Hazard Analysis on a System of Systems using the Hazard Ontology

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***Abstract*— Today, well-established hazard analysis techniques are available and widely used to identify hazards for single systems in various industries. However, hazard analysis techniques for a System of Systems (SoS) are not properly investigated. SoS is a complex system where multiple systems work together to achieve a common goal. However, the interaction between systems may lead to unforeseen interactions and interdependencies between systems. This increases the difficulty of identifying and assessing system failures and potential safety hazards. In this paper, we explore whether Hazard Ontology (HO) can be applied to an SoS and whether it can identify emergent hazards, their causes, sources, and consequences. To conduct our exploration, we apply the HO to a quarry automation site (an SoS) from the construction equipment domain. The results indicate that the HO is a promising technique that facilitates the identification of emergent hazards and their components.**

***Index Terms*—hazard analysis, a system of systems, Hazard Ontology, safety, hazards**

I. Introduction

A System of Systems (SoS) refers to a set of independent systems or components that work together to provide a unique capability that cannot be achieved by any individual system alone [1]. A capability can be, for example, a collaborative or complex service delivered to the system's end users or other subsystems/systems. For instance, several vehicles form a coalition in a platoon driving system and drive with a short intervehicle distance to reduce traffic congestion and fuel consumption. SoS has become popular in many emerging intelligent systems in our daily lives, e.g., smart grids, intelligent transportation, robotics, and smart production systems. However, the collaborative behavior of SoS poses numerous safety-related challenges due to the potential consequences of any malfunction within the SoS. Hence, SoS require strict design guidelines and strict adherence to safety properties for all interactions to realize their potential while ensuring safety fully.

Furthermore, identifying potential hazards in the SoS remains a complex challenge because traditional hazard analysis techniques [2] for single systems are typically not developed to deal with the complexity and scale of an SoS. As a result, analyzing hazards for each independent system cannot guarantee the safety of the whole SoS. Ensuring the safe behavior of each system in an SoS is crucial. This requires identifying hazards that result from the interaction between the different independent systems in the SoS. Simply ensuring the correct behavior of each system is insufficient because the behavior systems from the interaction of multiple systems, which cannot be attributed to an individual system and cannot be specified for each participant system. Therefore, we need a hazard analysis technique that would consider hazards for the whole SoS, including interaction hazards. Ali et al. [3] proposed a composite hazard analysis technique called SafeSoCPS in which authors combined three hazard analysis techniques by defining the relationship among the hazard analysis artifacts of constituent systems to analyze hazards for an SoS. The outcome of their hazard analysis provides fault traceability among systems in the SoS. The authors developed a tool called SoCPSTracer that automatically generates a fault propagation graph for SoS. However, this approach assumes that all hazard artifacts for constituent systems should be available, and it also restricts safety engineers to only three hazard analysis techniques.

In this study, we apply the Hazard Ontology (HO) [4] on an SoS (a quarry site case study) to see whether the HO can be applied to identify hazards for an SoS and facilitate the identification of interaction hazards, their causes, sources, and consequences. In particular, we focus on the following research questions:

RQ1. Can a hazard analysis be performed in an SoS using the Hazard Ontology?
RQ2. Can we identify hazards related to interactions in or among an SoS using the HO?

We select the HO for hazard identification in SoS because it provides a structured, standardized way to describe and categorize hazard concepts, properties, and relationships. This can help understand the interdependencies and potential safety hazards present in the SoS and support decision-making processes to improve its overall safety. In addition, the HO can serve as a common understanding of safety among stakeholders and facilitate communication and collaboration in the design, development, and operation of the SoS.

The structure of this paper is organized as follows: Section II briefly introduces background information on a system of systems, hazard identification process, ontologies, and Hazard Ontology. Section III provides a detailed insight into related work. Section IV introduces the case study. Section V provides a practical application of the HO in an SoS and then discusses the results of this application. Finally, section VI includes concluding remarks and proposed future work.

