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Online Distributed Interdependency Estimation with Partial Information Sharing

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Abstract— **Infrastructures are becoming more and more interoperable, while stakeholders are not aware of the overall behavior. In order achieve a global awareness, in this paper the need for cooperation is stressed; however, due to security and commercial issues, only few, very abstract data can be shared. In this paper a distributed interdependency estimation framework is provided, able to grant a minimal disclosure of data among the infrastructures, while letting operators make decisions with a wider perspective. The final objective of this research is to define an effective framework for the problem at hand, and then implement and validate an on-line distributed state/interdependency estimator within the EU IST MICIE project.**

I. INTRODUCTION

In order to improve the security of Critical Infrastructures (CIs), isolated approaches are not sufficient; there is then the need that the operators become rapidly aware of the state of other infrastructures, and then cooperate to minimize the threats. To this end a very first step is the definition of interdependency models. Based on the Input-Output Inoperability approach [1], in this paper a model with a deeper insight view is proposed, decomposing each infrastructure in its *components* and *services*. There is, then, the need to define an on-line, distributed, tool able to quantify possible threats and prompt the operators. The main obstacle, however, is that usually the control centers are not interconnected, and the policies and countermeasures adopted by different stakeholders are often limited as a consequence of their narrow point of view.

Indeed, the problem is relevant because there is the need to share information and policies among the infrastructure's owners and, at the same time, this shared information must be partial and limited, for security, commercial and technological issues. Moreover, there is the need to design a consistent and reliable state estimator; in fact, as exposed above, an on-line tool must necessarily be a *distributed* tool, and many synchronization issues may arise, due to the delays introduced by the local elaboration and transmission of the information and due to the partiality of the information being exchanged. The design and implementation of a tool with the above characteristics is the main objective of the EU IST project MICIE (http://www.micie.eu). In order to solve the major issues of this problem, in [4] the authors provide a first solution in the case of linear models with complete information. In this paper a further step is done by letting each distributed tool exchange only the state of the *services*. This step introduces non-trivial synchronization issues; however, basing on the iteration of *consensus* strategies, a common view is reached. The paper is organized as follows: in Section II a simple interdependency model able to take into account both low-level and high abstract representations of the interdependent infrastructures is introduced; in section III a framework for the online distributed interdependency estimation based on such model is introduced, while in section IV some considerations about future directions are exposed.

II. INTERDEPENDENCY MODELING

In the literature, many approaches have been introduced in order to address the challenging complexity of interdependency modeling; in this paper, however, we will refer to the simple, yet powerful, *Input-Output Inoperability Model* (IIM) [1], because it is linear, and then particularly suitable for the definition of an initial distributed state estimation framework. Such abstract model will be further extended, decomposing each infrastructure in its *components* and *services*.

A. IIM Interdependency Model

The IIM model main objective is to represent within a simple framework the global effects of negative events in an highly interdependent scenario. The *inoperability* of each infrastructure is introduced, as the inability (in percentage) to correctly operate. The inoperability of each infrastructure is assumed to linearly depend on the inoperability of the others and on external failures. In its discrete fashion the IIM model is described by the following system [1]:

$$\mathbf{x}(k+1) = \mathbf{A}\,\mathbf{x}(k) + \mathbf{c}(k) \tag{1}$$

where $\mathbf{x}$ represents the vector of the inoperability of each infrastructure and $\mathbf{c}$ is the vector of induced failures. Such an approach is very simple and powerful; however it is very abstract and does not take into account the internal structure of each CI.

B. Component-Service IIM Interdependency Model

Any critical infrastructure is a complex, geographically dispersed cluster of systems; there is then the need to decompose each infrastructure into a web of interconnected entities, whose links may easily cross the bounds of the single infrastructure.

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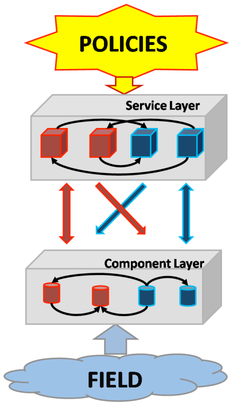

Fig. 1. Component-Service IIM model. The System of Systems is decomposed into a component layer and a service layer; besides their interdependencies, the components rely on the inputs coming from the field, while the services depend on the policies of human operators and stakeholders.

In the literature such a bottom-up approach, namely *Agent Based Modeling and Simulation* (ABMS)[2] is gaining momentum rapidly. From such a point of view, it is possible to have a better view of the behavior of each system and its parts, and model interdependencies with a finer grain.

However a mere in-the-small approach is not sufficient to represent the complex mechanisms that may arise in highly interdependent scenarios. The resulting System of Systems, in fact, is not just a sum of components, its behavior depends on some functional entities (i.e. services, policies, etc.) that are not easy to model with a pure reductionistic vision. There is then the need to consider different, yet interrelated levels of abstractions; this is the goal of *Mixed Holistic-Reductionistic* approaches [3].

