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Survey on Cloud Robotics Architecture and Model-Driven Reference Architecture for Decentralized Multicloud Heterogeneous-Robotics Platform

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ABSTRACT Robotics engineering is gradually becoming an essential part of our daily life. However, it has been generating Big Data and seeking large computation cost because of the diversified sensors and processing requirements involved in heterogeneous robotics and their workflows. Therefore, cloud computing has become the incumbent platform for robotics. There are numerous works related to the architecture for cloud robotics. However, most cloud robotics architectures are ad hoc and are not based on a model. Inherent drawbacks of ad hoc approaches include being strictly domain specific and minimally customizable and adaptable. Moreover, heterogeneous cloud robotics platforms have been operating diverse requirements of industries and households. Nevertheless, there are certain benchmarks set to be achieved by Industry 4.0 and norms by Society 5.0. Those benchmarks and norms lead to new products and services in cross industries and alleviate the impending drawbacks. However, those should be achieved while retaining both the sovereignty and security of the respective systems and industries. This is equally applicable and an enormous challenge to the system-of-systems involving the cloud robotics domain. Therefore, we surveyed cloud robotics architectures. Then, we learned a top-down design approach involving a unified architectural framework as the cognitive approach for the highly variable and systematically complex challenges to be achieved in the next-generation cloud robotics domain. Reference architecture is a well-known approach for instantiating top-down unified architectural framework processes. Therefore, we proposed an architectural design process and modeling for the reference architecture for next-generation cloud robotics platforms.

INDEX TERMS Cloud robotics, Industry 4.0, model-driven, reference architecture, Society 5.0.

I. INTRODUCTION

The global robot market, which combines industrial and non-industrial (domestic and personal) robots, shows an average yearly growth of 30% and forecasts the demand will reach USD 209 billion by 2025.[1] Meanwhile, the demand for the industrial robot market has increased by 61% and nonindustrial robot demand has increased by 52% compared with 2017.[2] This implies that the robotics field shows exceptional growth in highly diversified industries.

A. BACKGROUND

Robots in highly diversified use cases involving diverse industries (such as aerospace, consumer, disaster response, exoskeletons, industrial, medical, military, self-driving cars, and underwater) and with varied processing requirements are called heterogeneous robotics. Therefore, considering the increasing demand for the heterogeneous robotics and the exponential growth of the demand for their research and development, the Japanese government inaugurated the first and thus far the only all-in-one public heterogeneous-robotics testing field (RTF) at Minnamisoma, Fukushima, Japan,which is named the Fukushima-RTF, facilitating research and developing and testing works of heterogenous-robotics for international

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[1] www.statista.com/statistics/760190/worldwide-robotics-market-revenue

[2] ifr.org/post/market-for-professional-and-domestic-service-robots-booms-in-2018

researchers and industries. Fig. 1 outlines the services provided by Fukushima-RTF.

Heterogeneous robots are equipped with diverse sensors, and they have been generating enormous amounts of data that have been used for diversified use cases (robots and processing requirements) involving various stages of the robotics workflows. Then, cloud computing becomes the refuge from which to address such high volumetric, velocity, and variety (3Vs) of Big Data involving robotics workflows. That implies cloud robotics (CR) and CR architecture have been playing pivotal roles in the robotics domain. Therefore, it is essential to establish an all-in-one platform for heterogeneous robotics that have wide range of data processing requirements, such as data lake (data acquisition and maintenance), and diverse requirements of processing including analytics of wide range of robots in Fukushima-RTF. Thus, the complexity of the end solution for the heterogeneous requirements of CR becomes the system-of-systems (SoS).

Moreover, the CR platforms and architectural solutions are common and trending in the field of CR. Therefore, we have performed a literature review related to the platforms and architecture for the CR platform. For that, we studied existing architectural works under five levels (L1 [1]–[11], L2 [12]–[19], L3 [20]–[37], L4 [38]–[44], and L5 our work with [45], [46]). L1 and L2 are system architectures (SA) and framework solutions before and after 2017, L3 is reference architectures (RA) and framework solutions, L4 is RoboEarth and Rapyuta related projects, and L5 is literature works discussing beyond Industry 4.0 next-generation CR. According to our requirements, we perceived that the architectural design process (ADP), provisions for industrial evolution (PIE), and provisions for secured heterogeneity (PSH) are three of the most important for heterogeneous-robotics platforms. Based on the literature review, there is a considerable gap in the next-generation works studied, including ADP, PIE, and PSH. Nevertheless, the top-down (model-based) ADP is laying a solid foundation for the sustainable end product of the SoS. Thus, we employed a top-down design approach. Moreover, considering the complexity constraints of SoS, our experiences in CR domain, and survey of CR architecture, we learned that unified architecture framework (UAF) is a cognitive approach. Therefore, we proposed a model-driven next-generation CR (MNCR) platform (MNCRP). More details related to the literature review and reasoning both UAF and MNCRP have been discussed in Subsection A of Section VI.

FIGURE 1. Fukushima robot test field and facilities.