II. Background

A. System of systems

According to the ISO/IEC/IEEE 21841:2019 standard [5], SoS refers to the "set of systems or system elements that interact to provide a unique capability that none of the constituent systems can accomplish on its own." The constituent system is the independent system that interacts or collaborates with other constituent systems to form an SoS.

An SoS combines the capabilities of multiple independent systems to provide extended functionality that any individual system could provide alone. The steps in hazard analysis for SoS include identifying, evaluating, mitigating, monitoring, and verifying potential hazards that could compromise the safe operation of the SoS. In this paper, we only focus on identifying hazards for SoS.

B. Hazard identification

Hazard identification requires identifying the SoS's potential hazards, including those posed by its constituent systems, interactions, and operating environment. There are various hazard analysis approaches used in the hazard identification process [2], such as the Hazard and Operability Study (HAZOP) [6], that require manual analysis of each component of the system to identify the potential hazards. For example, applying HAZOP divides the system into smaller components that are analyzed for potential hazards. The main drawbacks of traditional practices applied in hazard identification are 1) a lack of common understanding of concepts; and 2) there is a need to formalize the experiences and lessons learned from previous systems development into a structured format for reuse, as hazard identification heavily depends on the expertise of analysts.

In this study, we apply HO [4] to an SoS to identify the potential hazards, including the interaction hazards that emerge due to interaction among/between constituent systems of SoS. Therefore, in this subsection, we briefly introduce the HO. Fig. 1 illustrates the concepts and relationships of the HO as a UML class diagram. The HO includes eleven concepts and fourteen relationships. The concepts of the HO are grounded in six concepts of a Unified Foundational Ontology (UFO) [7] (i.e., kind, role, disposition, relator, event, and situation). Generally, HO is a reference model that includes a set of hazard-related concepts (e.g., the Mishap, Hazard, Initiating Event, etc.) and relations (i.e., causal relations) that serve as a conceptual foundation for identifying hazards.

The HO concepts and their definitions provided in [8] and [9] and UFO [7] types are presented in Table I.

III. Related Work

Baumgart et al. [10] have proposed a newly structured process for identifying potential hazards in systems-of-systems (HISoS). This approach helps streamline the hazard analysis

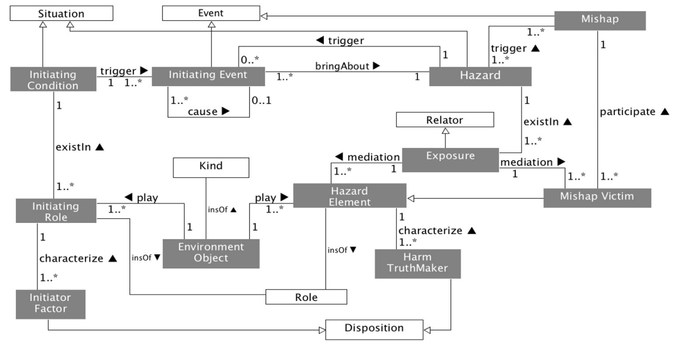

Figure 1. A UML diagram of the HO proposed in [4] and [8]. UFO concepts are white, whereas HO concepts are gray rectangles. Lines with a reading direction represent relationships

Table I
Definitions of HO concepts [8] and their UFO types

HO concepts	UFO type	Definition
Environment Object	Kind	refers to a certain thing or a set of things (e.g., living beings, objects, or places) that can play a specific role in initiating condition or a hazard.
Initiator Factor	Disposition	refers to a property of the initiating role (e.g., weakness of the initiating role).
Initiating Role	Role	refers to the role that is a required component of an initiating condition that causes initiating events.
Hazard Element	Role	refers to a role played by different environment objects.
Initiating Condition	Situation	refers to a situation that jeopardizes the component that causes initiating events.
Initiating Event	Event	refers to an unexpected event that causes a hazardous situation.
Harm Truthmaker	Disposition	refers to the critical properties in a hazard.
Exposure	Relator	refers to the relations in which victim(s) are harmed by hazard element.
Hazard	Situation	refers to a situation where a set of basic conditions and other possible conditions cause serious mishaps.
Mishap	Event	refers to an accidental event that will result in personal injury, environmental damage, or significant financial loss.
Mishap Victim	Role	refers to a role object that should not, but might be damaged or injured.

