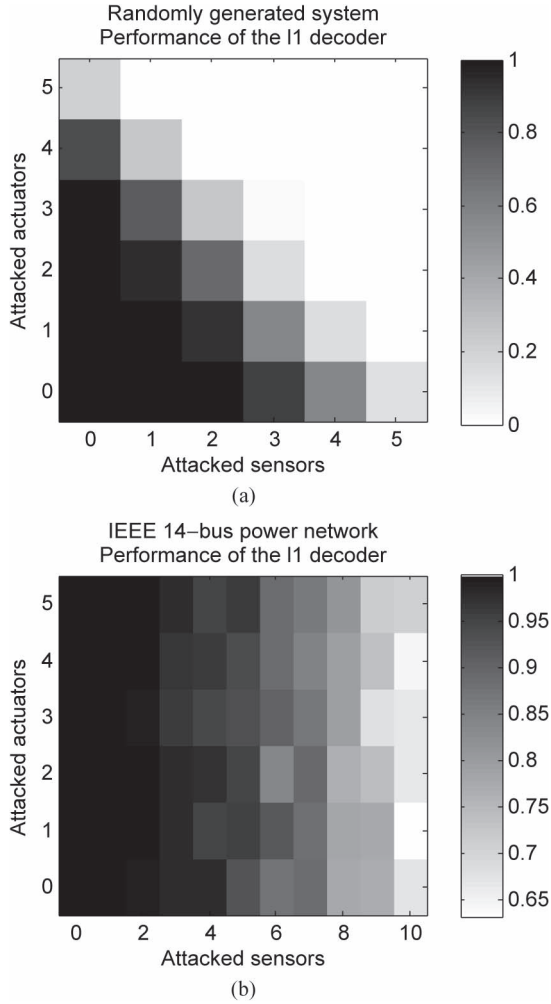


Fig. 4. (Left) Performance of the ℓ_1/ℓ_2 decoder (12) (with constant $\lambda = 10$) on a randomly generated system with $n = 15$ states, $m = 10$ actuators and $p = 10$ sensors. Dark color indicates a high success rate and white color indicates a low success rate. We observe that when the number of attacked sensors and actuators is small enough the decoder correctly recovers the state of the system. Also we remark that the resilience with respect to attacked sensors decreases as the number of attacked actuators increases, and vice-versa. (Right) Performance of the ℓ_1/ℓ_∞ decoder (12) (with $\lambda = 10^{-3}$) on the IEEE 14-bus power network example of Section III-E-2. We observe that when the number of attacked sensors is small enough, the decoder correctly recovers the state of the system, independently of the number of attacked generators.

that the objective function $\sum_{i=1}^p \|\hat{E}_i\|_{\ell_r} + \lambda \sum_{i=1}^m \|\hat{W}_i\|_{\ell_r}$ is nothing but a weighted sum of the ℓ_1 norms of the vectors $(\|\hat{E}_i\|_{\ell_r})_{i=1,\dots,p} \in \mathbb{R}^p$ and $(\|\hat{W}_i\|_{\ell_r})_{i=1,\dots,m} \in \mathbb{R}^m$. Note that we have introduced a tuning parameter λ to control the relative weight between the term corresponding to the attacks on sensors and the term corresponding to the attacks on actuators.

b) Numerical simulations: To illustrate the behavior of the ℓ_1 decoder, we tested it on a synthetic randomly-generated system with $n = 15$ states, $m = 10$ actuators and $p = 10$ sensors.⁶ Fig. 4(a) shows the performance of the decoder as a function of the number of attacked sensors and actuators.

⁶The system was generated in the same way as the example of Section III-E: the entries of A, B, C are iid standard Gaussian, and A was normalized so it has spectral radius 1.

We see that on this example the ℓ_1 decoder correctly recovers the state of the system despite the attacks when the number of attacked sensors and actuators is small enough.

Note that the decoder as given in (12) depends on the choice of the parameter λ . For the simulations of Fig. 4(a) we used the value $\lambda = 10$ which we empirically found to be a suitable value for the system we considered. It would be interesting however to see if there is a simple and systematic way to directly find the best value of λ from the data and the parameters of the system.

We also tested the decoder (12) on the power network example of Section III-E2. Recall that the IEEE 14-bus network we considered is comprised of 5 generators and 14 buses, and is modeled by a linear dynamical system with $2 \times 5 = 10$ states (rotor angle δ_i and frequency $\omega_i = d\delta_i/dt$ for each generator i) and 35 sensors. An attack on an actuator here corresponds to an attack on the mechanical power input to a generator i and is modeled by an additive input w_i affecting the equation governing the frequency ω_i of generator i [31].

