Designing Multi-agent Systems for Resilient Engineering Systems

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Abstract. Our modern life has grown to depend on many and nearly ubiquitous large complex engineering systems. Many disciplines now seemingly ask the same question: "In the face of assumed disruption, to what degree will these systems continue to perform and when will they bounce back to normal operation". This presentation argues that multi-agent systems (MAS), as decentralized and intelligent control systems, have an indispensable role to play in enabling the overall resilience of the combined cyber-physical engineering system. To that effect, it first draws from recently published work that provides measures of resilience for large flexible engineering systems. These measures define the system's actual & latent resilience as it goes through physical disruptions. The role of a multi-agent system is then introduced so as to intelligently bring about reconfigurations that restore the system performance back to its original level. Naturally, the implementation of such a multi-agent system requires a distributed architecture. To this effect, the recent literature has used the quantitative resilience measures to distill a set of principles that design resilience into the multi-agent system. These are specifically discussed in the context of production systems and power grids. The presentation concludes with several avenues for advancing multi-agent systems to support resilient engineering systems.

1 Introduction

Our modern life has grown to depend on many and nearly ubiquitous large complex engineering systems [24]. Transportation, water distribution, electric power, natural gas, healthcare, manufacturing and food supply are but a few. These systems are characterized by an intricate web of interactions within themselves [17] but also between each other [25]. Our heavy reliance on these systems coupled with a growing recognition that disruptions and failures; be they natural or man-made; unintentional or malicious; are inevitable. Therefore, in recent years, many disciplines have seemingly come to ask the same question: "How *resilient* are these systems?" Said differently, in the face of assumed disruption, to what degree will these systems continue to perform and when will they be able to bounce back to normal operation [21]. Furthermore, the major disruptions of 9/11, the 2003 Northeastern Blackout, and Hurricanes Katrina and Sandy have caused numerous agencies [3,14,28] to make resilient engineering systems a policy goal.

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2 Static Resilience Measures in Engineering Systems

Given the growing importance of designing resilient engineering systems, the literature has stressed the need for formal quantitative definitions, frameworks and measures [3–5,13,16,21,23,29,30]. While many works measure resilience as an output in response to a disruption as an input, ultimately such approaches effectively treat the physical system as a "black-box" that does not necessarily shed light as to *why* a particular disruption leads to a particular change in performance[]. Many other works approach resilience from a graph theoretic perspective where nodes represent physical locations and edges represent their interconnections [1,2,6,15,18–20,22,26,27,30]. And yet such works neglect the natural functional *heterogeneity* found in many engineering systems. More recently, a set of static resiliece measures have been developed on the basis of Axiomatic Design for Large Flexible Engineering Systems (LFES) where the system function and form are succinctly captured in a LFES knowledge base [8,9,11]. These measures explicitly consider the presence of sequence dependent and sequence independent constraints, and the possibility of multi-valued service paths. They also distinguish between actual and latent resilience where the former considers the drop in performance due to a disruption and the latter measures how the overall system "health" has degraded. In all, these resilience measures allow for heterogeneous function, form, and operands to support a wide class of engineering systems.

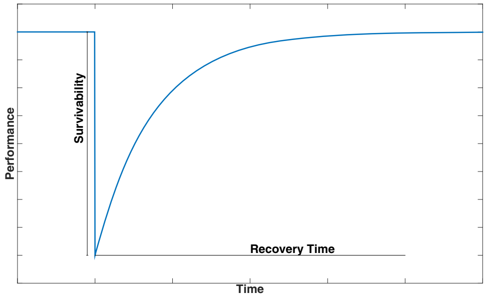

Fig. 1. Conceptual Representation of Resilient Performance

3 Enabling Dynamic Resilience with Multi-agent Systems

Once resilience measures for the physical engineering system have been established, the attention shifts to enabling grater dynamic resilience with multi-agent systems. Such a MAS constitutes a decentralized control system. It is decentralized so to continue operation as one or more parts of the system suffer disruption. It is intelligent in that it can make decisions to reorganize and reconfigure the physical system in response to measurements of system structure *and* performance. Consequently, the MAS (like other control systems) must be designed specifically for the restrictions imposed by the structure and behavior of the physical system.