B. REQUIREMENTS, ISSUES, AND PROPOSED SOLUTIONS OF SYSTEMS INVOLVING SoS

The storage and file systems are two key components of the cloud platform. The centralized cloud server architecture inherits certain shortcomings, such as loss of control (privacy and data breaches), unexpected expenses (maintenance, bandwidth, and bottlenecks), and single point of failure [47]–[49]. Then, these issues are major reasons for discouraging the adoption of a centralized platform of cloud computing for heterogeneous robotics. This issue can be addressed by employing a containerized federated environment (such as maintaining multiple Kubernete clusters) and a decentralized cloud environment. However, a containerized federated architecture tends to hinge on the end user, and its software is limited by its supporting container providers as well as seamless connection, geo-distribution, and cross-connection (intra and inter) constraints. However, using a decentralized cloud is a relatively more holistic approach and can better address the aforementioned constraints than the centralized federated architecture [48], [49]. Therefore, decentralized cloud computing has been proposed to mitigate issues in centralized cloud architecture. Commonly it uses the central cloud and edge computing layers in a decentralized architecture [50]–[52].

Nevertheless, according to our experiences and observations regarding the time constraints of robot workflows (in data acquiring, storing, processing, and delivering/transmitting the results), we identified three layers of emergencies; the first layer and the foremost emergency is the real time, the second is the middle layer, and the last is the batch process (can tolerate certain delaying times). Therefore, we proposed a three-layered decentralized architecture, including edge, fog, and central cloud layers to address the time constraints of robotics workflows.

The real-time workflows seek real-time results that involve embedded data and data in a fog layer. Near real-time workflows consume data in edge, fog, and some amount of central cloud layers; and the third central cloud layer involves multiple batches of data sources used in AI, machine learning, and predictive analytics. Microsoft Databox and Amazon Snowball and Snowmobile are tools that are becoming popular for edge computing, and they facilitate multicloud (edge, fog, and central) synchronization [53], [54]. Therefore, to address issues in time constraints and mitigate issues in the central cloud architecture, we proposed a multilayered cloud computing environment that comprises edge, fog, and central cloud layers. We called this decentralized cloud environment the decentralized multicloud (DMC) and the proposed DMC for the MNCRP is called the DMC framework module.

In addition, heterogeneous CR involving NCGRP should manage extremely large volumes of data that show the

3Vs. Then, it is an obvious requirement to cope with the cost of hardware, scalability of file systems, failures, and recovery of the file system. The Hadoop distributed file system (HDFS) is the prevalent technology to address the presented issues [55], [56]. However, most of the robots, including drones, self-driving vehicles, and disaster response robots, are highly dynamic and move in geographically different locations. Then, HDFS should be able to accommodate geo-distribution behavior as well [57]–[59]. Therefore, we proposed DMC to adapt to the framework module for geo-distributed HDFS (GD-HDFS).

Moreover, the robot operating system (ROS) is the prevalent middleware for the robot domain [60]. Therefore, the ROS must be adapted for the MNCRP. Koubaa *et al.* and Ali *et al.* discussed ROS adapted for the HDFS [9], [10]. With respect to the GD-HDFS awareness in the MNCRP, we propose to extend the HDFS ROS to the GD-HDFS supporting ROS. Nevertheless, a gateway for adapting utility technologies must be maintained for the GD-HDFS. Therefore, we proposed a framework for adapting middleware for utility technologies (MUT) in GD-HDFS that included ROS.

Nevertheless, scaling and containerizing are two trending requirements in the robots, such as swarm robots, in synchronized fleets of drones and warehouse robots. Therefore, we proposed to employ a container orchestration engine (COE) such as Docker-swarm, Kubernete, or Apache Mesos Marathon [61]–[64]. We proposed COE for the MNCRP called the COE framework module.

Meanwhile, using the Industry 4.0 set gives us enormous opportunities, involving the digital transformation of the industry with the integration and digitalization of industrial processes that comprise the value chain empowered by Big Tech (IoT, robotics, AI, and Big Data) and characterized by adaptability, flexibility, and efficiency that can cover customers' needs in the current market. Autonomy, interoperability, and sustainability [65], [66] are certain benchmarks set to be achieved as the goals of Industry 4.0. Meantime, those gains result in certain drawbacks to the current society, which is Society 4.0 [67].

Therefore, Society 5.0 has been introduced by the Japanese government to alleviate the socio-economic crisis that tends to be caused by the Big Tech of Industry 4.0. Society 5.0 aims to address the fissional society structure caused by the fusion of cyber and physical spaces. Moreover, the prime objective of Society 5.0 is to balance the economic advancement with the resolution of social problems and restore a human-centric society and its values [68]–[71]. Therefore, a cross-sectional knowledge sharing, cooperation, and reform ecosystem has been defined as the set of norms for Society 5.0 and are the key areas that need to be achieved.

This implies that Industry 4.0 and Society 5.0 are inseparable entities that should be considered when engaging in next-generation research and development. Therefore, we try our best to adhere to those benchmarks and norms with this proposal.