For different values of $|L|$ (number of attacked generators), and $|K|$ (number of attacked sensors), we ran the ℓ_1/ℓ_∞ decoder of (12) and we recorded its success rate⁷ over 200 simulations with different initial conditions and attack sets that were randomly generated like in the previous examples of Section III-E2. The results of the simulations are shown in Fig. 4(b). We see that when the number of attacked sensors is small enough, the decoder correctly recovers the state of the system. We also remark that, unlike the previous example of Fig. 4(a), the performance of the decoder is not really affected by the number of attacked generators. This suggests that the system is highly resilient against attacks on the generators since despite these attacks the state of the system can still be correctly recovered from the measurements (when the number of attacked sensors is small).

IV. THE CONTROL PROBLEM WITH OUTPUT-FEEDBACK

In this section we consider general linear control systems with output feedback of the form

$$\begin{aligned} x^{(t+1)} &= Ax^{(t)} + BU^{(t)} \left(y^{(0)}, \dots, y^{(t)} \right) \\ y^{(t)} &= Cx^{(t)} + e^{(t)}. \end{aligned} \quad (13)$$

One of the main questions that we address in this section is to determine whether for a given system (A, B, C) , there exists a control law (i.e., a family $(U^{(t)})_{t=0,1,\dots}$) that drives the state of the system (13) to the origin even if some of the sensors are attacked. Observe that the sensor attacks can affect the control inputs (since the control inputs are function of the $y^{(t)}$'s) which can in turn deviate the state $x^{(t)}$ from its nominal path.

⁷We declare the decoder to be successful after T steps if it correctly recovers the whole sequence of states up to time $T - 1$ (i.e., with a delay of $d = 1$). Indeed, due to the very special structure of the C matrix of the system (the sensors only measure the rotor angles and not the frequencies), it is impossible to reconstruct the state perfectly without delay.

Note that if there were attacks on the actuators then such a stabilizing control law does not exist in general, and that is why we focus only on sensor attacks in this section.

It is clear that if q sensor errors are correctable (in the sense defined in the previous section, i.e., that it is possible to recover the state despite any attacks on q sensors), then one can stabilize the system in the presence of attacks: indeed, one can simply decode the state (since q errors are correctable), and then apply a standard *state* feedback law of the form $u = Kx$, for example.⁸ The main contribution of this section is to show that the converse of this statement is essentially true. More specifically, we show in Theorem 1 that if $(U^{(t)})_{t=0,1,\dots}$ is any feedback law that stabilizes the system (with a fast enough decay) despite attacks on any q sensors, then necessarily q errors are correctable. This theorem shows that one can essentially decouple the problem of estimation and of control in the scenario we consider: in other words, there is no loss of resilience in searching for an output feedback law that is the composition of a decoder with a standard *state* feedback.

A. Some Properties

We start by defining the notion of correctability of q errors for systems with output-feedback control inputs. We will see in particular that it is independent of the feedback law used. Recall that the symbol $E_{q,T}$ denotes the set of attack sequences of length T on any q sensors

$$E_{q,T} = \left\{ \left(e^{(0)}, \dots, e^{(T-1)} \right) \in (\mathbb{R}^p)^T \mid \begin{aligned} &\exists K \subset \{1, \dots, p\}, \text{ with } |K| = q \\ &\text{s.t. } \forall t \in \{0, \dots, T-1\}, \text{supp} \left(e^{(t)} \right) \subset K \end{aligned} \right\}.$$

We also use the notation $y(t, x^{(0)}, e)$ to denote the output at time t of the control system (13) when the initial state is $x^{(0)}$ and for the attack sequence $e \in E_{q,T}$. We now give the definition of correctability of q errors for systems with output-feedback control inputs:

Definition 3: Let a control system of the form (13) be given. We say that q errors are correctable after T steps if there exists a function $\mathcal{D} : (\mathbb{R}^p)^T \rightarrow \mathbb{R}^n$ such that for any $x^{(0)} \in \mathbb{R}^n$ and any attack sequence $e \in E_{q,T}$, we have $\mathcal{D}(y(0, x^{(0)}, e), \dots, y(T-1, x^{(0)}, e)) = x^{(0)}$.

