Reachable Sets of Hidden CPS Sensor Attacks: Analysis and Synthesis Tools

Carlos Murguia * Nathan van de Wouw ** Justin Ruths ***

* Singapore University of Technology and Design, Center for Research in Cyber Security (iTrust). e-mail: murguia_rendon@sutd.edu.sg
** Eindhoven University of Technology, Mechanical Engineering Department, Eindhoven, The Netherlands; Delft Center for Systems and Control, Delft University of Technology, Delft, The Netherlands; Department of Civil, Environmental and Geo-Engineering, University of Minnesota, Minneapolis, USA.
** University of Texas at Dallas, Departments of Mechanical and Systems Engineering. e-mail: j Ruths@utdallas.edu

Abstract: For given system dynamics, control structure, and fault/attack detection procedure, we provide mathematical tools—in terms of Linear Matrix Inequalities (LMIs)—for characterizing and minimizing the set of states that sensor attacks can induce in the system while keeping the alarm rate of the fault detector sufficiently close to its false alarm rate in the attack-free case. This quantifies the attack’s potential impact when it is constrained to stay hidden from the detector. Simulation results are presented to illustrate the performance of our tools.

© 2017, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.

Keywords: cyber physical systems; security; stochastic systems; model-based fault detectors; reachable sets.

1. INTRODUCTION

During the past decades, scientific and technological advances have greatly improved the performance of control systems. From heating/cooling devices in our homes to cruise-control in our cars, to robotics in manufacturing centers. However, these new technologies have also led to vulnerabilities of some our most critical infrastructures—e.g., power, water, transportation. Advances in communication and computing have given rise to adversaries with enhanced and adaptive capabilities. Depending on their resources, attackers may deteriorate the functionality of systems even while remaining undetected. Therefore, designing efficient attack detection schemes and attack-robust control systems is of key importance for guaranteeing the safety and proper operation of critical systems. Tools from sequential analysis and fault detection have to be adapted to deal with the systematic, strategic, and persistent nature of attacks. These new challenges have attracted the attention of many researchers in the control and computer science communities, see e.g., (Cárdenas et al., 2011; Pasqualetti et al., 2013; Mo et al., 2010; Kwon et al., 2013; Miao et al., 2014; Bai et al., 2015), and references therein.

* This work was supported by the National Research Foundation (NRF), Prime Minister’s Office, Singapore, under its National Cybersecurity R&D Programme (Award No. NRF2014NCR-NCR001-40) and administered by the National Cybersecurity R&D Directorate.

This paper addresses the problem of characterizing the impact of sensor attacks on Linear Time-Invariant (LTI) stochastic systems when fault detection techniques are deployed for attack detection, see, e.g., (Chen and Patton, 1999; Kyriakides and Polycarpou, 2015; Pasqualetti et al., 2013; Cárdenas et al., 2011). The main idea behind fault detection theory is the use of an estimator to forecast the evolution of the system dynamics. If the difference between measurements and the estimation is larger than expected, there may be a fault in or an attack on the system. The complete fault detection scheme consists of two parts: the estimator and a change detection procedure (used to decide whether the estimator and the system are sufficiently different to declare the presence of faults/attacks). We use observers, (Luenberger, 1966; Nijmeijer and Mareels, 1997), as estimators; and the chi-squared procedure for change detection (Gustafsson, 2000).

The main contribution of the paper is a set of mathematical tools for quantifying and minimizing the impact of sensor attacks on the system dynamics. This effect depends on where, when, and how, the attack occurs in the system. To capture this, we model attacks as additive perturbations affecting sensors measurements (Kyriakides and Polycarpou, 2015; Pasqualetti et al., 2013; Cárdenas et al., 2011). These perturbations are propagated to the system dynamics through output-based controllers. To quantify the effect of attacks, we need to introduce some measure of impact. However, because malicious adversaries may launch any arbitrary attack, we need a measure which can
capture all possible states that the attacker can induce in the system, given how it accesses the dynamics (i.e., through the control scheme by tampering with sensor measurements). We propose to use the reachable set of the attack (Boyd et al., 1994) as our measure of impact. We remark that all detectors produce false alarms – due to the stochastic nature of the system and measurement noise. We refer to attacks that are able to maintain the alarm rate of the detector equivalent to its attack-free false alarm rate as hidden attacks (since they make the behavior of the detector of the attacked system indistinguishable from its behavior without attacks). Contrast hidden attacks with zero alarm attacks, which ensure that no alarms are raised during an attack by maintaining the detection statistic just beneath its detection threshold, see, e.g., (Murguia and Ruths, 2016a,b; Giraldo et al., 2016; Cardenas et al., 2009). In this work, we characterize the reachable sets that hidden attacks can induce in the system. We refer to these sets as the hidden reachable sets of the attack sequence. In general, it is intractable to compute these sets exactly. Instead, for given system dynamics, control structure, and attack detection procedure, we derive ellipsoidal bounds on the hidden reachable sets using Linear Matrix Inequalities (LMIs), (Boyd et al., 1994). We provide synthesis tools for minimizing these bounds (minimizing thus the hidden reachable sets) by properly redesigning controllers and detectors. There are a few results in this direction already; chiefly the work in (Mo and Sinopoli, 2016), where a recursive algorithm to compute ellipsoidal inner and outer bounds of hidden reachable sets is provided. We assess our analysis tools are more constructive and easier to implement, which we achieve by reformulating the problem of computing the ellipsoidal bounds as a convex optimization problem in terms of LMIs. Another aspect that takes our work beyond the analysis results of (Mo and Sinopoli, 2016) is that we also provide synthesis tools for minimizing the hidden reachable sets by redesigning controllers and detectors.