Automation is a key part of autonomy [65], and we have identified three key areas of automation that need to be implemented, including the front end, middle end, and back end. At the front end, automation mechanisms need to acquire raw data and release a requested output. At the back end, they need to automate the workflow requirements of the robotics processes involved in the platform. Moreover, at the middle end, they need to manage all requests (incoming and outgoing) of internal resources (SoS) with respect to their allocated tasks within their defined boundaries. In addition, the middle end should smoothly communicate with the front end and back end. The multiagent technique is a cognitive approach that handles different intelligent approaches as a unified solution for multiagent for automation (MAA) framework modules. Moreover, the MAA front-end (MAA-FE) agent remains abstract. Regarding the MAA middle-end (MAA-ME) requirement, the agent needs to smoothly communicate with the resources (SoS) within the infrastructure and both MAA-FE and MAA-BE. Open platform communication unified architecture (OPC-UA) is a well-known and prevalent technique that satisfies that requirement [72]–[74]. Therefore, we proposed to employ OPC-UA as the MAA-ME. Moreover, workflow automation (MEE-BE requirement) is one of the trending and leading concerns in the domain. Robots heavily involve big data (3V data); consequently, the big data involving workflows must be automated. Nevertheless, we are working on cloud-infrastructure and then web services became the preferred technique for data analysis in the cloud era. Then, a framework for automatic service composition (ASC) is a cognitive solution to automate Big Data involving robotic workflows [75], [76]. Therefore, we propose to employ ASC-based workflow automation intelligent agent to fulfill the requirement of the MAA-BE. We propose the extended works of ASC [75], [76] to facilitate the intelligent back-end agent requirements of the MAA.

Moreover, as shown in previous studies, a digital twin is the next important factor behind autonomy [77], [78]. A digital twin is the virtual representation of physical components that allow for optimizing, monitoring, controlling, and real-time predicting improved decision making and failures via the data and simulators. The representation employs computational pipelines, multi-physics solvers, artificial intelligence, big data cybernetics, data processing, and management tools to realize the digital twin [65], [66], [77]. It is an important and emerging trend in many applications of the robotics domain. NASA, Boeing, and robotics involving various industries are rapidly employing a digital twin as a tool [78]. Therefore, we proposed a framework module for digital twin modeling, and simulation (DTMS).

With respect to the benchmarks of Industry 4.0, autonomy and interoperability seemingly conflict with each other, and it is therefore challenging to provide both together. Moreover, interoperability may lead to creating new products and services, and drone information can be shared with weather forecasting, photogrammetry, and streaming [79]–[81]. DMC leads to an increase in the autonomy and helps to maintain the isles of each data and resource repos in a given platform. However, we should facilitate interoperability in addition to the autonomy that may reduce the quality factor of autonomy because both are inversely proportional. Blockchain is one of the leading practices in the industry that provides a solid foundation for secured interoperability as well as a single point of failure in central cloud architecture [82], [83]. However, blockchain suffers severe latency. Crosschain has been introduced to alleviate the latency concern in blockchain networks [82]–[84]. Therefore, we propose to employ a framework module for extended crosschain-based blockchain (ECB) to facilitate interoperability as well as secured autonomy.

Knowledge sharing is one of the leading trends in the robotics domain. That allows access and enables robots to autonomously share knowledge with each other and to generate new knowledge from previously stored data. As a result, robots do not have to gain the same knowledge repeatedly, but they can build upon it right from the start. RoboEarth, DAvinCi, and Rapyuta are well-known knowledge-sharing platforms that currently exist [1], [42], [43]. However, they facilitate intra-platform knowledge sharing. The knowledge-sharing norm set by Society 5.0 is both side of cross platforms (inter and intra) supporting knowledge-sharing techniques, thus allowing for the generation of new products and services. Ontology knowledge management is one of the leading knowledge representation and reasoning techniques [3], [17], [42], [44]. Therefore, we proposed a framework module for information as a service based on domain ontology and web services (ISOW) for the overall robotic domain and maintaining individual instances (meta-ontology) as a subset of the respectful domain. Then, information owners can define access limits (encapsulation) of their knowledge bases, and knowledge seekers can write rules and queries for the required information (information/ knowledge) within their access limits via the web services.

Cooperation is another way to achieve interoperability of two or more instances, which provides service for third-party users in the domain. We hope framework modules of ECB and ISOW facilitate the cooperation of the MNCRP. The sustainability benchmark set by Industry 4.0 and the reform ecosystem are seemingly quite parallel. As long as an ecosystem is stable and facilitates reformation (adaptable), it is a sustainable solution. We propose a model for the RA and conceive RA from the proposed model, both of which are well-known generic solutions [85], [86]. Therefore, by providing a model and a generic solution rather than an ad hoc and bespoke/strict solution, we strongly believe our solution can adapt to provide necessary improvements and is customizable for future requirements. In addition, our proposal, which aggregates benchmarks of Industry 4.0 and norms of Society 5.0, is generations ahead of Industry 4.0. Moreover, Industry 5.0 reflects personalized autonomous manufacturing with a human-centric solution. Nevertheless, the proposed solution (Industry 4.0 and Society 5.0) is just behind Industry 5.0. Therefore, we call our proposal the Industry 4.5 generation.

C. OUTLINE

Our three key contributions are listed as follows:

1. Elucidating a model for the MNCRP design process.
2. Deriving RA and abstract SA of the MNCRP from the proposed model.
3. Administering a survey for CR architectures with respect to ADP, PIE, and PSH.

Regarding the limitations, the proposed RA and abstract SA are high-level-capability architecture without rich operations and resource architectures. To the best of our knowledge, we are the first to propose performing a detailed survey with respect to the ADP, PIE, and PSH and developing a model for the MNCRP, RA, and abstract SA representations.

