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Resilience-based System Importance Measures for System-of-Systems

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Abstract

Systems-of-systems (SoS) like the air transportation system and missile defense are gaining increasing attention in both the academic and practitioner communities. This research investigates one crucial aspect of SoSs: their ability to recover from disruptions, or their *resilience*. We develop a family of system importance measures (SIMs) that rank the constituent systems based on their impact on the overall SoS performance. The SIMs address some of the major weaknesses that have prevented researchers from identifying a single resilience metric. While trade-space analyses are standard practice in systems engineering, conducting trades on SoS resilience is difficult because, to date, no reliable and consistent metrics have been developed for SoS resilience. Some metrics have been proposed, but these measures assume homogenous networks, thus ignoring one of the key features of SoSs: the combination of heterogeneous systems (e.g., airports and aircraft) to achieve a common goal (e.g., transport). Instead of focusing on an overall metric, the set of SIMs provides designers with specific information on where an SoS is lacking resilience (or has excess resilience) and hence on where improvements are needed (or where downgrades are possible).

Keywords: Resilience, system-of-systems, importance measures

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1. Introduction

All systems are subject to change over their lifetimes. Resilience is the ability of a system to survive and recover from these changes. Implementing resilience is a challenging task because it is highly context-dependent. Systems may be resilient to certain types of disturbances but vulnerable to others. Long-lasting systems, such as infrastructure networks (e.g., energy, transportation, or communications), may initially be resilient to certain disruptions, but as time passes after systems are fielded, changes in the operating environment may make the networks less resilient to both old and new types of threats. Once a failure occurs, resilience is the inherent ability of a system to *survive* and *recover* from this disturbance. And so, resilience is represented as a combination of survivability and recoverability, as shown in Fig. 1. This notional representation is widely used in the literature[1,2,3] to depict the fundamental ideas behind resilience. While it appears easy to represent resilience conceptually, it is much harder to define, assess, and design resilient systems.

A system-of-systems (SoS) is a large-scale integrated network of systems that are heterogeneous and independently operable on their own, but collaborate for a common goal. For example, the national air space (NAS) and the national highway systems are SoSs. While trade-space analyses are standard practice in systems engineering, conducting trades on SoS resilience is difficult because, to date, no reliable and consistent metrics have been developed for SoS resilience. Several metrics have been proposed, but these measures assume homogenous networks, ignoring one of the key features of SoS: the combination of heterogeneous systems (e.g., airports and aircraft) to achieve a common goal (e.g., transport). Rather than attempting to create a single metric that glosses over the complexities of an SoS, we present here a family of System Importance Measures (SIMs) that capture different aspects of SoS resilience. Analogous to component importance measures in reliability theory, the SIMs provide a way to rank or prioritize the constituent systems of an SoS based on different threats. Specifically, these SIMs provide analysts and designers with informative guidance on where an SoS is lacking resilience (or has excess resilience) and hence on where improvements are needed (or where downgrades are possible).

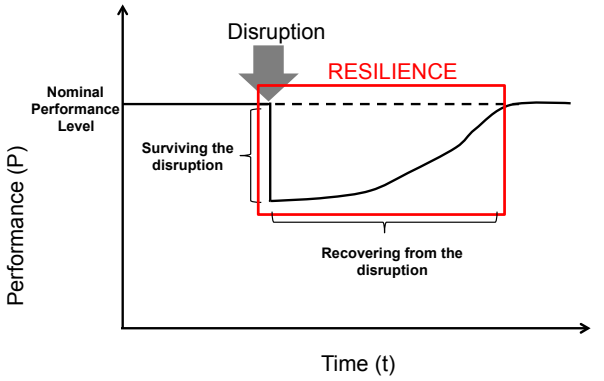

Fig. 1. Notional SoS resilience following a disruption

The remainder of this paper is organized as follows: Section 2 describes two System Importance Measures (SIMs) and presents the mathematical formulation behind these metrics. Section 3 demonstrates the use of these two SIMs with illustrative examples. Section 4 presents two additional System Importance Metrics. And, finally Section 5 concludes the paper.

2. System Importance Measures

Measuring resilience is a critical first step in any framework that aims at addressing or improving resilience. However, establishing a single, all-encompassing resilience metric will be challenging, if not impossible. Since a two-dimensional representation of resilience (see Fig. 1) is necessary to capture the main aspects of this attribute, a single metric to measure resilience could be insufficient. Given the two dimensions (time and performance), there will always exist cases where a single-dimensional metric will yield the same result for two different curves. For