IoT-based Systems of Systems

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Abstract. *Systems of Systems* (SoS) and the *Internet of Things* (IoT) have many common characteristics. For example, their constituents are heterogeneous, autonomous and often distributed. Moreover, both IoT and SoS achieve intended goals by means of the highly dynamic cooperation among their constituents. In this paper we study the relation between IoT and SoS. We discuss the characteristics of both concepts and highlight common aspects. Furthermore, we introduce the concept System of Emergent Configurations (*SoECs*) to describe IoT-based SoS.

Keywords: System of Systems (SoS), Internet of Things (IoT), Emergent Configurations (ECs), System of Emergent Configurations (SoECs)

1 Introduction

The Internet of Things (IoT) enables heterogeneous and distributed smart objects to connect, communicate and collaborate to achieve common goals [4]. Such objects involve, e.g., sensors, actuators, computer-based systems, smart-phones and other smart physical objects. The number of devices connecting to the Internet is exponentially increasing and is expected to reach 24 billions by 2020 [6]. Thus, the IoT is expected to emerge in almost every aspect of the daily life.

The concept System of Systems (SoS) involves the dynamic collaboration of distributed and heterogeneous systems to achieve common goals. The evolution of integration and communication technologies enabled legacy, existing and new systems to collaborate and realize the concept SoS. The (SoS) term is widely used in the literature and several efforts have been done to define the concept. However, due to the wide range of applicable definitions stemming from various research backgrounds and perspectives, common characteristics are defined to better describe the concept.

In this paper, in Section 2, we review the characteristics of IoT and SoS domains and highlight the shared aspects between them. In addition, we analyze the concept of Emergent Configurations in the context of SoS. Moreover, a case study is presented to explain IoT-based SoS. Section 3 concludes the paper.

2 The Internet of Things as System of Systems

This section illustrates the relationship between the Internet of Things and the System of Systems concepts. The characteristics of both domains are identified and compared in order to clarify the correlations between the two concepts.

2.1 A review of SoS and IoT Characteristics

IoT characteristics. This part presents several characteristics of the IoT [5]: (i) *Devices heterogeneity*: IoT involves a variety of connected heterogeneous objects of which some are smart and can make decisions autonomously. (ii) *Distributed components*: huge number of smart objects join IoT -thus the IoT is constantly *evolving*. (iii) *Ubiquitous data exchange capabilities*: smart objects and computational units exchange tremendous amount of information. (iv) *Localization and tracking capabilities*: IoT objects are uniquely identified and traceable. (v) *Self-organizing capabilities*: IoT components may have self-adaptable capabilities due to dynamic IoT environments. (vi) *Semantic interoperability and data management*: intelligent data management techniques are required to analyse exchanged data among IoT components. Semantic interoperability requires designing well-defined and standard semantic models.

SoS characteristics. Maier defined five characteristics of SoS [7]: (i) *Operational Independence*: SoS constituents are autonomous and can keep achieving their goals even if detached from the SoS. (ii) *Managerial Independence*: SoS constituents are self-controlled and managed. (iii) *Geographical Distribution*: SoS constituents might be distributed in several locations. (iv) *Evolutionary Development*: SoS evolves as constituents evolve continuously. (v) *Emergent Behaviour*: as dynamic and heterogeneous constituents interact, new behaviours are introduced to the SoS level.

Maier considers systems which possess operational and managerial independence to be SoS regardless of the complexity and geographical distribution of relevant constituents [8]. Boardman and Sauser add three more characteristics [1]: (i) *Belonging*: achieving overall goals is attributed to SoS and not to any individual constituent. (ii) *Connectivity*: constituents can exchange messages and information. (iii) *Diversity*: constituents are heterogeneous, evolving and *interoperable*. Another important characteristic is *interdependence* [2]. Interdependent constituents rely on each other to satisfy common goals.

