Preventing Failures of Smart Human-Centric Ecosystems

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Abstract

Smart Human-centric Ecosystems (*SHEs*), like smart cities, emerge from the co-existence of heterogeneous systems with independently defined specifications. *SHEs* may fail despite the correct behavior of the systems that comprise the *SHE*, yet current approaches overlook the critical need of ensuring the reliability of *SHEs*.

Our main goal is to ensure the reliability of *SHEs* by testing, predicting and ultimately preventing failures in *SHEs*. We propose (i) a clear and precise definition of the quality of *SHEs* in terms of healthiness and failures, (ii) a transformer-autoencoder anomaly detection approach to predict *SHE* failures, (iii) an approach to prevent *SHE* failures and restore the normal state of the *SHE*, and (iv), a multi-agent architecture for Digital Twins (*DTs*) of *SHEs*.

CCS Concepts

• Software and its engineering → Ultra-large-scale systems; **Software testing and debugging**; **• Computing methodologies → Anomaly detection**.

Keywords

Smart Human-centric Ecosystems, Digital Twins, Failure Prediction, Autoencoders

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1 Research Problem

We aim to improve the reliability of Smart Human-centric Ecosystems (*SHEs*), that El Moussa *et al.* characterize as *'multifaceted systems that emerge from the composition of independently-operated and autonomous systems with smart functionalities and that evolve over time'* [22]. The individual components that comprise a *SHE* raise new challenges that derive from the distinctive characteristics of *SHEs*: (i) *Autonomy:* The components of a *SHE* are heterogeneous, with a high degree of operational autonomy; (ii) *Implicit interactions:* The components of a *SHE* implicitly interact with each other in a shared environment; (iii) *Implicit contradictions:* The components of a *SHE* may have contradicting requirements, which may lead to unexpected behaviors and failures [22]. These characteristics challenge both the traditional notion of correctness, defined as compliance with specifications, and the replication of *SHEs* behaviors in controlled environments. *SHEs* cannot be fully deployed on testbeds in advance, and exhaustive real-world testing is infeasible. Thus, Digital Twins (*DTs*) [15] are essential to test *SHEs*.

Recent studies agree that *SHE* failures are unavoidable [13], may occur independently of the correctness of the comprising systems [9], and escape classic approaches to correctness [22]. Sommerville *et al.* [25] well exemplify the distinctive nature of *SHE* failures with the Flash Crash, the U.S. equity markets crash of May 6, 2010, an exceptional stock market crash that caused a temporary loss of about 800 billion U.S. dollars of market value, the cause of which *'cannot be attributed to a software bug, but rather to a combination of interactions that implicitly led to an unforeseeable scenario'* [9, 17]. The ultimate goal of this Ph.D. is to define a framework for preventing *SHE* failures.

2 Related Work

SHEs are studied since the late nineties as *virtual systems of systems* [19], *ultra-large scale systems* [13], *large-scale complex IT systems* [25], and *cyber-physical systems* [5]. El Moussa *et al.* [22] capture the architectural complexity, the heterogeneous nature, the presence of smart functionalities, and the dynamic behavior of *SHEs*. Hurrah *et al.* [14] further characterize *SHEs*, stressing the cross-cutting role of human-centeredness.

Several studies show that failures in *SHEs* are inevitable [5, 22, 25]. However, existing solutions fall short in addressing the complexity and dynamics of *SHE* failures, as they primarily focus on offline testing of individual components rather than on the emergent behavior of the whole *SHE* in production. Cioroaica *et al.* present a platform for simulating complex interactions among the components of cyber-physical systems, to ensure reliability and performance of automotive *SHEs* [5], discuss *DTs* for evaluating trust in collaborative systems in real-time scenarios [7], and address the challenge of ensuring trustworthiness in open ecosystems where systems of varying origins collaborate [4, 6, 8]. Cioroaica *et al.* 's work focuses on the trustworthiness of the individual components, rather than on the reliability of the *SHE* as a whole. Batool *et al.* [2] propose the integration of Internet of Things (IoT) and Artificial Neural Networks (ANNs) to address potential challenges in smart city ecosystems, by focusing on the optimization of smart city functions. Trimananda *et al.* [26] present IoTCheck, a tool that identifies conflicts among different applications of a smart home by continuously checking the specifications of the individual systems.

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Manikas *et al.* [20] introduce the concept of *health* to characterize the intuitive concept of wellness of software ecosystems. El Moussa *et al.* [22] refine the concept of *SHE* healthiness, intuitively characterize *SHE* failures, and argue the usefulness of free energy to predict *SHE* failures. We leverage these preliminary studies to design an approach that monitors *SHE* healthiness to predict, localize and prevent *SHE* failures.

3 Research Objectives

The main goal of our study is to ensure the reliability of *SHEs* by testing *SHEs*, predicting and ultimately preventing otherwise unavoidable *SHE* failures. To meet our main goal, we address the following research objectives:

O1. *SHE* healthiness monitor: Define a monitor of *SHE* healthiness that can predict *SHE* failures.

O2. *SHE* failures prevention: Define a failure prevention approach for *SHEs* that leverages the predictions of the monitor to take corrective actions to prevent *SHE* failures.