The remainder of the paper is structured as follows. In Section II, we discuss the motivation scenarios. In Section III, we present ADP and disambiguation of RA. Section IV presents reasoning abstract model and derives RA for MNCRP. In Section V, we discuss use cases and abstract SA. Section VI discusses the conducted survey on the existing works of CR architecture with respect to the heterogeneous architectural perspective, and Section VII concludes the paper.

II. MOTIVATING SCENARIO: FUKUSHIMA-RTF

Our objective is to find and propose an MNCRP. We plan to derive abstract normative and nonnormative representations for the MNCRP. Scenario 1 and scenario 2 are focused on development while considering those two perspectives. As shown in Fig. 2(a), scenario 1 improves the ease of developing a model for the MNCRP. Then, as shown in Fig. 2 (b), in scenario 2, we propose abstract SA solutions for the MNCRP. Moreover, frequently used acronyms are listed in Table 1.

Scenario 1: This scenario involves the architectural design and the modeling process of the MNCRP. As shown in Fig. 1,

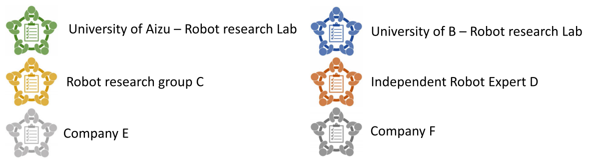
TABLE 1. Frequently used acronyms used in the paper.

Term	Description
CR	Cloud-robotics
MNCRP	Model-driven next-generation cloud-robotics platform
RA, SA	Reference architecture, system architecture
DCM	Decentralized multi-cloud
GD-HDFS	Geo-distributed Hadoop distributed file system
MUT	Middleware for adapting utility technologies
COE	Container orchestration engine
MAA, FE, ME, BE	Multi agent for automation, Front-end, Middle-end, Back-end
ASC	Automatic service composition
DTMS	Digital twin modelling and simulation
ECB	Extended crosschain for blockchain
ISOW	Information as service based on domain ontology and web services
L1, L2	Literature SA works published before 2012, and after 2012
L3	Literature works related to RA
L4, L5	Literature related Robot earth & Rapyuta, and Industry 5
ADP	Architectural design process
PIE	Provisions for industrial evolution
PSH	Provisions for secured heterogeneity

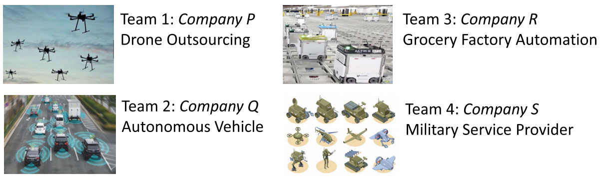
Fukushima-RTF is a resource center for research, development, and test facilities for heterogeneous-robotics works of private and public researchers around the globe. Therefore, now it is an essential requirement for a cloud platform for a data lake as well as processing requirements of CR. Therefore, Fukushima-RTF has begun an initiative for the joint research for a cloud platform for heterogeneous CR requirements. Fig. 2(a) shows the key stakeholders responsible for innovating and renovating Fukushima-RTF. The University of Aizu (UoA) CR research group is the designated key software solution designer and provider of the Fukushima-RTF. Therefore, this project became one of their main projects on behalf of the Fukushima-RTF. Because of the complexity of the SoS project, it has involved other stakeholders (public and private partners of the Fukushima-RTF) of this research project. Public partners are the University of B, Robot research group C, and independent researcher D. Private partners are Company E and Company F. Therefore, the project has become a crowdsourced research project. Moreover, in the beginning, the UoA CR research team was responsible for proposing a bespoke RA for CR that could initiate research and develop a sophisticated CR platform for Fukushima-RTF. Nevertheless, Fukushima-RTF is a government-funded project. Meanwhile, the Japan prime minister office set norms for Society 5.0, and they also have certain benchmarks for achieving Industry 4.0. Then, the UoA CR team should consider government initiatives for the sustainable ICT development of Japan.

Scenario 2: This involves four end-user teams of MNCRP. Fig. 2(b) depicts the teams involved in scenario 2.

Team 1: *Team 1* involves a fleet of drones outsourced with diversified business requirements by *company P*. *Company P* mainly focuses on three areas. First, it outsources drones to deliver goods and groceries for retail customers of e-commerce *company R*. Next, it outsources to collect acute weather information (humidity, temperature, smoke, methane, carbon dioxide, wind speed, and direction). Moreover, it involves photogrammetry and streaming services for on-demand requests for various third-party end users such as traffic involving, self-driving vehicles, land surveying, rescue, and military companies. That information is used by *companies Q, R,* and *S.*



(a): Scenario 1 involving stakeholders (R&D) for MNCRP



(b): Scenario 2 involves stakeholders (end users) of MNCRP

FIGURE 2. Scenario 1 and scenario 2 involve stakeholders.

Team 2: *Team* 2 is a self-driving vehicle vendor *company Q*. Those vehicles aim to drive the shortest time possible while minimizing constraints including traffic disturbance, collisions, accidents, and weather constraints. Vehicles in the fleet exchange dynamic information about traffic and other information about the road. To enhance the operational efficiency of *company Q*, on-demand weather and photography services from *company P* are solicited.