In order to provide a simple framework for the interconnection of distributed state estimators with partial information, let's introduce the *services* as functional entities able to provide an aggregate resource to other services or components, even belonging to a different infrastructure.

The *Component-Service* IIM model is therefore in the form:

$$\begin{bmatrix}\mathbf{x_s}(k+1)\\ \mathbf{x_c}(k+1)\end{bmatrix} = \begin{bmatrix}\mathbf{A_{ss}} & \mathbf{A_{cs}}\\ \mathbf{A_{sc}} & \mathbf{A_{cc}}\end{bmatrix}\begin{bmatrix}\mathbf{x_s}(k)\\ \mathbf{x_c}(k)\end{bmatrix} + \begin{bmatrix}\mathbf{c_s}(k)\\ \mathbf{c_c}(k)\end{bmatrix} \tag{2}$$

Where the state vector of the overall system is decomposed into n_c components ($\mathbf{x_c}$) and n_s services ($\mathbf{x_s}$). The $\mathbf{A}$ matrix of the standard IIM model is extended in order to consider the interaction among services ($\mathbf{A_{ss}}$), among components ($\mathbf{A_{cc}}$), the effects of components on services ($\mathbf{A_{cs}}$) and vice versa ($\mathbf{A_{sc}}$). Note that the only constrain of the proposed modeling framework is that a component may influence only services belonging to its infrastructure; therefore $\mathbf{A_{cs}}$ is a block diagonal matrix in the form:

$$\mathbf{A_{cs}} = diag\{\mathbf{A_{c_i,s_i}}\}; \forall i = 1, \cdots n \tag{3}$$

Where $\mathbf{A_{c_i,s_i}}$ represents the effects of the components of the i-th infrastructure on its services. The external cause of failure $\mathbf{c}$ is also extended in order to consider the induced failures on components ($\mathbf{c_c}$) and the effects of external events on services ($\mathbf{c_s}$). Note that, while $\mathbf{c_c}$ is the representation of the negative inputs coming from the field, $\mathbf{c_s}$ represents the effects of policies and management actions on services (i.e. suspension, maintenance, etc..). The resulting model is depicted in Figure 1.

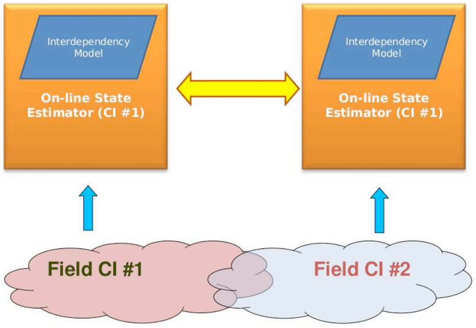

Fig. 2. Example of Distributed Interdependency Estimators with partial information sharing; the black arrows represent the exchange of the quality of services required during the consensus procedure.

III. ON-LINE DISTRIBUTED RISK PREDICTION

In order to obtain a global awareness on the state of the overall system of system, there is the need to consider multiple distributed tools with the *same* shared model; however each tool will receive only the inputs coming from its particular field, while the model will rely on the policies of the particular stakeholder. Due to the different inputs, each tool will provide a different evolution of the state of the overall system; therefore there is the need to connect them and share as many information as possible; to this end we chose to let the tools exchange only the state of their services, masking the underlying behavior of their components (see Figure 2). Within the proposed interdependency estimation system the $i-th$ tool behaves as follows:

1) Based on the actual state $x^i(k) = [x^i_s(k), x^i_c(k)]^T$ and on the inputs $c^i_s(k)$, $c^i_c(k)$ a *prediction* Π^i
$$\Pi^i = \{x^i(k+1), \cdots, x^i(k+m)\}$$
of the evolution of the overall system is generated, where each step corresponds to time interval of T_s.
2) If the prediction highlights a change in the state of some service, a *consensus* procedure is performed, until each tool converges to the maximum possible inoperability value of services $\hat{x}_s(k+1)$.
3) The state is updated according to $\hat{x}_s(k+1)$ and the prediction is also updated.
4) When T_s is reached the actual state becomes $x^i(k+1)$, inputs $c^i_s(k+1)$ and $c^i_c(k+1)$ are considered and step 1 is iterated.

It is worth to notice that, although each tool may perform a different prediction, it computes the state of the overall system, including the other infrastructures. Let T_p be the time required for each of the m prediction steps, while T_c is time required for the consensus procedure; the only time constraint of the proposed interdependency estimation system is therefore:

$$2mT_p + T_c \leq T_s \tag{4}$$

The above time constraint can be easily satisfied, considering that typically infrastructure dynamics are relatively slow, while compared with other dynamic systems; therefore it is possible to chose a T_s big enough to grant the correct functioning of the system, while allowing many prediction steps. In the next subsection the consensus procedure adopted will be detailed.

A. *Consensus Procedure*

Let $G(V, E, A, \mathbf{X})$ be a dynamic network composed of n nodes (V), some edges (E), non-negative edge weights (A) and n dynamic agents, whose dynamic is, in the discrete form, $\mathbf{X}(w+1) = F(\mathbf{X}(w), \mathbf{U}(w))$.