2. SYSTEM DESCRIPTION & ATTACK DETECTION

We study LTI stochastic systems of the form:

\[
\begin{align*}
    x(t_{k+1}) &= Fx(t_k) + Gu(t_k) + v(t_k), \\
    y(t_k) &= Cx(t_k) + \eta(t_k),
\end{align*}
\]

with sampling time-instants \( t_k \), \( k \in \mathbb{N} \), state \( x \in \mathbb{R}^n \), measured output \( y \in \mathbb{R}^m \), control input \( u \in \mathbb{R}^l \), matrices \( F, G \), and \( C \) of appropriate dimensions, and i.i.d. multivariate zero-mean Gaussian noises \( v \in \mathbb{R}^n \) and \( \eta \in \mathbb{R}^m \) with covariance matrices \( R_1 \in \mathbb{R}^{n \times n}, R_1 \geq 0 \), and \( R_2 \in \mathbb{R}^{m \times m}, R_2 \geq 0 \), respectively. The initial state \( x(t_1) \) is assumed to be a Gaussian random vector with covariance matrix \( R_0 \in \mathbb{R}^{n \times n}, R_0 \geq 0 \). The processes \( v(t_k), \eta(t_k), k \in \mathbb{N} \) and the initial condition \( x(t_1) \) are mutually independent. It is assumed that \( (F,G) \) is stabilizable and \( (F,C) \) is detectable. At the time-instants \( t_k, k \in \mathbb{N} \), the output of the process \( y(t_k) \) is sampled and transmitted over a communication network. The received output \( \bar{y}(t_k) \) is used to compute control actions \( u(t_k) \) which are sent back to the process, see Fig. 1. The complete control-loop is assumed to be performed instantaneously, i.e., the sampling, transmission, and arrival time-instants are supposed to be equal. In this paper, we focus on attacks on sensor measurements. That is, in between transmission and reception of sensor data, an attacker may replace the signals coming from the sensors to the controller, see Fig. 1. After each transmission and reception, the attacked output \( \bar{y} \) takes the form:

\[
\bar{y}(t_k) := y(t_k) + \delta(t_k) = Cx(t_k) + \eta(t_k) + \delta(t_k),
\]

where \( \delta(t_k) \in \mathbb{R}^m \) denotes additive sensor attacks. Denote \( x_k := x(t_k), u_k := u(t_k), v_k := v(t_k), \bar{y}(t_k) := \bar{y}(t_k), \eta_k := \eta(t_k), \) and \( \delta_k := \delta(t_k) \). Using this new notation, the attacked system is written in the following compact form:

\[
\begin{align*}
    x_{k+1} &= Fx_k + Gu_k + v_k, \\
    \bar{y}_k &= Cx_k + \eta_k + \delta_k.
\end{align*}
\]

2.1 Observer

To estimate the state of the process, we use the observer

\[
\hat{x}_{k+1} = F\hat{x}_k + Gu_k + L(\bar{y}_k - C\hat{x}_k),
\]

with estimated state \( \hat{x}_k \in \mathbb{R}^n, \hat{x}_1 := E[x(t_1)] \), where \( E[.] \) denotes expectation, and observer gain matrix \( L \in \mathbb{R}^{n \times m} \). Define the estimation error \( e_k := x_k - \hat{x}_k \). Given the system dynamics (3) and the observer (4), the estimation error is governed by the following difference equation

\[
e_{k+1} = (F - LC)e_k + v_k - L\eta_k - L\delta_k.
\]

The pair \((F,C)\) is detectable; hence, the observer gain \( L \) can be selected such that \((F - LC)\) is Schur. Moreover, under detectability of \((F,C)\), the covariance matrix \( P_k := E[e_ke_k^T] \) converges to steady state (in the absence of attacks) in the sense that \( \lim_{k \to \infty} P_k = P \) exists, see Aström and Wittemark (1997). For \( \delta_k = 0 \) and given \( L \) (such that \((F - LC)\) is Schur), it can be verified that the asymptotic covariance matrix \( P = \lim_{k \to \infty} P_k \) is given by the solution \( P \) of the following Lyapunov equation:

\[
(F - LC)(F - LC)^T - P + R_1 + LR_2L^T = 0,
\]

where \( 0 \) denotes the zero matrix of appropriate dimensions. It is assumed that the system has reached steady state before an attack occurs.

