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Smart Cyber-physical System-of-Systems using Intelligent Agents and Multi-agent Systems

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Abstract. The Cyber-Physical Systems (CPS) are complex, multi-disciplinary, physically-aware future's paradigms which are integrating embedded computing technologies (cyber part) into the physical world (physical part). The interaction requirement with the physical world makes the CPS unpredictable because of the real-world's dynamic behaviours. So a CPS needs to reason these changes and adapt its behaviour accordingly. Moreover, a CPS can cooperate with multiple CPSs to establish cyber-physical system-of-systems (CPSoS). This creates a distributed and heterogeneous environment where we are challenged by unpredictability. To address the challenges of the CPSoS, new methodologies and new approaches need to be developed. One way to tackle these challenges is by making them smart with intelligent agents and modelling them explicitly. To make intelligent decisions it is needed to do reasoning and to use decision-making mechanisms. In this way, they can handle the unpredictable changes encountered both internally and externally. Nevertheless, suitable reasoning, smartness, and awareness mechanisms must be studied, implemented, and applied to achieve smart CPSoS.

Keywords: Software Agents · Intelligent Agents · Smart Cyber-physical system of systems, · sCPSoS

1 Introduction

The advancement of networked systems has introduced new design challenges in the embedded systems. Naturally, Cyber-Physical Systems (CPSs) are more complex compared to their pioneered paradigm embedded systems. This complexity is inherited both from embedded software that is covered by the cyber part and physical phenomena which have to be monitored and/or interacted with. During the interaction with the physical world, there are phenomena that have to be reacted by the cyber part, which causes change state in the system, after which feedback information is sent. The computational part of these systems plays a key role and needs to be developed to handle uncertain situations with their limited resources. Since in a distributed CPS, unpredictable change in a component or the environment can affect the rest of the system and even the whole infrastructure that contains the CPS, it highly requires to perform intelligent behaviours and reasoning mechanisms. This intelligent mechanism needs to react according to the dynamic changes, control the physical part, and adapt the unpredictable behaviour of the system to a reasonable limit. The reasoning mechanism should start with sensor data gathering, extracting the key information from this data, and proving knowledge out of this information to adapt the system's behaviour to control the components.According to the [19], success of the current approaches have the following gaps i) awareness and adaptation of behaviours are considered as system smartness, but they cannot be achieved by traditional approaches, ii) model-based and component-based approaches insufficiently support the development of reasoning mechanisms for sCPSs, iii) frameworks for the development of smart CPS should support compositional model-based design. Inspired by these research gaps, we are motivated to initialize this research as well as pointing the need for intelligence to establish a smart cyber-physical system of systems.

2 Related Work

This study proposes an agent-based integrated methodology for the design and development of smart cyber-physical system-of-systems (sCPSoS), including modelling and reasoning mechanisms, to support the life-cycle of these distributed, complex and mobile systems. In the literature, there are surveys, projects, and research papers that partially provide solutions for the challenges of CPS and CPSoS. The study [6] addresses Industrial Internet-of-Things (IIoT) and CPS common features and provides methodologies for the application of IoT-enabled solutions to Cyber-physical production systems. Their study points to the interoperability of IoT and CPS paradigms. Additionally, they also present modelling approaches for IIoT systems as well as architectures that can be reused for our goal, while the study [16] provides IoT-based layered solutions using software agents. These studies show that IoT based solutions and modelling approaches [7] can also be applied for the sCPSoS. These studies show that smartness, organisation, and networking requirements can be addressed using intelligent agents and the complexity of sCPSoS can be reduced using model-driven approaches. In [10], agents' capabilities for CPS are discussed. Generally, agents are good at creating collaboration and integrity when they are distributed, providing smart decisions when unpredictability exists. The study [16] mentions the cognitive requirement of CPS and presents the necessity of the distributed intelligence, and envisions MAS's usefulness as they fit the CPS. Their autonomous decisions in a decentralised way can address the CPS challenges. They benefit from layered IoT architecture to enable organised decentralisation of data acquisition, actuation, monitoring, analysing, planning, decision making at Fog level and Edge level.A survey [1] reports the uncertainty in self-adaptive systems [22]. The participants in the survey agree on implementing self-adaptation mechanisms to cope with unanticipated changes in a system. They also suggest that uncertainty can be represented using runtime models (e.g. MAPE-K loop). In the study [5], ontological classification is made considering past, present, and future CPS technologies emphasising the requirement of intelligence.The study focuses on today's sCPSoS requirements while showing the research gaps in this domain.