2.2 Discussion

It is clear that IoT and SoS share some major characteristics. For instance, like SoS, IoT components are heterogeneous, autonomous, able to communicate, often distributed, operational and managerial independent. Both domains are evolving and operate in dynamic situations leading to emergent behaviours. In this context, the Internet of Things can be regarded as a System of IoT-based systems.

In the context of IoT, we refer to the term Emergent Configurations (ECs) of Connected Systems as "*a set of things with their functionalities and services that connect and cooperate temporarily to achieve a goal*" [3].

Within SoS, the emergent behaviour concept has been defined as "*the behaviours that arise as a result of the synergistic collaboration of constituents*" [2]. Functional and non-functional emergent properties result from having heterogeneous and distributed constituents collaborating in dynamic environments. Emergent behaviours are desirable in case they contribute positively to SoS goals. On the contrary, they are undesirable in case they adversely affect achieving goals. Systems monitor, detect, analyze, and self-adapt to undesirable emergent behaviours in order to provide consistent functionalities. Self-adaptation mechanisms are out of the scope of this work.

Considering the EC concept, the IoT can be seen as a collection of ECs. In other words, we see an IoT system as an EC. Since constituents of an IoT-based SoS are IoT systems, an IoT-based SoS is referred as a *System of Emergent Configurations* (SoECs). The section below introduces the smart street lamppost case, and illustrates how this IoT-based System of Systems is considered as a SoECs.

2.3 Smart Street Lamppost System

In this section, we take the case[1] of the *Smart Street Lamppost System* (basic system) described in [3] and extend it (scenario) to illustrate the concept of SoECs discussed above.

Basic System. The main idea, in this case, is to adapt a smart lampposts sphere of light for each road user. This means that the number of lampposts that light up depends on the speed of vehicles, bikes or pedestrian. Yellow lights are dimmed down, to save energy, when there is no traffic. Lampposts turn on red lights when drivers go over speed limits -this contributes to increase safety and traffic awareness. Each lamppost has the following capabilities: (i) Detects the presence of vehicles, bikes or pedestrian through motion detection sensors. (ii) Measures the speed of moving objects through a computation unit. (iii) Decides the brightness of its light, using either yellow or red lights through a pair of actuators. (iv) Computes the number of neighbour lampposts that should light up (yellow or red lights). (v) Exchanges messages with neighbour lampposts. Lampposts are grouped into areas and an Area Reference Unit (ARU) manages each lampposts group. ARUs have powerful computational capabilities and storage capacities. The collaboration of the above components is an Emergent Configuration. The main emergent behaviour of the case is to switch on red lights when car B exceeds the speed limit. An emergent property is to warn car A about the speed of car B.

Scenario. To extend the work done on the case above we introduce the scenario below. (i) Lampposts collaborate with ARUs to detect accidents through

[1] This case has been realized, including the hardware and software, in a collaboration between Malmö University, Internet of Things and People (IoTaP) Research Center, and Sigma Technology under the ECOS project [9]

the GPS technology, see [10]. (ii) An ARU reports an accident to the relevant Health Management System including the location and number of cars involved. (iii) The driver of car B suffers from serious heart disorders, so she/he puts on wearable health monitoring sensors regularly. These sensors report her/his medical status to the HMS *(emergent configuration)*. (iv) The HMS specifies the number of ambulances needed and redirect the closest ones. Meanwhile, a specialist in the operations room analyses the data being received from the driver's health monitoring sensors.

As illustrated in the above scenario, the two emergent configurations (systems) collaborated together composing a System of IoT-based Systems.

3 Conclusion

In this paper we analyzed the characteristics of the Internet of Things and System of Systems domains. It can be noted that the domains share the core characteristics like operational and managerial independence, evolving systems and emerging behaviors/properties. Moreover, we look at SoS from the perspective of IoT emergent configurations (ECs). In this context IoT-based SoS can be seen as a System of Emergent Configurations (SoECs). We presented the Smart Street Light case, and extended it to illustrate temporal collaboration between two emergent configurations composing an IoT-based System of Systems.

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