process efficiently and enables faster certification of SoS. The HISoS provides a systematic process for analyzing complex interactions between multiple systems in their early phase of design, which can help identify previously unknown risks associated with these interactions. HISoS methodology also offers an effective way to reduce complexity when designing these complex interactions between multiple systems while ensuring safety. In addition, the authors argue that HISoS systematically analyzes risks associated with emergent behavior set up by an SoS, which may not have been revealed through traditional single-system analyses.

Traditional hazard analysis techniques are insufficient when dealing with the complexity and size of SoS; therefore, Michael et al. [11] examine the nature and types of hazards associated with such system architectures, presenting a new technique for analyzing a kind of interface-related emergent hazards. In addition, the authors proposed a well-defined validation metrics framework that uses HAZOP as a hazard analysis technique and derived software requirements for mitigating identified hazards as proxies to gauge the sufficiency of safety requirements early on while developing an SoS. Finally, it classified the emergent hazards into three categories and presented a new process for analyzing interface hazards.

Identifying the interaction routes in SoS is challenging because failures among constituent systems in SoS propagate through those routes. Daneth et al. [12] proposed a unique model interaction language, CyPhyML+, which can identify component interactions of realized functions in collaborative systems (a kind of SoS). It improves existing studies such as ontology and integration of semantic languages for specifying component interactions in an SoS. The authors used Automatic Incident Detection System (AIDS) as a collaborative system example to validate their approach. However, the authors did not apply it to discovering the component interactions in an SoS.

Ali et al. [13] have used ontologies to identify potential faults in a smart home system. The authors first used Failure Modes, Effects, and Criticality Analysis (FMECA) to analyze the hazards and then transformed FMECA into a UML class diagram, and lastly, from a class diagram, they transformed it into an ontological representation. The authors mentioned that ontological approaches could be used for fault identification in an efficient manner. However, the ontologies were not directly used for hazard analysis.

IV. The case study - A Quarry Automation Site

In this section, we explore a quarry automation site (an SoS) from the construction equipment domain where autonomous and manually operated vehicles are used for crushing, collecting, and transporting material in a quarry site as shown in Fig. 2.

The quarry automation site consists of a manually operated vehicle (i.e., an excavator) that collects large stones and feeds them to a primary crusher, which then feeds the crushed material to an autonomous vehicle (i.e., a dump truck). An autonomous wheel loader also loads the crushed materials into an autonomous dump truck. Finally, dump trucks transport the material to a secondary crusher. In a quarry site, a control station provides wireless communication and controls all the operating systems. The wheel loader and dump truck are autonomous vehicles and can operate independently, communicate wirelessly, interact with the environment, and adapt to changing external conditions.

The case study of a quarry site can be considered an SoS, incorporating both manually operated systems and several autonomous systems that are independently managed and owned throughout their life cycle. This system is a direct SoS in which the constituent systems collaborate to achieve