In [21], the authors provide an MBSE perspective to manage heterogeneity in CPS. They propose to use various domain-specific views for each subsystem. According to this study, the system model should be represented by different levels of abstraction for each subsystem. The study in [18] discusses how an agent development framework called SEA_ML++ is used for the design and implementation of a CPS garbage collection system. The authors apply MDD techniques to synthesise a part of the agent-based software. These studies are in the scope of interest to this study as they map on different parts of sCPSoS. They mostly cover model-based development of sCPSoS and partly reasoning mechanisms, but not smart agents and agent-CPSoS integration.

3 Problem Statement

In this study, it is aimed to define new methods using intelligent agents [12] and modelling techniques [8, 20] to overcome the current challenges of CPSoS while considering CPSoS sustainability and providing a tool that facilitates the lifecycle of CPSoS. The underlying idea is the integration of agent-based system engineering (ABSE) and model-driven development (MDD) techniques. The approach is to apply multi-paradigm modelling principles to create such methods to provide an agent-based CPSoS modelling framework. To achieve this, the multi-paradigm modelling approach is preferred, because, it advocates the explicit modelling of all parts of a system at different abstraction levels using different formalisms. At the centre of the approach, agents and organizations of agents are used as the main abstractions orthogonally integrated with model-driven techniques. A CPSoS inherently have both CPS and system-of-systems (SoS) characteristics that increase the complexity. They are brought together within the SoS umbrella to achieve specific tasks that cannot be achieved by a single CPS. This increases the necessity of high-level modelling and solution finding to address the complexity of CPSoS while ensuring each CPS is consistent within itself. Here, consistent refers to having a degree of autonomy, intelligence and adaptive reasoning. They require decentralised supervision and management for each subsystem. Therefore, the CPSoS has to include the following characteristics to address the aforementioned challenges: i) a large amount of data related to systems and the environment has to be handled ii) each system should have self-awareness and self-adaptation for robust operation iii) the user's behaviour and goals must be considered intelligently to prevent anomalies iv) the smartness can be provided using intelligent software agents v) collaborative, cognitive, and consensus-based mechanisms should be implemented.

For this purpose, as Figure 1 shows, integrating agent-based system engineering [4, 2] with model-driven approaches is considered while referring to the use of proper paradigms/formalisms with the philosophy of modelling different aspects/phases of sCPSoS lifecycle explicitly in an appropriate level of abstraction (in design and/or run time). These systems are highly complex from both structural and behavioural points of view, which can be addressed with well-known techniques of Model-based System Engineering (MBSE) to cover the lifecycle of sCPSoS[3]. This raises the need to integrate MBSE and ABSE processes for the development of sCPSoS, which is an open issue. This study aims to improve the lifecycle of sCPSoS development by using MDD, ABSE and intelligent agents. This multi-paradigm approach aims to solve the challenges of creating and sustaining CPSoS by providing adaptive behaviour for environmental uncertainty, distributed cooperation for decentralised topology, and reasoning for intelligence requirements while integrating self-awareness and self-adaptation capabilities.

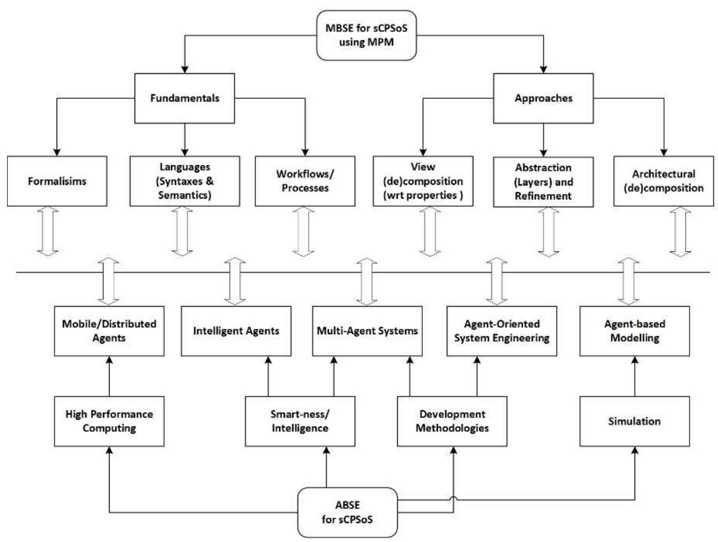

Fig. 1. Architecture for orthogonal integration of MBSE and ABSE [3].

4 Proposed Solution & Methodology

The main goal is to gain the smartness feature for cyber-physical systems. As a methodology, intelligent agents and CPS integration need to be established at the cyber part. This smartness mechanism can benefit from agent architecture such as belief-desire-intention architecture using their adaptive reasoning capabilities. This integration can also be enhanced using fuzzification methodology to cope with the uncertainty of the environment while selecting fuzzified plans for executing multiple actions. In this way, self-awareness and self-adaption can be improved and flexibility can be gained into the system. The second goal is to create a model-based framework to support the development of CPSoS so that a higher-level abstraction can be provided for the end-user. In this way, the user can create sCPS and sCPSoS using model elements in a user-friendly manner and generate target system codes, including agent software, embedded software, reasoning codes encapsulated by intelligent agents. The last goal is defining a methodology encapsulating the embedded device's software into agent software. In this way, the agents will have full control over system inputs, outputs, networking, and configuration.