Team 3: *Team 3* mainly involves the automated grocery factory chain of *company R*. Moreover, *company R* depends on on-demand real-time weather and traffic information outsourced by *company P.*

Team 4: *Team 4* is a security contractor of *Company S*. *Company S* uses heterogeneous military robots that are specialized under given joint missions with dedicated tasks in air, under water, and on the ground. *Company S* also solicits required information from *Company P*. However, the information in *company S* is considered highly sensitive and confidential.

III. ADP AND DISAMBIGUATION OF RA

In this section, we propose the ADP and disambiguation of RA for heterogeneous-robotics platform.

Subsection A discusses the background, and Subsection B discusses the multidimensional space and its subdimensions involving the ADP for the framework of MNCRP.

A. BACKGROUND

Our objectives are designing/modeling a framework for MNCRP that involves collaboration to derive a consumable concrete solution from the framework for MNCRP. Fig. 3 shows the abstract flow that we planned to go through from the beginning to the concrete solution. As shown in the figure, our context is CR, and the goal is the framework for MNCRP. Afterward, first, it goes through the modeling process, and in the next stage, it derives a consumable solution. In the modeling phase, first, the process modeled a framework for RA. Next, we derived a RA for MNCRP, and as the third and final step, we derived SA from the RA. Moreover, in this paper, we focused on the aforementioned two steps of the modeling phase.

Fig. 4 derived from Fig. 3. In the modeling process of a framework for RA for MNCRP, we observed that Angelov *et al.* proposed that designing and modeling RAs is one of the key contributions in the field [86]. However, our final goal includes not only designing/modeling a framework for MNCRP but also deriving respective RA, SA, and consumable solutions. Moreover, their work shows key constraints with respect to our final goal. One of them is that only two standard *RA* works have been proposed, which are beyond our requirements. The first one is standardization RAs, which are incorporated with only fully tested and accepted elements. The second one is facilitation RAs, which are designed at multiple organizations by multiple software organizations. According to them, such works imply that software organizations might lose their advantage over their competitors without obtaining any benefits from this effort. Moreover, user organizations will not have an incentive to design a RA that facilitates their software providers as well. However, we have to satisfy certain benchmarks of Industry 4.0 and norms of Society 5.0 that are changing the technological landscape, and most of the solutions for both cases are still in the abstract definition stage or research and development (R&D) stage. Nevertheless, our goal is mission oriented rather than being profit oriented; consequently, it is more likely to be crowdsourced. Therefore, our objective deviates from two key RAs of Angelov's work. Therefore, we extend his work to comply with our requirement of having necessary improvements to adapt to our scenario/requirement.

Generally, RA refers to abstractions of concrete software architecture from a certain domain. Here, software architecture refers to the SA. Then, the CR context and modeling for architecture are used to accomplish the constraints c_i, i set of constraints set off against the goals of the objective. Fig. 4 is derived from Fig. 3 and shows the necessary steps that we plan to go through when modeling. Therefore, according to Fig. 4, we follow the given abstract flows of the model and determine the end solution. Here *context* C, *goal* G, and *model* M comprise the multidimensional space of the overall ADP. Then, C is C_{CR}, C_{CR} is fixed to the CR domain with the CR goal G framework solution to MNCRP for a given $R_{i,}\, i$ representing a class of CR requirements, and M decides with respect to the G. Next, we have to decide the flow of deciding the *RA* and *SA* for the given R_i of the C_{CR}. Fig. 4 shows that the RA consumes the relevant model and principle for MNCRP for the *RA* of the CR. Moreover, it prepares *SA* based on the *RA*.

Besides, according to the MNCRP architectural planning and designing perspective, we observe four important properties from the literature and our experiences: (p_1) Abstract definition of the core of the CR. (p_2) There is more than data lake, workflow automation, data processing, map generation, coordination and configuration engines, databases, and monitoring. (p_3) Several architectural principles have been applied, and loose coupling and scalabilities are essential. (p_4) There seem to be more consensus about the principles and best practices such as adhering to benchmarks of Industry 4.0 and norms of Society 5.0. Therefore, the proposed RA belongs to the structured RA domain with respect to the structured and unstructured classification of the RA.

Next, we aim to identify the abstraction model for the RA and model the framework for MNCRP, as shown in Fig. 4.

B. MULTIDIMENSIONAL SPACE AND ITS SUBDIMENSIONS

Fig. 5 depicts the multidimensions indicated in Fig. 4, their subdimensions, and types of RAs. First, we define three main dimensions, their subdimensions, and our objective behind RA with respect to the reference modeling. Fig. 5 shows the pathway for reasoning and modeling the abstraction model for the RA. Afterward, we model the adequate RA for MNCRP. First, we define the stakeholder.

Definition 1 (Stakeholder): A *stakeholder* is an individual, organization, or institution that adopts and adapts an adequate software reference model to R&D to scale up or down to comply with a set of specific requirements R_i, i representing a class of given requirements and under a certain domain. A given *stakeholder* can belong to either a requirement provider (end users and experts) for *RA* or the model users of the *RA*.

The *Context* (C) main dimension as shown in Fig. 5 and subdimensions of C are as follows: C_1: *Where will it be used?*; C_2: *Who defines it?*; and C_3: *When is it defined.*

According to scenarios 1 and 2, *Stakeholders* provide requirements R_i^{CR} for CR domain called as consumer/client of CR, and a *stakeholder* works to model a solution to satisfy a given R_i^{CR} called the modeling architect *stakeholder* of CR.