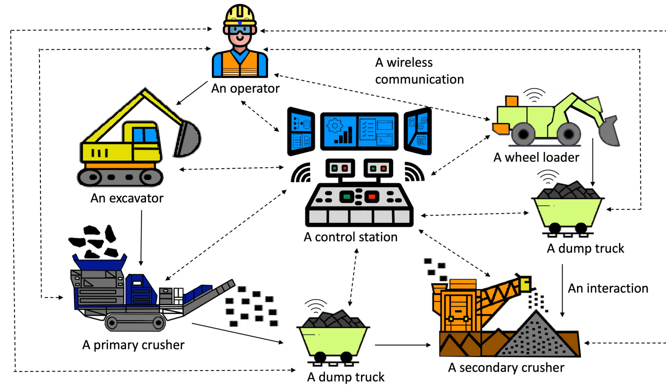

Figure 2. A quarry site is an example of a system of systems with manually operated and autonomous systems. The systems interact with each other and communicate via a wireless network. The black arrows represent interactions between systems, and the dashed arrows represent wireless communication between systems.

specified quarry production goals. During long-term operation, the system is managed centrally by a control station to achieve previously identified objectives and add new ones as needed by the system owners. Although the systems at the quarry site can work independently, their normal operating mode is subordinated to the centrally managed objectives.

The autonomous vehicles in the quarry site are expected to follow a specified path and receive commands to load, cooperate, transport, and unload without additional human action. Therefore, the SoS includes personnel carrying out activities alone or collaborating with autonomous vehicles.

The SoS aims to collaborate in the aggregate production process at every stage. This process takes place in various weather and terrain conditions. Due to the various conditions, the quality of the remote control, communication, and collaboration between systems could be degraded. Any irrational behavior can change the life cycle of the SoS and cause hazards for both humans and vehicles at the site. Some emergent behaviors can also be attributed to the constituent systems, which may be undesirable or dangerous. Systems constituting an SoS typically belong to more than one system, and their involvement is likely to change over time, e.g., as new parts are added, or as old parts are removed.

All possible scenarios and processes, including potential hazards, must be considered and analyzed to ensure safe operation at the quarry site. For example, a hazardous scenario could be one in which constituent systems have changed their states for internal reasons and may have assumed new functions that none of their counterparts had. An example is a vehicle in repair mode whose position cannot be considered. A second example is when a particular system depends on the accuracy of information provided by another system (e.g., an error in signal transmission, or a reception error, can lead to a critical situation). However, in analyzing the hazards of a single system alone, such hazards would not appear.

V. Using HO for Hazard Identification

In this section, we follow three steps to apply the HO for hazard identification and relationships among/between them:

1) Concepts are identified from the case study scenarios to analyze hazards for the quarry automation site.
2) Relationships are identified between previously identified concepts to determine the hazards that emerge due to interactions between components of a constituent system or between the constituent systems of an SoS.
3) UML diagrams are created to illustrate the hazardous concepts and their relationships for each scenario.

Explore the application of HO [4] in an SoS with the help of the three scenarios presented in Fig. 3, 4 and 5 to illustrate the process of identifying hazards, including emergent hazards and their causes, sources, and consequences. The case study of a quarry site is transformed into an ontological representation. The transformation from the case study to the HO representation requires identifying the different entities composing the HO.

In this paper, we select only three scenarios due to simplicity and page limitations. The description of scenarios is as follows.

Scenario 1: An operator attempts to update a wheel loader, which malfunctions and sends outdated data to other systems within an SoS. In this scenario, due to an inability to update a wheel loader, a dump truck collides with and damages it. It is an example of an interoperability hazard, as shown in Table II and Fig. 3. *An operator* and *a wheel loader* are identified as kind objects. *An operator* can play the role of *updater*, which can also be an initiating role. *A wheel loader* can play role *beingUpdated* and can also be a hazard element. A wheel loader *cannot be updated* and this state is identified as an initiator factor, *a wheel loader is malfunctioning* is an initiating condition, and *a wheel loader sends outdated data* is an initiating event. *An inability to update a wheel loader* is a harm truthmaker, and *updating* is an exposure. A hazard is a situation when *a dump truck collides with a wheel loader.* A mishap is an event when *a wheel loader is damaged* and *a wheel loader* is a mishap victim.