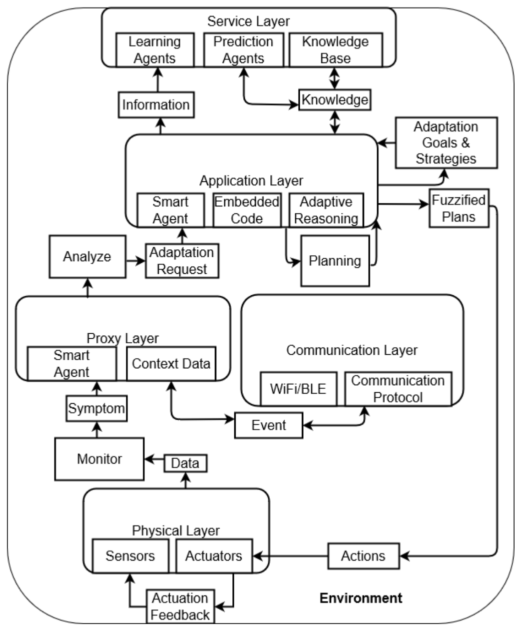

Fig. 2. High-level view of the proposed solution (adapted from [14])

However, before implementing all of these three goals, shown in Figure 2, a consistency workflow model should be established. To achieve this, MAPE-K control loop for self-adaptive systems are presented. First, real-world data is monitored and analyzed by physical devices to achieve self-awareness by reasoning the context of the system. If any violations occur against the system's robustness, this problem is reasoned to select an adaptation plan. Then, the compensated state is executed. When this execution is realized then, it is also sensed by the system considering the sense-decide-act-sense approach. Therefore, the consistency between the cyber-part and physical part can be satisfied once the actuation state is known by and in sync with the cyber part. While this process is on-going, the knowledge-based is updated and a general solution scheme towards similar-cases are generated benefiting from these run-time experiences [17]. The knowledge base should store the information about physical and cyber context of CPS related to sensor data, actuation operations, and process steps regarding with time. Moreover, the knowledge-base should also contain goals, general scheme plans, states and past experiences of the system.

In study [17], the authors propose MAPE-K loop-based self-adaptive smart lighting case. They control the light intensity according to the illumination value of the environment. However, comparing a static light control system with a highly dynamic production system, it can be seen that controlling light intensity is less complex and risky. Because most of the CPS covers mobile robots and motion-based applications where the determinism is less and uncertainty is expected. Therefore, fuzzy-based approaches should also be applied to the MAPE-K loop along with BDI agents. In this way, perception, plan selection, believes, and plan execution (actions) will be fuzzy values instead of being either true or false. In this way, the highest acceptable plan or multiple fuzzy plans will be executed. Additionally, the system should have an adaptive reasoning mechanism. Because an agent should have the ability to change its behaviour both in the short-term and the long-term to respond to the changing requirements of its problem-solving situation. In this way, agents can react appropriately to unanticipated events, including opportunities and failures while focusing on appropriate goals to achieve. Further, they can select suitable actions to realize their goals.

To evaluate the proposed study, we established a LEGO technology-based smart production system and a line follower robot with an adaptive cruise control robot to establish a production management system. We established agent-based communication and ran reactive agents on these sub-systems. We aim to advance this case study to achieve an industrial-like CPSoS, then apply industrial requirements to test the adaptiveness of the system. During the evaluation, the goal is to achieve fully-fledged production system and product/source transportation system. The system should adapt itself and sustain its operation while dealing with dynamic requirements (e.g. more production or lack of sources), recognizing the process failures (stuck of materials etc.) and being aware of the unexpected or faulty interplay between sub-CPS. Lastly, we will apply MDD techniques to create a modelling framework [7].

5 Conclusion

The adaptation of MAS to CPS is an open research domain and require gaps to be filled. The evolution of industrial paradigms and communication technology provided solutions but also created new challenges. While communication technology is evolving, this creates distributed and decentralized systems where traditional control and store methodologies cannot be used anymore. As discussed by many researchers, the necessity of intelligence in CPS is underlined and proposed as a solution. To achieve this, intelligent software agents are selected as one of the best-fit solutions. It is necessary to develop new solutions as well as adapting existing standards such as IoT [15, 11], Distributed AI, and Embedded technology [9] as well as model-based engineering techniques [13].

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