2.2 Residuals and Hypothesis Testing

Attacks can be regarded as intentionally induced faults in the system. Then, it is reasonable to use existing fault detection techniques to identify sensor attacks. The main idea behind fault detection theory is the use of an estimator to forecast the evolution of the system. If the difference between what it is measured and the estimation is larger than expected, there may be a fault in or attack on the system. Although the notion of residuals and model-based detectors is now routine in the fault detection literature, the primary focus has been on detecting and isolating faults with specific structures (e.g., constant biases in
Proceedings of the 20th IFAC World Congress

Design parameter: which evolves according to the difference equation:

\[ r_k := y_k - Ce_k + \eta_k + \delta_k, \]

which evolves according to the difference equation:

\[
\begin{align*}
E[r_{k+1}] &= CE[r_{k+1}] + E[\eta_{k+1}] = 0_{m \times 1}, \\
\Sigma &:= E[r_{k+1}r_{k+1}^T] = CPC^T + R_2.
\end{align*}
\]

It is assumed that \( \Sigma \in \mathbb{R}^{m \times m} \) is positive definite. For this residual, we identify two hypotheses to be tested: \( H_0 \) the normal mode (no attacks) and \( H_1 \) the faulty mode (with faults/attacks). Then, we have

\[
H_0: \begin{cases} 
E[r_k] = 0_{m \times 1}, \\
E[r_k r_k^T] = \Sigma,
\end{cases} \quad H_1: \begin{cases} 
E[r_k] \neq 0_{m \times 1}, \text{or} \\
E[r_k r_k^T] \neq \Sigma,
\end{cases}
\]

where \( 0_{m \times 1} \) denotes an \( m \)-dimensional vector composed of zeros only. In this manuscript, we use the chi-squared procedure for examining the residual and subsequently distinguishing between \( H_0 \) and \( H_1 \).

### 2.3 Distance Measure and Chi-squared Procedure

The input to any detection procedure is a distance measure \( z_k \in \mathbb{R} \), \( k \in \mathbb{N} \), i.e., a measure of how deviated the estimator is from the sensor measurements. We employ distance measures any time we test to distinguish between \( H_0 \) and \( H_1 \). The chi-squared procedure uses a quadratic form as distance measure to test for substantial variations in the covariance of the error between the measured output and the estimate. Consider the residual sequence \( r_k \), and its covariance matrix \( \Sigma \), (10).

**Chi-squared procedure:**

If \( z_k := r_k^T \Sigma^{-1} r_k > \alpha \), then \( \hat{k} = k \).

**Design parameter:** threshold \( \alpha \in \mathbb{R}_{>0} \).

**Output:** alarm time(s) \( \hat{k} \).

Therefore, the procedure is designed so that alarms are triggered if \( z_k \) exceeds the threshold \( \alpha \). The normalization by \( \Sigma^{-1} \) makes setting the value of the threshold \( \alpha \) system independent. This quadratic expression leads to a sum of the squares of \( m \) normally distributed random variables which implies that the distance measure \( z_k \) follows a chi-squared distribution with \( m \) degrees of freedom, see, e.g., Ross (2006) for details.

### 2.4 False Alarms

The occurrence of an alarm in the chi-squared when there are no attacks to the CPS is referred to as a false alarm. Operators need to tune this false alarm rate depending on the application. To do this, the threshold \( \alpha \) must be selected to fulfill a desired false alarm rate \( \mathcal{A}^* \). Let \( \mathcal{A} \in [0, 1] \) denote the false alarm rate of the chi-squared procedure defined as the expected proportion of observations which are false alarms, i.e., \( \mathcal{A} := \text{pr}[\delta_k \geq \alpha] \), where \( \text{pr}[-] \) denotes probability, see van Dobben de Bruyn (1968) and Adams et al. (1992).

**Proposition 1.** [Murguia and Roths (2016b)]. Assume that there are no attacks on the system and consider the chi-squared procedure (11) with residual \( r_k \sim \mathcal{N}(0, \Sigma) \) and threshold \( \alpha \in \mathbb{R}_{>0} \). Let \( \alpha = \alpha^* := 2P^{-1}(\frac{\alpha}{2}, 1, -\mathcal{A}^*) \), where \( P^{-1}(-, \cdot) \) denotes the inverse regularized lower incomplete gamma function (see Ross (2006)), then \( \mathcal{A} = \mathcal{A}^* \).