Scenario 2: A dump truck's object detection can be disrupted when dump truck operates near an operator during bad weather conditions. In this scenario, a dump truck cannot detect an operator and hits and injures that operator as a result. Scenario 2 is an example of an integration (proximity) hazard, as shown in Table III and Fig. 4. *A dump truck* and *an operator* are identified as kind objects. *A dump truck* can play the role of *detector*, which can also be an initiating role. *An operator* can play the role of *beingDetected* and can also be a hazard element. The occurrence of *bad weather conditions* is identified as an initiator factor, while *a dump truck is operating near an operator* and is considered an initiating condition. *A dump truck cannot detect an operator* is an initiating event. *A dump truck's object detection is disrupted* is a harm truthmaker, and *detection* is an exposure. A hazard is a situation when *a dump truck hits an operator.* A mishap is an event when *an operator is injured* and *an operator* is a mishap victim.

Table II
HO applied for scenario 1.

HO concepts	Scenario 1	HO relationships	Scenario 1
Environment Object	an operator a wheel loader	play play	is is
Initiator Factor	a wheel loader cannot be updated	characterize	describe
Initiating Role	Updater	existIn	inheres in
Hazard Element	BeingUpdated	x	x
Initiating Condition	a wheel loader is malfunctioning	trigger	cause
Initiating Event	a wheel loader sends outdated data	bring About /cause	induce cause
Harm Truthmaker	an inability to update a wheel loader	characterize	describe
Exposure	updating	mediation /mediation /existsIn	involvement involvement inheres in
Hazard	a dump truck collides with a wheel loader	trigger /trigger	cause cause
Mishap	a wheel loader is damaged	x	x
Mishap Victim	a wheel loader	participate	engage

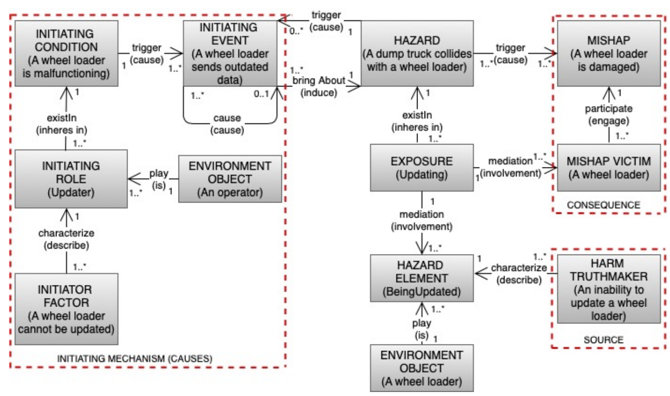

Figure 3. Scenario 1 illustrates an interoperability hazard. HO concepts are written in capital letters, and the elements of the quarry site are written in parentheses. The dashed lines in the diagram represent the causes, sources, and consequences of potential hazards.

Scenario 3: As a result of wifi signal loss, a dump truck cannot be remotely controlled as it is disconnected. When a dump truck is out of remote control, an excavator collides with it and damages it. It is an example of a reconfiguration hazard, as shown in Table IV and Fig. 5. *An operator* and *a dump truck* as kind objects are identified. *An operator* can play the role of *controller*, which can also be an initiating role. *A dump truck* can play the role of *beingControlled* and can also be a hazard element. The occurrence of *wifi signal loss* is identified as an initiator factor, while *a dump truck is disconnected* and is considered an initiating condition. *A dump truck cannot be controlled remotely* is an initiating event. *A dump truck is out of remote control* is a harm truthmaker, and *control* is an exposure. A hazard is a situation when *An excavator collides*

Table III
HO APPLIED FOR SCENARIO 2.