Definition 2 (Context (C)): A reference model satisfies a set of certain constraints $c_i's$ by stakeholders and a set of properties p_i for a solution.

With respect to scenario 1, the *context* becomes C^{CR}. Subdimensions of the C^{CR} are, C_1^{CR}, C_2^{CR}, and C_3^{CR}.

Definition 3 (C_1): Where will it be used? Stakeholders of the proposed *RA* are described under this subdimension. The division of the *Stakeholders* depends on the desired basic clientele/end-user properties. The proposed C_1 can be termed *single*, *many*, or *heterogeneous*. *Single* represents an independent user for identical user requirements of the proposed system, *many* implies an analogous (same) type of many organizations or companies for the same types of multiple requirements, and *heterogeneous* implies diverse types of users or organizations who are focused on diverse requirements.

Definition 4 (C_2): Who defines it? C_2 refers to the modeling aspect of the *RA*. *Stakeholder* represents the purpose of the *RA* and the overall system. It involves either *requirement-specification* or *modeling* for adopting or adapting the system.

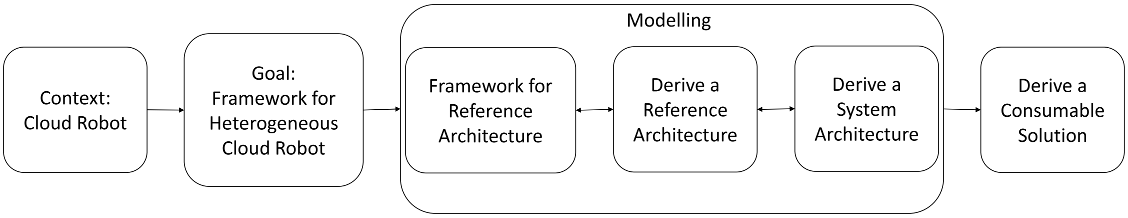


FIGURE 3. Abstract flow of decide, design, and derive a solution.

The *requirement-specification* provider is a user or users of C_1. The *modeler* for adopting or adapting is either *a research group, software company,* or *policy makers.* The *research group* is either an independent researcher or group of researchers or nonprofit software organization; a *software company* means a commercial software vendor group, and *policy maker* is a governmental or nongovernmental organization or independent who is working for policy decisions on *structured* or *unstructured* systems.

Definition 5 (C_3): When is it defined? C_3 refers to the timing aspect of the proposed system. The C_3 comprises *preliminary*, *classical*, or *hybrid*. The *preliminary* refers to the proposed RA composed components (software, technologies, and algorithms) that are still being considered to inspire per the guideline for the domain, while *classical* implies the proposed RA composed components (software, technologies, and algorithms) that already exist and are verified for public use. The *hybrid* RA refers to the set of components showing *preliminary* characteristics and the remaining components show *classical* characteristics.

According to the main dimensions C and respective subdimensions of C, we define Eq. set (1) as follows.

$$Context\ C = \{C_1, C_2, C_3\} \tag{1}$$
$$C_1 = [single, many, heterogeneous] \tag{1a}$$
$$C_2 = [req.\text{-}specifying\text{-}user, modeling\text{-}user] \tag{1b}$$
$$req.\text{-}specifying\text{-}user = C_1$$
$$mod.\text{-}user = (research, software\text{-}comp, policymakers)$$
$$C_3 = [preliminary, classical, hybrid] \tag{1c}$$

According to the Eq. set (1), the main dimension C^{CR} refers to the main dimensions adapted for CR.

Moreover, according to our objectives of the MNCRP and scenario 1, respective subdimensions that are considered refer to C_1^{CR} being the *stakeholder* who will use the end product. According to scenario 1, the end product is for heterogeneous MNCRP users for their heterogeneous CR requirements. Therefore, C_1^{CR} becomes *heterogeneous*.

C_2^{CR} refers to when the *stakeholder* involves CR modeling either the *requirement-specification-provider* or adapting RA for the CR requirement. Alternatively, the *stakeholder* can represent the *stakeholder* role described in C_1. Thus, in our case, it is *heterogeneous*.

Nevertheless, the proposed *RA* should be extendable and adaptable for evolving CR requirements and characteristics of *RA*. Therefore, the proposed C_3^{CR} remains *hybrid*.

Eq. set (1) is adapted as Eq. set (1') as follows:

$$C^{CR} = [C_1^{CR}, C_2^{CR}, C_3^{CR}], \tag{1'}$$
$$C_1^{CR} = [heterogeneous], \tag{1a'}$$
$$C_2^{CR} = [req.\text{-}specifying\text{-}user :: heterogeneous\text{-}org, modeling\text{-}user :: heterogeneous\text{-}org], \tag{1b'}$$
$$C_3^{CR} = [hybrid]. \tag{1c'}$$

Next, we define the *Goal* (G) of Fig. 5 and subdimensions.