It is not hard to see that, since the systems we consider are linear and since the control inputs only depend on the measurements, the property of correctability of q errors just defined above does not depend on the control law nor on B , and in fact only depends on A and C . Indeed, saying that q errors are not correctable (after T steps) for the controlled system $(A, B, C, (U^{(t)})_{t=0,1,\dots})$ means that there exists $x_a \neq x_b$, and error vectors $e_a, e_b \in E_{q,T}$ such that $y(t, x_a, e_a) = y(t, x_b, e_b)$

⁸Note that the decoders considered in Section III recover the state $x^{(t-T)}$ rather than the current state $x^{(t)}$, where T is the horizon used. Thus if such a decoder is used, one would have to propagate $x^{(t-T)}$ to the current state $x^{(t)}$ using the known inputs before feeding it to the controller.

for all $t = 0, \dots, T-1$. In other words, we have, for all $t \in \{0, \dots, T-1\}$

$$\begin{aligned} CA^t x_a + C[B, AB, \dots, A^{t-1}B] \begin{bmatrix} u_a^{(t-1)} \\ \vdots \\ u_a^{(0)} \end{bmatrix} + e_a^{(t)} \\ = CA^t x_b + C[B, AB, \dots, A^{t-1}B] \begin{bmatrix} u_b^{(t-1)} \\ \vdots \\ u_b^{(0)} \end{bmatrix} + e_b^{(t)} \end{aligned} \quad (14)$$

where $u_a^{(\tau)} = U^{(\tau)}(y(0, x_a, e_a), \dots, y(\tau, x_a, e_a))$ and $u_b^{(\tau)} = U^{(\tau)}(y(0, x_b, e_b), \dots, y(\tau, x_b, e_b))$ for $\tau = 0, \dots, t-1$. Now observe that the terms on the left-hand side and right-hand side of (14) with the control inputs are equal (since $y(s, x_a, e_a) = y(s, x_b, e_b)$ for all s and thus $u_a^{(\tau)} = u_b^{(\tau)}$). Hence the equality (14) is equivalent to saying that for all $t \in \{0, \dots, T-1\}$, we have

$$CA^t x_a + e_a^{(t)} = CA^t x_b + e_b^{(t)}.$$

And this exactly means that q errors are not correctable for (A, C) . This therefore shows that the notion of correctability does not depend on the control law used.

In other words, one can use the conditions developed earlier for correctability of q errors for linear systems with no inputs and apply them to systems with output-feedback control inputs. For example we have that q errors are correctable for the control system (13) if, and only if, $|\text{supp}(Cz) \cup \dots \cup \text{supp}(CA^{T-1}z)| > 2q$ for all $z \neq 0$.

B. Main Result: Separation of Estimation and Control

We are now ready to state our result on separation of estimation and control.

Theorem 1: Let A, B, C be three matrices of appropriate sizes and assume that a control strategy given by the $(U^{(t)})_{t=0,1,\dots}$ is such that: for any $x^{(0)} \in \mathbb{R}^n$ and for any sequence of error vectors $e \in E_{q,T}$, the sequence $(x^{(t)})$ defined by

$$\begin{aligned} x^{(t+1)} &= Ax^{(t)} + BU^{(t)} \left(y^{(0)}, \dots, y^{(t)} \right) \\ y^{(t)} &= Cx^{(t)} + e^{(t)} \end{aligned} \quad (15)$$

satisfies

$$\|x^{(t)}\| \leq \kappa \alpha^t \|x^{(0)}\|$$

where $\kappa > 0$ and where $0 \leq \alpha < 1$ is small enough: $\alpha < \min\{|\lambda| \mid \lambda \text{ eigenvalue of } A\}$. Then necessarily q errors are correctable after n steps.

Proof: We proceed by contradiction. Assume that q errors are not correctable after n steps. Then this means there exists a nonzero initial state $\bar{x} \neq 0$ that is indistinguishable from the initial state 0. In other words, there exist $e_a, e_b \in E_{q,T}$ such that the outputs of the control system (15) in the two different executions:

- 1) $x^{(0)} = \bar{x}$ and $e^{(t)} = e_a^{(t)}$; and
- 2) $x^{(0)} = 0$ and $e^{(t)} = e_b^{(t)}$

are equal for all $t = 0, \dots, n-1$. But by the Cayley-Hamilton theorem, it is not hard to see that the sequences e_a and e_b can

be extended to $t \geq n$ so that the outputs of the system (15) are equal for all $t \geq 0$. Observe now that since the control law $U^{(t)}$ only depends on the outputs, this means that in these two executions, the same sequence of inputs, $u^{(t)}$, will be used.