HO concepts	Scenario 2	HO relationships	Scenario 2
Environment Object	a dump truck an operator	play play	is is
Initiator Factor	bad weather conditions	characterize	describe
Initiating Role	Detector	existIn	inheres in
Hazard Element	BeingDetected	x	x
Initiating Condition	a dump truck is operating near an operator	trigger	cause
Initiating Event	a dump truck cannot detect an operator	bring About /cause	induce cause
Harm Truthmaker	a dump truck's object detection is disrupted	characterize	describe
Exposure	detection	mediation /mediation /existsIn	involvement involvement inheres in
Hazard	a dump truck hits an operator	trigger /trigger	cause cause
Mishap	an operator is injured	x	x
Mishap Victim	an operator	participate	engage

Table IV
HO APPLIED FOR SCENARIO 3.

HO concepts	Scenario 3	HO relationships	Scenario 3
Environment Object	an operator an excavator	play play	is is
Initiator Factor	wifi signal loss	characterize	describe
Initiating Role	Controller	existIn	inheres in
Hazard Element	BeingControlled	x	x
Initiating Condition	a dump truck is disconnected	trigger	cause
Initiating Event	a dump truck cannot be controlled remotely	bring About /cause	induce cause
Harm Truthmaker	a dump truck is out of remote control an excavator	characterize	describe
Exposure	control	mediation /mediation /existsIn	involvement involvement inheres in
Hazard	an excavator collides with uncontrolled dump truck	trigger /trigger	cause cause
Mishap	a dump truck is damaged by an excavator	x	x
Mishap Victim	a dump truck	participate	engage

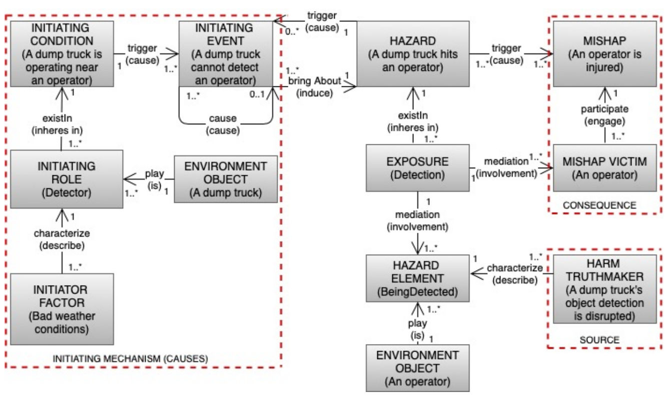

Figure 4. Scenario 2 illustrates an integration (proximity) hazard.

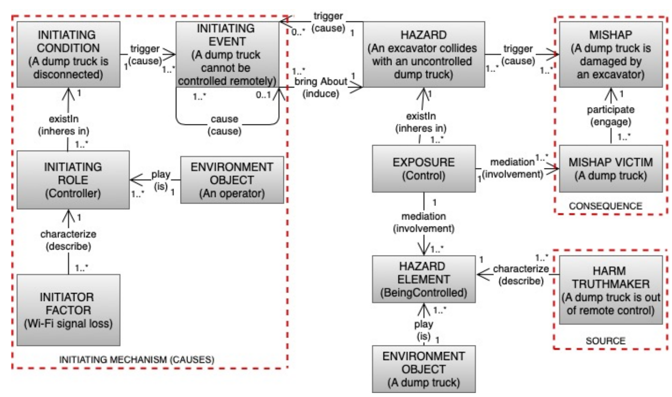

Figure 5. Scenario 3 illustrates a collision hazard caused by a communication hazard.

with an uncontrolled dump truck. A mishap is an event when *a dump truck is damaged by an excavator* and *a dump truck* is a mishap victim.

These scenarios illustrate some hazards that can be identified using the HO. The presented scenarios do not exhaust the range of possibilities, but they should be sufficient to explain the general hazard identification in an SoS with autonomous vehicles.

A. Results

In this subsection, we discuss some representative examples of hazards identified during our hazard analysis for the quarry automation site. During our hazard analysis, we found several system hazards and hazards that emerge due to interactions in an SoS.