4 Multi-agent System Design Principles

From this foundation of resilience measurement and the specific characteristics of physical systems that multi-agent system design principles may be developed. The recent literature has followed such a process and provides such design principles for multi-agent systems in power systems [7, 10] and production systems [12]. As both systems may be classified as large flexible engineering systems, they have several design principles in common (restated here with application neutral terminology).

Principle 1. *Application of Independence Axiom: The agent architecture must be explicitly described in terms of the physical system's structural degrees of freedom.*

Principle 2. *Existence of Physical Agents: As a decision-making/control system, the multi-agent system must maintain a 1-to-1 relationship with the set of physical capabilities that* **exist** *in the system.*

Principle 3. *Functional Heterogeneity: The structural degrees of freedom within the agent architecture must respect the heterogeneity of capabilities found within the physical system be they stochastic or deterministic processes or their various types: transformation or transportation.*

Principle 4. *Physical Aggregation: The agent architecture must reflect the physical aggregation of the objects that they represent.*

Principle 5. *Availability: The agent architecture must explicitly model the potential for sequence independent constraints that impede the* availability *of any given structural degree of freedom.*

Principle 6. *Interaction: The agent architecture must contain agent interactions along the minimal set of physical sequence-dependent constraints (i.e. nearest neighbor interactions).*

Principle 7. *Maximum Reconfiguration Potential: Aside from the minimal set of physical sequence-dependent constraints, the agent architecture should avoid introducing any further agent interactions (which may impose further constraints).*

Principle 8. *Scope of Physical Agents: Agents' scope and boundaries should be aligned with their corresponding physical resources and their associated structural degrees of freedom.*

Principle 9. *Encapsulation: Physical system information should be placed in the agent corresponding to the physical entity that it describes.*

These nine design principles are common to production and power systems and are likely to find application in other large flexible engineering systems. That said, each type of LFES has its unique characteristics that customize the MAS design. In production systems, the system operands (i.e. the products & delivered services) are generally quite complex in their own right and require significant informatic description. Managing such heterogeneous information either within the product (in the form of "intelligent products") or amongst the resources that operate on them is a central challenge and directly affects system reconfiguration. Therefore, for production systems, an additional principle is added:

Principle 10. *Reconfiguration Method: The same reconfiguration process can require significantly different effort (measured in time, cost, or energy) depending on the method used to conduct the reconfiguration (and not just the reconfigured resources).*

Power systems are distinguished by the many time scales in their dynamics. Naturally, power system operation & control techniques are specifically tailored to one or more of these time scales. Therefore, for power systems, several MAS design principles are added to address these dynamic characteristics:

Principle 11. *Scope of Physical System Model & Decision Making: The physical system model must describe the physical system behavior at all time scales for which resilient decision-making/control is required. These time scales are described by characteristic frequencies for continuous dynamics and characteristic times for discrete (pseudo-steady-state) processes.*

Principle 12. *Temporal Scope of Execution Agent/Real-time Controller: The characteristic frequencies in the physical system model must be controlled by at least one execution agent/real-time controller capable of making decisions 5x faster than the fastest characteristic frequency.*

Principle 13. *Temporal Scope of Coordination Agent: A coordination agent may not take decisions any faster than 5x slower than the slowest characteristic frequency in the physical system model.*

Principle 14. *Equivalence of Agent Hierarchy & Time Scale Separation: If the physical system model has two or more characteristic frequencies or times that are (mathematically proven or practically assumed to be) independent then the associated agent may be divided into an equal number of hierarchical agents each responsible for decision-making/control for the associated characteristic frequency or time.*

Together, these MAS design principles can help to support resilience in large complex engineering systems. The MAS itself is decentralized and therefore should be able to continue operation in spite of disruption,

5 Conclusion and Future Work

This extended abstract summarizes the presentation given at HoloMAS 2015 where it is further detailed with the underlying mathematics and practical examples. In all, the presentation draws together several recent research contributions in resilience measurement and multi-agent system design. Because the design principles are based upon the resilience measures, they directly support quantitatively driven design decisions as the MAS is developed and is likely to support resilience in many types of complex engineering systems. The production and power system cases further illustrate the need for methods to customize MAS design to their respective application domain.

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