Furthermore, since we must have in both cases, $\|x^{(t)}\| \leq \kappa\alpha^t\|x^{(0)}\|$, this leads, for the case where $x^{(0)} = 0$, that $x^{(t)} = 0$ for all $t \geq 0$, and so necessarily, $Bu^{(t)} = x^{(t+1)} - Ax^{(t)} = 0$ for all $t \geq 0$. Hence for the first case (when $x^{(0)} = \bar{x}$), the recurrence relation is $x^{(t+1)} = Ax^{(t)}$, which gives $x^{(t)} = A^t\bar{x}$. We now get a contradiction since $x^{(t)}$ should decay at rate of α , but the eigenvalues of A are all strictly larger than α . This completes the proof. ■

Remark: Note that the assumption on the decay rate to be fast enough is necessary; otherwise the result is not true. Indeed, if for example A is already a stable matrix, one cannot deduce anything from the mere existence of a stabilizing control law (since the system is by itself stable!). For a concrete example, take $A = 0.5I$, $B = I$, $C = I$ (note that A is stable). We know from the characterization of the number of correctable errors that even 1 error is not correctable after any number of steps (for example if we take $x = (1, 0, \dots, 0)$, then $|\text{supp}(Cx) \cup \text{supp}(CAx) \cup \dots| = 1 \not\geq 2q$ if $q > 0$). Now if we consider the trivial output feedback law $U^{(t)} = 0$ for all t , the resulting system is of course stable despite any number of attacks (the state evolution is simply $x^{(t+1)} = 0.5x^{(t)}$ and does not even depend on the sensor outputs), but as we just saw one cannot even construct a decoder to correct even 1 error!

V. CONCLUSION

In this paper we considered the problems of estimation and control of linear systems when some of the sensors or actuators are attacked. For the estimation problem we gave a characterization of the number of attacks that can be tolerated so that the state of the system can still be exactly recovered, and we showed how one can increase the resilience of the system by state-feedback while guaranteeing a certain performance. We then showed that there is an explicit (though computationally hard) decoder that can correct the maximal number of attacks. The decoder was then relaxed to obtain a computationally feasible decoding algorithm which we analyzed theoretically in Proposition 6, and which looked promising on numerical simulations. We then considered the problem of designing an output feedback law to stabilize a linear plant where at most q sensors are attacked. Our main result was to show that if such a resilient output-feedback law exists, then necessarily there also exists a decoder that is resilient against q attacks. This shows in particular that there is no loss of resilience in searching for an output-feedback law that is the composition of a decoder with a standard state feedback law.

In our study of the resilience of a system to attacks, we mainly focused on the case of attacks on sensors for the interest of space and also because the results in this case are especially nice and simple to state. One could extend results such as Proposition 2 to the case of attacks on actuators but unfortunately they are not as simple to state. For the ℓ_1 decoder we showed in Section III-F how to extend it to handle both attacks on sensors and actuators.

There are many important open questions which remain unanswered in this paper. For example, the question of constructing an iterative estimator (where the estimate of the state is updated by a simple iterative rule each time a new measurement is received), instead of the one-shot ℓ_1 estimator in this paper, would be interesting in particular from a computational point of view. Another subject of interest is to study the effect of exogenous noise on the performance of the estimator presented in this paper. Also, another interesting question would be to study the performance of the proposed decoders from a structural systems theory point of view, using graph-theoretic concepts. Finally, ideas on how to specialize the techniques proposed here to particular applications, by taking into account structural vulnerabilities (in terms of sets of sensors and actuators attacked) might be of interest.