HO application for SoS (RQ1): From our experience, while applying HO for our case study, we see that the HO supports hazard analysis for an SoS by identifying the roles of the objects, knowledge about activities performed by these objects, and other properties, which facilitates the identification of hazards in the constituent systems of an SoS (Tables II, III and IV). Additionally, we observe that early identification of the objects and their roles help provide the necessary information to continuously identify new hazards in an SoS. More specifically, from Fig. 3, 4 and 5, we have seen that HO was able to identify hazards as the traditional hazard identification techniques do. For instance, a communication hazard was identified (Fig. 5) caused by the loss of WiFi signals in a dump truck. Compared to other hazard identification techniques, HO identified this hazard in a systematic way where the initiating condition, event, initiating factors, environmental objects (operator in our case), etc., and finally, the mishap were identified using concepts, roles, and relationships.

HO and identification of interaction hazards in SoS (RQ2): From the results, we see that HO enables us to identify relationships between the components of constituent systems and also between constituent systems of an SoS. It led to identifying interaction-related hazards in the quarry automation site (an SoS). Fig. 3 and Fig. 4 show representative examples of hazards related to interactions in an SoS. We report that using the property of *relationship* among the *concepts* in HO, we were able to identify interoperability, integration, and reconfiguration that stem from the interaction between constituent systems in an SoS. Using HO for an SoS, we have been able to identify such hazards; otherwise, we could omit that kind of hazards. For instance, the proximity hazard (Fig. 4) was identified in our case study, where autonomous and human-operated machines dangerously come close to each other due to bad weather conditions. This hazard was identified easily using the concept of HO. However, we also observed that the ontological approach results in a vast amount of data that need to be handled and analyzed. To cope with this problem, we are in the process of developing tool support to handle the data effectively and efficiently.

Therefore, we can conclude that the HO can assist in identifying new types of hazards or multiple hazards in an SoS. When searching for dispositions, the properties of the role are considered, among which are different weaknesses and strengths that may be the causes of a hazard are distinguished. When the roles' disposition is known, the objects that play them are also understood. Identification of an event, such as an initiating event, allows us to understand what can bring about the hazard and what can be triggered by the hazard, including emergent hazards in an SoS with autonomous vehicles. By identifying the initiating mechanism, the causes of emergent hazards in an SoS with autonomous vehicles can be more readily recognized. Identifying a mishap victim allows us to recognize the consequences of emergent hazards in an SoS with autonomous vehicles.

Applying the HO in an SoS with autonomous vehicles requires a good domain understanding because a formal ontological representation can be complicated. A structured and precise identification of the objects, their roles, properties thereof, and the relationships between them helps to extend the ontological representation. The process we followed to identify the hazards and the relationships between them, can be used to identify hazards in any domain. The reported results show that using the HO allows for a detailed analysis of potential interactions between systems and can facilitate the identification of emergent hazards and components thereof in an SoS with autonomous vehicles.

VI. Conclusions and Future Work

In this paper, we used the HO proposed in [4] as a structured way to perform a hazard analysis in an SoS with autonomous vehicles. The aim was to explore using the HO as a structured method to perform a hazard analysis in an SoS with autonomous vehicles and to identify hazards and their causes, sources, and consequences in an SoS. Furthermore, three examples demonstrated how the HO could be used in an SoS with autonomous vehicles. The results show that the HO can support hazard analysis for both single systems and SoS. Moreover, the examples presented in this paper are not exhaustive, and the HO can be employed in other systems.

In the future, we plan to extend the HO with security concepts and relationships to enable the analysis of safety hazards and security threats in an SoS. Furthermore, we will also examine to what extent the security extensions address the needs and concepts of a system of systems.

Acknowledgment

This work was supported by the research profile DPAC - Dependable Platform for Autonomous Systems and Control project, funded by the Swedish Knowledge Foundation, grant number: 20150022 and by the Swedish Foundation for Strategic Research through the Serendipity project.

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