### 2.5 Output Feedback Controller

We consider observer-based output feedback controllers of the form:

\[
\hat{x}_k := K\hat{x}_k,
\]

where \( \hat{x}_k \in \mathbb{R}^n \) is the state of the observer (4) and \( K \in \mathbb{R}^{l \times n} \) denotes the control matrix. The pair \((F, G)\) is stabilizable; hence, the matrix \( K \) can be selected such that \((F + GK)\) is Schur. The closed-loop system (3),(4),(12) can be written in terms of the estimation error \( e_k = x_k - \hat{x}_k \):

\[
\begin{align*}
\hat{x}_{k+1} &= (F + GK)x_k - GK e_k + v_k, \\
\hat{e}_{k+1} &= (F - LC)e_k + v_k - L\eta_k - L\delta_k.
\end{align*}
\]

Note that the attack sequence \( \delta_k \) directly affects the estimation error dynamics, whereas the effect of the attack on the system dynamics is through the interconnection term \( GK e_k \) due to the control structure.

### 3. Hidden Reachable Sets

In this section, we provide tools for quantifying (for given \( L \) and \( K \)) and minimizing (by selecting \( L \) and \( K \)) the impact of the attack sequence \( \delta_k \) on both the estimation error and the state of the system when the chi-squared procedure is used for attack detection. We are interested in attacks that can change the false alarm rate \( \mathcal{A} \) of the detector by a small amount, say \( \epsilon \in \mathbb{R}_{>0} \), i.e., \( \mathcal{A} < \mathcal{A} + \epsilon \), where \( \mathcal{A} \) denotes the alarm rate under the attacker’s action. This class of attacks is what we refer to as hidden attacks. Here, we characterize ellipsoidal bounds on the set of states that hidden attacks can induce in the system. In particular, we provide tools based on Linear Matrix Inequalities (LMIs) for computing ellipsoidal bounds on the reachable set of the attack sequence \( \delta_k \) given the system dynamics, the control strategy, the chi-squared procedure, and the bias \( \epsilon \) on the false alarm rate \( \mathcal{A} \).

Define the stacked noise vector \( \omega_k := (v_k^T, \eta_k^T)^T \). Following Mo and Sinopoli (2016), we re-write the estimation error as \( e_k = e_k^{\omega_k} + e_k^{\delta_k} \), where \( e_k^{\omega_k} \) denotes the part of \( e_k \) that is driven by noise and \( e_k^{\delta_k} \) is the part driven by the attack sequence. Similarly, write the state of the system as \( x_k = x_k^{\omega_k} + x_k^{\delta_k} \) and the residual as \( r_k = r_k^{\omega_k} + r_k^{\delta_k} \). Using this new notation, because the system and the observer are linear, we can write the closed-loop dynamics (13) as follows:
Proceedings of the 20th IFAC World Congress

and the distance measure as \( z_k = \| \Sigma^{-\frac{1}{2}} (r_{k, \omega k} + r_{k, \delta k}) \|_2^2 \), where \( \Sigma^{-\frac{1}{2}} \) denotes the symmetric squared root matrix of \( \Sigma^{-1} \). Note that, in the absence of attacks, \( r_{k, \omega k} \) and \( r_k \) have the same asymptotic distribution. Hence, the contribution of attacks to the alarm rate of the detector is solely determined by \( r_{k, \delta k} \) generated by (15). Moreover, using the triangle inequality, we can write the following

\[
|z_k| = |\Sigma^{-\frac{1}{2}} (r_{k, \omega k} + r_{k, \delta k})| \leq (|\Sigma^{-\frac{1}{2}} r_{k, \omega k}| + |\Sigma^{-\frac{1}{2}} r_{k, \delta k}|)^2,
\]

then, if the attack sequence is restricted to satisfy

\[
|\Sigma^{-\frac{1}{2}} r_{k, \delta k}|^2 \leq |\Sigma^{-\frac{1}{2}} (C \xi_{k, \delta} + \delta_k)|^2 \leq \kappa, \quad \forall k \in \mathbb{N}, (16)
\]

for some \( \kappa \in \mathbb{R}_{\geq 0} \), it is intuitive to think that \( \bar{A} < A + \epsilon \) for some \( \epsilon \in \mathbb{R}_{\geq 0} \), i.e., the alarm rate under the attacker’s action, \( \bar{A} \), is biased from the false alarm rate, \( A \), by \( \epsilon \). This observation is slightly formalized in the following theorem, which is slightly modified from Mo and Sinopoli (2016).