REFERENCES

- [1] A. Cardenas *et al.*, "Challenges for securing cyber physical systems," in *Workshop Future Directions Cyber-Phys. Syst. Security*, Jul. 2009, DHS. [Online]. Available: <http://chess.eecs.berkeley.edu/pubs/601.html>
- [2] N. Adam, "Workshop on Future Directions in Cyber-Physical Systems Security," Department of Homeland Security (DHS), Tech. Rep., Jan. 2010.
- [3] A. Cárdenas, S. Amin, and S. Sastry, "Research challenges for the security of control systems," in *Proc. 3rd Conf. Hot Topics Security*, 2008, p. 6.
- [4] J. Slay and M. Miller, "Lessons learned from the maroochy water breach," *Critical Infrastructure Protection*, 2007.
- [5] R. McMillan, "Siemens: Stuxnet worm hit industrial systems," *Computer World*, 2010. [Online]. Available: http://www.computerworld.com/s/article/9185419/Siemens_Stuxnet_worm_hit_industrial_systems?taxonomyId=142&pageNumber=1
- [6] M. Massoumnia, G. Verghese, and A. Willsky, "Failure detection and identification," *IEEE Trans. Autom. Control*, vol. 34, no. 3, pp. 316–321, 1989.
- [7] M. Blanke, M. Kinnaert, J. Lunze, and M. Staroswiecki, *Diagnosis and Fault-Tolerant Control*. New York, NY, USA: Springer-Verlag, 2006.
- [8] K. Zhou and J. Doyle, *Essentials of Robust Control*, vol. 104. Englewood Cliffs, NJ, USA: Prentice-Hall, 1998.
- [9] L. Schenato, B. Sinopoli, M. Franceschetti, K. Poolla, and S. Sastry, "Foundations of control and estimation over lossy networks," *Proc. IEEE*, vol. 95, no. 1, pp. 163–187, 2007.
- [10] A. Gupta, C. Langbort, and T. Basar, "Optimal control in the presence of an intelligent jammer with limited actions," in *Proc. 49th IEEE CDC'10*, 2010, pp. 1096–1101.
- [11] F. Pasqualetti, F. Dorfler, and F. Bullo, "Attack detection and identification in cyber-physical systems-Part I: Models and fundamental limitations," *Preprint*, 2012. [Online]. Available: <http://arxiv.org/pdf/1202.6144v1>
- [12] F. Pasqualetti, F. Dorfler, and F. Bullo, "Attack detection and identification in cyber-physical systems-Part II: Centralized and distributed monitor design," *Preprint*, 2012. [Online]. Available: <http://arxiv.org/pdf/1202.6049>
- [13] S. Sundaram, M. Pajic, C. Hadjicostis, R. Mangharam, and G. Pappas, "The wireless control network: Monitoring for malicious behavior," in *Proc. 49th IEEE Conf. Decision Control (CDC'10)*, 2010, pp. 5979–5984.
- [14] S. Sundaram and C. Hadjicostis, "Distributed function calculation via linear iterative strategies in the presence of malicious agents," *IEEE Trans. Autom. Control*, vol. 56, no. 7, pp. 1495–1508, Jul. 2011.
- [15] A. Teixeira, S. Amin, H. Sandberg, K. Johansson, and S. Sastry, "Cyber security analysis of state estimators in electric power systems," in *Proc. 49th IEEE CDC'10*, 2010, pp. 5991–5998.
- [16] E. Candes and T. Tao, "Decoding by linear programming," *IEEE Trans. Inform. Theory*, vol. 51, no. 12, pp. 4203–4215, 2005.
- [17] F. Pasqualetti, F. Dörfler, and F. Bullo, "Cyber-physical attacks in power networks: Models, fundamental limitations and monitor design," *arXiv:1103.2795*, 2011.
- [18] H. Fawzi, P. Tabuada, and S. Diggavi, "Secure state-estimation for dynamical systems under active adversaries," in *Proc. 49th Annu. Allerton Conf. Commun., Control, Comp.*, 2011, pp. 337–344. [Online]. Available: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6120187