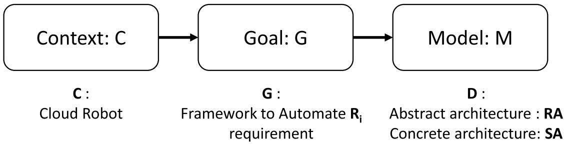
Definition 6 (Goal (G)): G refers to the objective of the RA and the proposed system. G may be a *subgoal* or a goal made by collections of subgoals. G involves intensions of stakeholders defined in C_2, and G can decompose into G_1: *Which stage needs to be defined?* and G_2: *Whose defined it?*

Definition 7 (G_1): Which stage needs to be defined? Subdimension G_1 refers to the stage of the *RA* and it comprises *standardization, facilitation*, and *incubation* stages. G_1 correlates with C_1 and C_3. If any member of *stakeholder* C_1 shows *preliminary* characteristics of C_3, then that *RA* is in the *standardization stage RA*. If the C_3 characteristics are *classical, then* that *RA* is in the *facilitation stage RA*, and if the C_3 characteristics are *hybrid, then* that *RA* is in *incubation stage RA.* All are proposed unilaterally by a company, group of researchers, or independent researcher. Nevertheless, components and elements in *incubation* RA works can comprise concrete, R&D, or abstract definition (hypothetical/conceptual) stages.

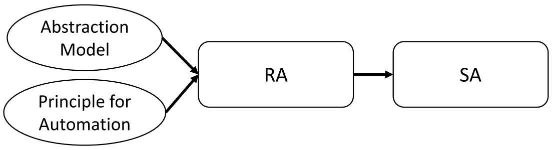
Definition 8 (G_2): Whose is defined? Subdimension G_2 represents the ownership and purpose of G. Therefore, G involves possible outcomes of the combinations of C_1 and C_2. G_2 is the primary end user of the combination of C_1 and C_2.

According to the main dimensions, G and respective subdimensions of G can line up in Eq. set (2) as follows.

$$Goal\ G = \{G_1, G_2\text{: } subgoal, \cup\ subgoal\} \tag{2}$$
$$G_1 = [C_1.C_3\text{: } standardization, facilitation, incubation] \tag{2a}$$



a. Abstract flow of decide a framework solution



b. Abstract flow of design a framework solution

FIGURE 4. Abstract decision flow for framework MNCRP.

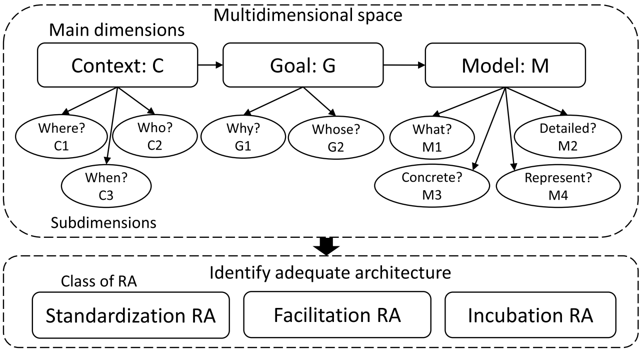


FIGURE 5. Subdimensions of multidimensions and classes of RAs.

$$G_2 = [single.C_2, many.C_2, heterogeneous.C_2] \tag{2b}$$

According to the Eq. set (2) and scenario 1, the main dimension G^{CR} refers to the main dimension G adapted for CR. The proposed *RA* for G^{CR} models the heterogeneous requirements of MNCRP. Moreover, C_3^{CR} is a *hybrid*, meaning that G_1^{CR} undergoes *incubation* with respect to the components involving the incubation stage and *heterogeneous stakeholders*. Nevertheless, representatives (*stakeholders*) of the respective goals of the CR will be *heterogeneous*. Here, G_1^{CR} and G_2^{CR} become multidimensional representations because they consume two-dimensional property values to representation.

Then Eq. set (2) adapts for CR, as shown in Eq. set (2').

$$G^{CR} = \{G_1^{CR}, G_2^{CR} : \cup \text{ subgoal}\} \tag{2'}$$

$$G_1^{CR} = [\text{Stakeholder:}\textit{hetero} \text{ ::stage:}\textit{incubation}] \tag{2a'}$$

$$\begin{aligned} G_2^{CR} = [&\text{Stakeholder:}\textit{hetero} \text{ ::OwnedBy:}\textit{req-spec-user},\\ &\text{Stakeholder:}\textit{hetero} \text{ ::OwnedBy:}\textit{model.-user}] \end{aligned} \tag{2b'}$$

Next, we define the respective main dimensions M and subdimensions of M, as shown in Fig. 5.

Definition 9 (Model (M)): The M dimension refers to abstract modeling aspects of the *RA* and overall system. In contrast, M refers to the design and specification. M comprises four subdimensions, including M_1: *What is described?;* M_2: *In how much detail is it described?;* M_3: *How concretely is it described?;* and M_4: *How is it represented?*

Definition 10 (M_1): What is described? The M_1 subdimension refers to the contents of the *RA*. M_1 briefs information of components (software, technologies, and algorithms), connectors, and flow of information, which is tailored for the context C of the *RA*.