Theorem 1. (Mo and Sinopoli (2016)). Consider the chi-squared procedure (11) with threshold \( \alpha \in \mathbb{R}_{>0} \). Let inequality (16) be satisfied for some \( \kappa \in \{0, \sqrt{\alpha}\} \); then

\[
\bar{A} \leq 1 - P\left( \frac{m}{n} \left( \frac{\sqrt{\alpha} - \alpha}{2} \right)^2 \right), \quad (17)
\]

where \( P(\cdot, \cdot) \) denotes the regularized lower incomplete gamma function (see Ross (2006)). Moreover

\[
1 - \lim_{\alpha \to 0^+} P\left( \frac{m}{n} \left( \frac{\sqrt{\alpha} - \alpha}{2} \right)^2 \right) = A. \quad (18)
\]

Therefore, by selecting \( \kappa \) sufficiently small, the attacker can make \( \bar{A} \) arbitrarily close to \( A \). This complicates the operator’s task to distinguish between the attacked system and the system without attacks. The set of feasible attack sequences that the opponent can launch while satisfying (17) can be written as the following constrained control problem on \( \delta_k \):

\[
\delta_k \in \mathbb{R}^m \quad \delta_k = (F + GK)x_{k+1, \delta} - GK x_{k, \omega k},
\]

\[
(\Sigma^{-\frac{1}{2}} (C \xi_{k, \delta} + \delta_k))^2 \leq \kappa, \quad \forall k \in \mathbb{N}, \quad (19)
\]

We are interested in the state trajectories that the attacker can induce in the system restricted to satisfy (19). To this end, we introduce the notion of a hidden reachable set, \( \mathcal{R}_\kappa \), defined as follows.

\[
\mathcal{R}_\kappa := \{ x_{k, \delta}, x_{k, \omega k} \in \mathbb{R}^n \mid x_{1, \delta} = 0, x_{2, \delta} \leq \delta, x_{k, \omega k} = 0 \text{ for } k \neq 1 \text{ and } x_{k, \omega k} \text{ satisfy (19)} \}.
\]

In general, it is analytically intractable to compute \( \mathcal{R}_\kappa \) exactly. Instead, using LMI s, for some positive definite matrices \( P_\kappa, P_\omega \in \mathbb{R}^{n \times n} \), we derive outer ellipsoidal bounds of the form \( \mathcal{E}_\kappa = \{ \delta \in \mathbb{R}^m \mid \Sigma_{\delta}^{-\frac{1}{2}} P_\delta \delta \leq 1 \} \) and \( \mathcal{E}_x = \{ x_{k, \delta} \in \mathbb{R}^m \mid x_{k, \omega k} P x_{k, \delta} \leq 1 \} \) containing \( \mathcal{R}_\kappa \). Note that the \( x_{k, \delta} \) dynamics in (19) does not depend on \( x_{k, \delta} \). Thus, we first compute \( \mathcal{E}_x \) and then analyze how it propagates to \( \mathcal{E}_\kappa \). The following result is used to compute these ellipsoids.

Lemma 1. [That et al. (2013)]. Let \( V_k \) be a positive definite function, \( V_1 = 0 \), and \( \mathcal{Q}_k \mathcal{Q}_k^T \leq \kappa \in \mathbb{R}_{>0} \). If there exists a constant \( a \in (0, 1) \) such that

\[
V_{k+1} - a V_k - \frac{1}{a} \mathcal{Q}_k^T \mathcal{Q}_k \leq 0, \quad \forall k \in \mathbb{N}, \quad (20)
\]

then, \( V_k \leq 1 \).

Define \( \mathcal{Q}_k := -\frac{1}{a} \mathcal{Q}_k \mathcal{Q}_k^T \), then, from (19), we can write the hidden reachable set of the estimation error, \( \mathcal{R}_e \), as follows.

\[
\mathcal{R}_e = \{ x_{k, \delta} \in \mathbb{R}^n \mid x_{k+1, \delta} = F x_{k, \delta} - L \delta_k, e_{1, \delta} = 0, \mathcal{Q}_k \mathcal{Q}_k^T \leq \kappa, \quad \forall k \in \mathbb{N} \}. \quad (21)
\]

Note that if for some \( k = k^* \), \( e_{k^*, \delta} \neq 0 \) and \( \mathcal{Q}_k^T \mathcal{Q}_k > 0 \), then \( \mathcal{R}_e \) is unbounded if the system is open-loop unstable. If \( \mathcal{Q}_k^T \mathcal{Q}_k \leq 0 \) then \( \mathcal{R}_e \) may or may not diverge to infinity depending on algebraic and geometric multiplicities of the eigenvalues with unit modulus of \( F \) (a known fact from stability of LTI systems), see Aström and Wittenmark (1997) for details.

Theorem 2. For given \( F \), observer gain \( L \), and residual covariance matrix \( \mathcal{S} \), consider the set \( \mathcal{R}_e \) in (21). If there exists a positive definite matrix \( P_\kappa \in \mathbb{R}^{n \times n} \) and \( \alpha \in (0, 1) \) satisfying the following matrix inequality:

\[
\begin{bmatrix}
a P_\kappa & F^T P_\kappa & 0 & 0 \\
0 & -P_\kappa L \mathcal{S}_2 & 0 & 0 \\
0 & 0 & I & 0 \\
0 & 0 & 0 & I
\end{bmatrix} \geq 0 \quad (22)
\]

then, \( \mathcal{R}_e \subseteq \mathcal{E}_e \), i.e., the hidden reachable set is contained in the ellipsoid \( \mathcal{E}_e = \{ \delta \in \mathbb{R}^m \mid x_{k, \delta} \in P_\epsilon \mathcal{E}_x \} \).