Note that the above dynamic system is not directly related to the dynamic of each estimator; in fact $\mathbf{X}(w)$ represents the overall *consensus* state over the network (i.e. the set of prediction steps $\{x_s^1(k+1), \ldots, x_s^n(k+1)\}$ of each estimator), while X_i is the state of the single agent (i.e. the single prediction step $x_s^i(k+1)$); $\{U_1, \ldots, U_n\}$ is the set of inputs applied to agents.

Let $\chi : R^n \rightarrow R$ be a function of $X_1, \ldots, X_n$. The χ-*consensus problem* [5] is a distributed way to calculate $\chi\big(\mathbf{X}(0)\big)$ by applying inputs U_i that only depend on the values of agent i and its neighbors. A *protocol* is defined as:

$$U_i(w) = \gamma_i(X_{j_1}(w), \ldots, X_{j_{m_i}(w)}) \tag{5}$$

Where $j_1, \ldots, j_{m_i} \in N(i)$, the neighborhood of i.

The χ-consensus problem was proved to have solution [6] if and only if there exist a *directed spanning tree* from each node to each other.

We are interested in the *max-consensus*, where each agent converges to the maximum value. The max-consensus dynamic for the $i-th$ agent is in the form:

$$X_i(w+1) = max\big(X_i(w), U_i(w)\big) \tag{6}$$

The problem was proved to have a solution[5] if the following protocol is adopted:

$$U_i(w) = max_{j \in N(i)}\big(X_j(w)\big) \tag{7}$$

Note that, whatever the topology is, if a solution exists, it is reached in n steps or less; therefore $T_c \leq nT_w$, where T_w is the time required for a consensus step.

In the next subsection a little but significant case study is exposed.

B. *Case Study*

Let's consider two different infrastructures, each composed of two components and two services. The dynamic matrix of each system is therefore an 8×8 matrix. A simulation of 30 time steps was performed, letting an external failure of 0.1 affect the first component of the first infrastructure from $k = 5$ and an external failure of 0.4 affect the first component of the second infrastructure from $k = 15$. In Figure 3 the inoperability of the four services is plotted; black stars and crosses represent, respectively, the prediction of the first and second tools when the corresponding input begins to affect components, while red empty boxes represent the predictions of both estimators, when each consensus procedure is executed and the consensus is reached.

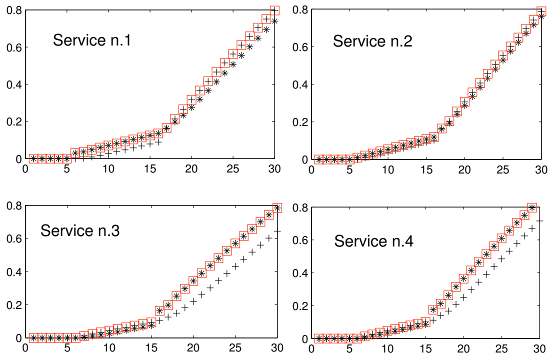

Fig. 3. For each service the isolated prediction of both infrastructures (black stars and crosses) and the consensus (red boxes) reached are plotted.

IV. CONCLUSIONS AND FUTURE WORK

In this paper the problem of on-line distributed interdependency estimation with partial information sharing has been addressed in the case of a simple, linear interdependency model. The proposed framework is very general, and does not depend on the particular interdependency model adopted. Future work will concern the implementation of a real tool based on a complex interdependency model, that will be validated on a real scenario, within the EU IST MICIE project.

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REFERENCES

[1] Y. Haimes and P. Jiang, Leontief-based Model of Risk in Complex Interconnected Infrastructures, *Journal of Infrastructure Systems*, pp. 1–12, 2001

[2] E.Casalicchio, E.Galli, S.Tucci "Federated Agent Based Modeling and Simulation: an Approach for Complex Critical Systems Analysis", 22nd Workshop on Principles of Advanced and Distributed Simulation, 2008. PADS. 3-6 June 2008 Page(s):147 - 147

[3] S. De Porcellinis, G. Oliva, S. Panzieri and R.o Setola, A Holistic-Reductionistic Approach for Modeling Interdependencies, Critical Infrastructure Protection III, M. Papa and S. Shenoi eds., Springer, pp. 215-227, 2009.

[4] A. Gasparri, G. Oliva and S. Panzieri, On the distributed synchronization of on-line IIM Interdependency Models, Proceedings of the 7th IEEE International Conference on Industrial Informatics, Cardiff (UK), June, 2009.

[5] R. Olfati-Saber and R. M. Murray, Consensus Problems in Networks of Agents with Switching Topology and Time-Delays, IEEE Transactions on In Automatic Control, IEEE Transactions on, Vol. 49, No. 9. (2004), pp. 1520-1533.

[6] R- Olfati-Saber, J. A. Fax and R. M. Murray, Consensus and cooperation in networked multi-agent systems, Proceedings of the IEEE, 2007.