O3. *DTs* for *SHEs*: Define a *DT* architectural framework for *SHEs* that replicates the dynamics of *SHEs*, thus enabling testing.

4 Research Methodology

In the first two years of this Ph.D. we defined:

- ***MAD***, a *Multi-Agent architecture for Digital twins* of *SHEs*, and
- ***SEM***: *Smart Ecosystem Monitoring* for predicting *SHE* failures.

MAD captures the decentralized, dynamic, and heterogeneous nature of *SHEs* to test the contradictory conditions that emerge in production, without interfering with the humans in the *SHE*.

Most common *DTs* for cyber-physical systems model the interaction between physical and digital components with a five-layer architecture [12, 24, 27]. *MAD* is a five-layer architecture for *DTs* of *SHEs* that models both cyber and human entities as autonomous agents capable of perceiving, reasoning, and acting according to their beliefs and goals, within a shared digital environment:

- ***SHE***: The physical *SHE*, which includes the Cyber-Physical systems, the Humans, and the Environment.
- **Data Exchange**: The bidirectional transmission of data between the *DT* and the physical *SHE*.
- **Digital Model**: The digital replica of the Environment of the *SHE*, and the Cyber and Human agents, which follow the **Belief-Desire-Intention** (BDI) paradigm [28].
- **Service**: The main functionalities of the *DT*: simulation, prediction, anomaly detection, feedback generation.
- **Data Management**: The Manager of both the data from the physical *SHE* and the data from the *DT* 's internals.

The multi-agent perspective and the explicit integration of human actors as first-class participants produce *DTs* that capture the relevant aspects for testing *SHEs* [16, 21, 23, 29, 29].

We validated *MAD* with MAD_{SF}, a level-2 *DT* (*Digital Shadow* (*DS*) [10**? ? ? ?**]) of the San Francisco ride-hailing *SHE*, that we built using public datasets and prior research. MAD_{SF} simulates the behavior of the core entities of the *SHE*: Uber and Lyft (Cyber-Physical systems), drivers and passengers (Humans), and the map and traffic of San Francisco (Environment).

Results show that (i) *MAD* keeps aligned with the *SHE* over time, significantly reducing total execution time compared to real-world constraints, (ii) *MAD* accurately replicates the *SHE*, with over 99% fidelity for traffic flow, passenger pick-ups and drop-offs, (iii) *MAD* adapts to the evolutions of the agents in the *SHE* with minimal impact on fidelity and responsiveness, and (iv) *MAD* shows strong robustness under high workload and disruptive scenarios.

SEM is a transformer-based approach for monitoring ***SHE* healthiness** and predicting ***SHE* failures**. *SEM* is the first concrete solution for predicting failures in *SHEs*. We define *SHE* healthiness from a set of system metrics that quantify the overall wellness of the *SHE*, and *SHE* failures as unacceptable degradations of a set of global indexes that captures the ultimate perception of the *SHE*. *SEM* includes three main steps:

- The **preprocessor** converts the input metrics collected from the *SHE* into the time series of indicators for the autoencoder. The input metrics offer a snapshot of the status of the *SHE*.
- The **denoising transformer autoencoder** computes the reconstruction error of the time series of indicators from the *preprocessor*. High reconstruction errors spot anomalous inputs.
- The **predictor** signals a failure if the reconstruction error consistently remains over the 99^{th} percentile of the distribution computed during training [3, 11].

We validated *SEM* on MAD_{SF} (the *DS* of the San Francisco ride-hailing *SHE*), and referred to a $failed\_requests$ index that captures the relevant global aspects of the *SHE*, that we defined as the ratio between the ride requests that are not served over all ride requests. We experience a failure of the *SHE* when the absolute value (hardiness), the standard deviation (consistency), and the moving average (resilience) of the $failed\_requests$ index remarkably deteriorate.

We trained the autoencoder with the 24 hours time series indicators of normal execution of the *DS*, and experimented with 18 critical scenarios inspired by real events and literature, including flash mobs and sudden demand/supply shocks.

We introduced a new provider in the *DS*, *Flat*, with fixed fares that we sourced from the San Francisco cab fares, to experiment with significant variations of the *SHE*. We used *memory-aware synapses* continual learning [1] to adapt *SEM* to the new conditions without *catastrophic forgetting* [18].

Our experimental results show that (i) the reconstruction error that the autoencoder computes on the indicators collected in normal execution conditions well reflects the *SHE* healthiness, in terms of value and stability, (ii) *SEM* correctly predicts *SHE* failures in all the failing scenarios, with an advance that allows for recovery actions (half an hour, on average), and (iii) *SEM* generalizes to significant variations of the *SHE*.

5 Evaluation Plan

We plan to complete the Ph.D. by

1. **completing the evaluation of both *MAD* and *SEM* with new disruptive scenarios and an ML-based personality model** of human agents in the *SHE*,
2. **evaluating the generalizability** of both *MAD* and *SEM* by instantiating them in a different context and domain,
3. **defining an approach to automatically select corrective actions at runtime to prevent *SHE* failures** and restore the normal execution state of the *SHE*.

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