Proof: For a positive definite matrix \( P_\kappa \in \mathbb{R}^{n \times n} \), consider the function \( V_k := e_{k, \delta}^T P_\kappa e_{k, \delta} \), then, from (21), inequality (20) takes the form:

\[
\begin{bmatrix}
\mathcal{Q}_k^T \mathcal{Q}_k & -P_\kappa L \mathcal{S}_2 \\
0 & -P_\kappa L \mathcal{S}_2 & 0 & 0 \\
0 & 0 & I & 0 \\
0 & 0 & 0 & I
\end{bmatrix} \mathcal{Q}_k^T \mathcal{Q}_k \leq 0,
\]

where \( \vartheta := (e_{k, \delta}^T \mathcal{Q}_k^T \mathcal{Q}_k)^T \). The above inequality is satisfied if and only if \( \mathcal{Q}_e \geq 0 \). Matrix \( \mathcal{Q}_e \) can be written as the Schur complement of a higher dimensional matrix \( \mathcal{Q}_e' \); hence, \( \mathcal{Q}_e \geq 0 \iff \mathcal{Q}_e' \geq 0 \), i.e.,

\[
\begin{bmatrix}
a P_\kappa & 0 & F^T P_\kappa & 0 \\
0 & \frac{1}{a} I & -P_\kappa L \mathcal{S}_2 & 0 \\
0 & 0 & P_\kappa & 0 \\
0 & 0 & 0 & I
\end{bmatrix} \geq 0 \quad (23)
\]

Finally, inequality (22) follows from (23) after the congruence transformation:

\[
\begin{bmatrix}
I & 0 & 0 & 0 \\
0 & I & 0 & 0 \\
0 & 0 & I & 0 \\
0 & 0 & 0 & I
\end{bmatrix} \mathcal{Q}_e \mathcal{Q}_e^T \begin{bmatrix}
I & 0 & 0 & 0 \\
0 & I & 0 & 0 \\
0 & 0 & I & 0 \\
0 & 0 & 0 & I
\end{bmatrix} \geq 0
\]

The assertion follows now from Lemma 1.
proportional to the volume of $e_{k}^{T}P_{e}c_{k,\delta k} = 1$. This is formally stated in the following corollary of Theorem 2, see Boyd et al. (1994) for further details.

**Corollary 1.** For given matrices $(F, L, \Sigma)$ and $a \in (0, 1)$, the solution $P_{e}$ of the following convex optimization:

$$
\begin{align*}
\min_{P_{e}} & \quad - \log \det P_{e}, \\
\text{s.t.} & \quad P_{e} > 0 \text{ and (22),}
\end{align*}
$$

minimizes the volume of the ellipsoid $\mathcal{E}_{e}$ bounding $\mathcal{R}_{e}$.

See Löfberg (2004) for an example of how to solve (24) using YALMIP.

As we now move toward designing $L$ to minimize the ellipsoids, we note that as $||L|| \to 0$, the volume of the ellipsoid $\mathcal{E}_{e}$ goes to zero because the attack-dependent term in (21), $L\Sigma^{k}\xi_{k}$, vanishes. To make this concrete, without any other considered criteria, the observer gain leading to the minimum volume ellipsoid is trivially given by $L = 0$. While this is effective at eliminating the impact of the attacker, it implies that we discard the observer altogether and, therefore, forfeit any ability to build a reliable estimate of the system. If we impose a performance criteria that the observer must satisfy in the attack-free case (e.g., convergence speed, noise-output gain, or minimum asymptotic variance), it has to be added into the minimization problem (24) so as to minimize the volume of $\mathcal{E}_{e}$ while still achieving the observer performance in the attack-free case. For completeness, in the following proposition, we provide an LMI criteria for ensuring that the $H_{\infty}$ gain from the noise to the residual $r_{k}$ in (8) is less than or equal to some $\gamma \in \mathbb{R}_{>0}$. Then, using this criteria and Theorem 2, we provide a synthesis tool for minimizing $\mathcal{E}_{e}$ while ensuring a desired $H_{\infty}$ performance in the attack-free case.