- [19] H. Fawzi, P. Tabuada, and S. Diggavi, "Security for control systems under sensor and actuator attacks," in *Proc. IEEE 51st Annu. Conf. Decision Control (CDC)*, 2012, pp. 3412–3417.
- [20] H. Fawzi, "Security and Error-Correction for Linear Systems," M.S. thesis, UCLA, Los Angeles, 2011.
- [21] B. Molinari, "Extended controllability and observability for linear systems," *IEEE Trans. Autom. Control*, vol. 21, no. 1, pp. 136–137, 1976.
- [22] V. Guruswami, J. Lee, and A. Wigderson, "Euclidean sections of ℓ_1^n with sublinear randomness and error-correction over the reals," in *Proc. RAN-DOM'08*, 2008, pp. 444–454. [Online]. Available: http://link.springer.com/chapter/10.1007/978-3-540-85363-3_35
- [23] J. Dion, C. Commault, and J. van der Woude, "Generic properties and control of linear structured systems: A survey," *Automatica*, vol. 39, no. 7, pp. 1125–1144, Jul. 2003.
- [24] A. M. Tillmann and M. E. Pfetsch, "The computational complexity of rip, nsp, related concepts in compressed sensing," *arXiv:1205.2081*, 2012.
- [25] P. Antsaklis and A. Michel, *Linear Systems*. Boston, MA: Birkhauser, 2005.
- [26] Y. Mo and B. Sinopoli, "False data injection attacks in control systems," in *Proc. First Workshop Secure Control Syst.*, 2010. [Online]. Available: https://www.truststc.org/conferences/10/CPSWeek/papers/scs1_paper_7.pdf
- [27] Y. Eldar and H. Bolcskei, "Block-sparsity: Coherence and efficient recovery," in *Proc. IEEE ICASSP'09*, 2009, pp. 2885–2888.
- [28] M. Davenport, M. Duarte, Y. Eldar, and G. Kutyniok, "Introduction to compressed sensing," in *Compressed Sensing: Theory and Applications*. Cambridge, U.K.: Cambridge Univ. Press, 2011, pp. 1–68.
- [29] M. Grant and S. Boyd, CVX: Matlab software for disciplined convex programming, version 1.21. [Online]. Available: <http://cvxr.com/cvx>
- [30] R. Christie, Power systems test case archive, 2000. [Online]. Available: <http://www.ee.washington.edu/research/pstca/>
- [31] F. Pasqualetti, A. Bicchi, and F. Bullo, "A graph-theoretical characterization of power network vulnerabilities," in *Proc. Amer. Control Conf.*, San Francisco, CA, 2011, pp. 3918–3923.



Hamza Fawzi received the Diplôme d'Ingénieur from Mines ParisTech, Paris, France, in 2010, the M.S. degree in electrical engineering from the University of California, Los Angeles, in 2011, and is currently pursuing the Ph.D. degree at the Laboratory for Information and Decision Systems, Massachusetts Institute of Technology, Cambridge, MA, USA.



Paulo Tabuada (SM'07) was born in Lisbon, Portugal. He received the "Licenciatura" degree in aerospace engineering from Instituto Superior Tecnico, Lisbon, Portugal, in 1998 and the Ph.D. degree in electrical and computer engineering from the Institute for Systems and Robotics (a private research institute associated with Instituto Superior Tecnico), Lisbon, Portugal, in 2002.

Between January 2002 and July 2003 he was a Postdoctoral Researcher at the University of Pennsylvania, Philadelphia. After spending three years at the University of Notre Dame, as an Assistant Professor, he joined the Electrical Engineering Department, University of California, Los Angeles, where he established and directs the Cyber-Physical Systems Laboratory. His latest book, on verification and control of hybrid systems, was published by Springer in 2009.

Dr. Tabuada received the NSF CAREER award in 2005, the Donald P. Eckman award in 2009 and the George S. Axelby award in 2011. In 2009 he co-chaired the International Conference Hybrid Systems: Computation and Control (HSCC'09) and in 2012 he was program co-chair for the 3rd IFAC Workshop on Distributed Estimation and Control in Networked Systems (NecSys'12). He also served on the editorial board of the *IEEE Embedded Systems Letters* and the *IEEE TRANSACTIONS ON AUTOMATIC CONTROL*.



Suhas Diggavi (S'93–M'98–F'13) received the B. Tech. degree in electrical engineering from the Indian Institute of Technology, Delhi, and the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, USA, in 1998.

After completing his Ph.D., he was a Principal Member Technical Staff in the Information Sciences Center, AT&T Shannon Laboratories, Florham Park, NJ, USA. After that he was on the faculty of the School of Computer and Communication Sciences, EPFL, where he directed the Laboratory for Information and Communication Systems (LICOS). He is currently a Professor, in the Department of Electrical Engineering, University of California, Los Angeles, CA, USA, where he directs the Information Theory and Systems laboratory. His research interests include wireless network information theory, wireless networking systems, network data compression and network algorithms.

Dr. Diggavi received the 2013 IEEE Information Theory Society & Communications Society Joint Paper Award, the 2006 IEEE Donald Fink prize paper award, 2005 IEEE Vehicular Technology Conference best paper award, the Okawa foundation research award and is a Fellow of the IEEE. He has served on the editorial board for Transactions on Information Theory, ACM/IEEE Transactions on Networking and IEEE. IEEE Communication Letters, a guest editor for IEEE Selected Topics in Signal Processing and was the Technical Program Co-Chair for 2012 IEEE Information Theory Workshop. He has 8 issued patents.