**Proposition 2.** For given matrices $(F, C, L)$, if there exists a positive definite matrix $P_{e} \in \mathbb{R}^{n \times n}$ and $\gamma \in \mathbb{R}_{>0}$ satisfying the following matrix inequality:

$$
\begin{align*}
P_{e} & \quad 0 \quad 0 \quad (F - LC)^{T}P_{e} C^{T} \\
0 & \quad \gamma^{2}I \quad 0 \quad -L^{T}P_{e} I \\
0 & \quad 0 \quad \gamma^{2}I \quad P_{e} C^{T} (F - LC) - P_{e} L P_{e} \quad I \\
C & \quad I \quad 0 \quad 0 \quad I 
\end{align*}
$$

then, the $H_{\infty}$ gain from the noise $\omega_{k} = (\eta_{k}^{T}, v_{k}^{T})^{T}$ to the residual $r_{k} = C_{e_{k}} + \eta_{k}$ of the estimation error dynamics (8) is less than or equal to $\gamma$.

The proof of Proposition 2 is omitted here due to the page limit. However, this is a standard result and details about the proof can be found in, e.g., Scherer and Weiland (2000) and references therein.

**Remark 1.** Note that the attack sequence $\delta_{k}$ enters the estimation error dynamics in the same manner as the sensor noise $\eta_{k}$ (see (8)). It follows that, in this particular configuration, minimizing the influence of sensor noise (e.g., by using $H_{\infty}$ techniques) would also reduce the effect of sensor attacks on the estimation error dynamics. This would tend to reduce the size of the hidden reachable sets but it would not necessarily lead to minimal ones. See Figure 5 in Section 4.

In the following corollary of Theorem 2 and Proposition 2, we formulate the optimization problem for designing the observer gain $L$ such that the volume of the ellipsoid $\mathcal{E}_{e}$ is minimized and a desired $H_{\infty}$ performance is achieved in the attack-free case.

**Corollary 2.** For given $(F, C, \Sigma)$, $a \in (0, 1)$, and $\gamma \in \mathbb{R}_{>0}$, if there exist matrices $P_{e} \in \mathbb{R}^{n \times n}$ and $M \in \mathbb{R}^{n \times m}$ solution to the following convex optimization:

$$
\begin{align*}
\min_{P_{e}, M} & \quad - \log \det P_{e}, \\
\text{s.t.} & \quad P_{e} > 0, \quad \begin{bmatrix}
\alpha P_{e} & F^{T}P_{e} & 0 & 0 \\
F P_{e} & -M\Sigma^{k} & 0 & 0 \\
0 & -\Sigma^{k}M^{T} & \frac{1}{\gamma^{2}}I & 0 \\
0 & 0 & 0 & I
\end{bmatrix} \geq 0, \quad \begin{bmatrix}
P_{e} & 0 & 0 & 0 \\
0 & \gamma^{2}I & 0 & -M^{T} I \\
0 & 0 & \gamma^{2}I & P_{e} 0 \\
C & I & 0 & 0 & I
\end{bmatrix} \geq 0,
\end{align*}
$$

then, the observer gain $L = P_{e}^{-1}M$ minimizes the volume of the ellipsoid $\mathcal{E}_{e}$ bounding $\mathcal{R}_{e}$ and guarantees that the $H_{\infty}$ gain from the noise $\omega_{k}$ to the residual $r_{k}$ of (8) is less than or equal to $\gamma$ in the attack-free case.

**Proof:** This follows from Theorem 2 and Proposition 2 and the linearizing change of variables $M = P_{e}L$.

Next, once we have an ellipsoid $\mathcal{E}_{e}$ such that $\mathcal{R}_{e} \subseteq \mathcal{E}_{e}$, from (19), we can write the attacker’s reachable states, $\mathcal{R}_{a}$, as:

$$
\mathcal{R}_{a} = \left\{ x_{k,\delta_{k}} \in \mathbb{R}^{n} \mid \begin{bmatrix}
x_{k+1,\delta_{k}} = (F + G\xi_{k})x_{k,\delta_{k}} \\
-GKP_{e}^{-1}\xi_{k} \\
x_{k,0} = 0, \quad \xi_{k} \leq 1, \quad \forall k \in \mathbb{N},
\end{bmatrix} \right\}.
$$

where $\xi_{k} := P_{e}c_{k,\delta_{k}}$ and the matrix $P_{e} \in \mathbb{R}^{n \times n}$ is such that $P_{e} = \bar{P}_{e}^{T}P_{e}$ (Cholesky factorization). Then, analogous to Theorem 2, we have the following result for computing ellipsoidal bounds on $\mathcal{R}_{a}$.

**Theorem 3.** For given matrices $(F, G)$, controller gain $K$, and positive definite matrix $P_{e}$, consider the set $\mathcal{R}_{a}$ in (27). If there exists a positive definite matrix $P_{a} \in \mathbb{R}^{n \times n}$ and $b \in (0, 1)$ satisfying the following matrix inequality:

$$
\begin{align*}
bP_{a} & \quad (F + G)^{T}P_{a} \\
P_{a}(F + G) & \quad -P_{a}GP_{a}^{-1} \quad 0 \\
0 & \quad -(GP_{a}^{-1})^{T}P_{a} \quad (1 - b)I \\
0 & \quad 0 & 0 & I
\end{align*}
$$

then, $\mathcal{R}_{a} \subseteq \mathcal{E}_{e}$, i.e., the hidden reachable set is contained in the ellipsoid $\mathcal{E}_{e} = \left\{ x_{k,\delta_{k}} \in \mathbb{R}^{n} \mid x_{k,\delta_{k}}^{T}P_{e}x_{k,\delta_{k}} \leq 1 \right\}$.

The proof of Theorem 3 follows the same lines as the proof of Theorem 2 and it is omitted here. As before, if an ellipsoid with minimal volume is required, we minimize $\det P_{a}^{-1}$ subject to (28). This is formally stated in the following corollary of Theorem 3.

**Corollary 3.** For given $(F, G, K, P_{e})$ and $b \in (0, 1)$ the solution $P_{a}$ of the following convex optimization:

$$
\begin{align*}
\min_{P_{a}} & \quad - \log \det P_{a}, \\
\text{s.t.} & \quad P_{a} > 0 \text{ and (28),}
\end{align*}
$$

minimizes the volume of the ellipsoid $\mathcal{E}_{e}$ bounding $\mathcal{R}_{a}$.

**Remark 2.** Similar to the case with the observer gain $L$ and $\mathcal{E}_{e}$, note that as $||K|| \to 0$, the volume of $\mathcal{E}_{e}$ tends to zero.
Consider the closed-loop system (3),(4),(12) with matrices:

\[ F = \begin{pmatrix} 0.84 & 0.23 \\ -0.47 & 0.12 \end{pmatrix}, \quad G = \begin{pmatrix} 0.07 \\ 0.23 \end{pmatrix}, \quad C = (1 \ 0), \]

\[ K = (-1.85 \ -0.96), \quad L = \begin{pmatrix} 1.16 \\ -0.69 \end{pmatrix}, \]

\[ R_1 = \begin{pmatrix} 0.45 & -0.11 \\ -0.11 & 0.20 \end{pmatrix}, \quad R_0 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad R_2 = 1, \]

\[ \Sigma = 3.26. \]

Using Proposition 2, the observer gain \( L \) is designed such that the \( H_\infty \) gain from the noise to the residual \( r_k \) of (8) is less than or equal to \( \gamma = 1.86 \) in the attack-free case. For \( \alpha = \{6.63, 3.84, 2.70, 1.64\} \) and corresponding \( A = \{0.01, 0.05, 0.10, 0.20\} \), as a function of \( \alpha \), Figure 2 depicts the upper bound on the alarm rate \( \bar{A} \) in (17), under hidden attacks. For a false alarm rate \( A = 0.10 \) (\( \alpha = 2.70 \)), we select \( \kappa = \{0.09, 0.17, 0.24\} \) which leads to, correspondingly, \( A \leq \{0.12, 0.14, 0.16\} \), i.e., increments of 2\% on \( A \). For these values of \( \kappa \) and \( a = 0.65 \) (this value of \( a \) leads to minimal volume ellipsoids), in Figure 3, we depict the ellipsoidal bounds \( E_\kappa \) through application of Corollary 2 to design the optimal observer gain.

Using Proposition 2, the observer gain \( L \) is designed such that the \( H_\infty \) gain from the noise to the residual \( r_k \) of (8) is less than or equal to \( \gamma = 1.86 \) in the attack-free case. For \( \alpha = \{6.63, 3.84, 2.70, 1.64\} \) and corresponding \( A = \{0.01, 0.05, 0.10, 0.20\} \), as a function of \( \alpha \), Figure 2 depicts the upper bound on the alarm rate \( \bar{A} \) in (17), under hidden attacks. For a false alarm rate \( A = 0.10 \) (\( \alpha = 2.70 \)), we select \( \kappa = \{0.09, 0.17, 0.24\} \) which leads to, correspondingly, \( A \leq \{0.12, 0.14, 0.16\} \), i.e., increments of 2\% on \( A \). For these values of \( \kappa \) and \( a = 0.65 \) (this value of \( a \) leads to minimal volume ellipsoids), in Figure 3, we depict the ellipsoidal bounds \( E_\kappa \) through application of Corollary 2 to design the optimal observer gain.
5. CONCLUSION

In this paper, for a class of discrete-time LTI systems subject to sensor/actuator noise, we have provided tools for quantifying and minimizing the negative impact of sensor attacks on the system performance given how the opponent accesses the dynamics (i.e., through the controller by tampering with sensor measurements). We have proposed to use the reachable set as a measure of the impact of an attack given a chosen detection method. For given system dynamics, control structure, and attack detection scheme, we have derived ellipsoidal bounds on these reachable sets using LMIs. Then, we have provided synthesis tools for minimizing these bounds (minimizing thus the reachable set) by properly redesigning controllers and detectors.

REFERENCES