Definition 11 (M_2): In how much detail is it described? The M_2 subdimension refers to the details of layers and components of the M_1 subdimensions. M_2 was further divided into three levels, *semidetailed*, *detailed*, and *aggregated,* as regards the information flow, layers, and components of the context C of the *RA*. It uses measuring methods because of the complexity of the detailing contents of M_1. A number of elements and several explicit aggregation levels of the RA were used as the specification. The *aggregation RA* refers to *RAs* having few elements and defines a single level of aggregation belonging to the other end of the dimension. The *semidetailed RA* refers to *RA*s comprising many elements, and two to four aggregation levels belong in this dimension. The *detailed RA* refers to *RA* work, which comprises more than five levels of aggregation.

Definition 12 (M_3): How concretely is it described? M_3 lists the possible levels of abstraction of a *RA*. Abstraction is related to the level of choices made in architecture in terms of technology, applications, and vendors. It needs to limit the values to *abstract*, *semiconcrete*, and *concrete*. As an example, a *semiconcrete RA* defines components that specify a specific class of options for each element in the architecture. A *concrete RA* specifies the choice from the class of options for each element. For example, an *abstract RA* may indicate that a given component is an edge layer, a *semiconcrete RA* may use the specification "edge-device/portable data source," while a *concrete RA* expresses "Microsoft Databox" or "Amazon Snowball," or "Amazon Snowmobile."

Definition 13 (M_4): How is it represented? The M_4 subdimension refers to the possible levels of formalization and semantics of *RA*. *Informal, semiformal,* and *formal* are levels of M_4. The respective three levels are operational as follows. An *informal* representation of (a part of) RA uses a general description or incomplete graphical representation. Therefore, it leaves freedom to expand the respective components with ambiguity. *Semiformal* implies that representation has been well-defined (however, modeling for the general solution has not yet been devised). Moreover, *formal* representation, however, still has freedom for ambiguity.

Eq. set (3) represents the values of the main dimension and respective subdimensions of M.

$$\textit{Model } M = \{M_1, M_2, M_3, M_4\} \tag{3}$$

$$M_1 = [\textit{components}, \textit{connectors}, \textit{information flow}] \tag{3a}$$

$$M_2 = [\textit{aggregated}, \textit{semidetailed}, \textit{detailed}] \tag{3b}$$

$$M_3 = [\textit{abstract}, \textit{semiconcrete}, \textit{concrete}] \tag{3c}$$

$$M_4 = [\textit{informal}, \textit{semiformal}, \textit{formal}] \tag{3d}$$

According to the Eq. set (3), the main dimension M^{CR} refers to the main dimensions adapted for CR. Moreover, M_1^{CR}, M_2^{CR}, M_3^{CR}, and M_4^{CR} refer to the respective subdimensions, which are adopted for the CR domain during proposing *RA*. Therefore, respective subdimensions with respective to our scenario can refer to the following Eq. set (3').

$$M^{CR} = \{M_1^{CR}, M_2^{CR}, M_3^{CR}, M_4^{CR}\} \tag{3'}$$

$$M_1^{CR} = [\textit{components}, \textit{connectors}, \textit{information flow}] \tag{3a'}$$

$$M_2^{CR} = [\textit{semidetailed}] \tag{3b'}$$

$$M_3^{CR} = [\textit{semiconcrete}] \tag{3c'}$$

$$M_4^{CR} = [\textit{semiformal}] \tag{3d'}$$

IV. REASONING ABSTRACTION MODEL AND DERIVES RA FOR MNCRP

This section discusses the reasoning the abstraction model for the framework for MNCRP and derives RA for the MNCRP.

Fig. 5 shows three classes of RA, which are *standardization, facilitation*, and *incubation*. Table 2 summarizes the properties and their values of multidimensional space scored by the proposed RA for the MNCRP. Our proposal mainly belongs to the *incubation* class dedicated to the *stakeholder* responsible for modeling by the *heterogeneous* systems. Moreover, each type of main class may contain many variations according to their type of *stakeholder* involved in the model *RA*. From here onward, we are limited only with respect to the variation shown in Table 2.

According to G_1^{CR}, the proposed solution is modeling to both adopt and adapt *heterogeneous* (stakeholder and use cases) as *incubation RA* work. G_2^{CR} is a joint contribution of C_1 and C_2, thus referring to the proposed *RA* for the heterogeneous users who are seeking to adapt (scale up or down) MNCRP architecture as a service with respect to the limit to access diverse resources and their requirements. Then, both aspects imply that the proposed solution is a kind of *crowdsource incubation RA* that works for the CR domain.

Then according the resultant modeling criteria of M_1^{CR}, M_2^{CR}, M_3^{CR}, and M_4^{CR}, Fig. 6 graphically represents the *incubation RA* for the CR *context*.

According to the M_1^{CR}, we determine the components (software, technologies, and algorithms), connectors, and flow of information of the proposed *RA*. Basically, we must determine the three main components of the C^{CR}. Those are deciding how to accomplish MNCRP. Next, at the M_2^{CR}, we determine the respective components at least in a *semidetailed* manner. Afterward, based on M_3^{CR}, we determine the respective property values in a *semiconcrete* manner. *Eq. set (4)* denotes the respect subdimensional values of M after adapting for our domain specifications.

$$\begin{aligned}
M_1^{CR} &= [components, connectors\ \&\ flow] && (4a)\\
M_2^{CR} &= [Physical\ Layer : end\text{-}use\ cases,\\
&\quad Infrastructure\ Layer : CR\text{-}Eco\text{-}Sys,\\
&\quad Analytical\ Layer : AMG\text{-}BE] && (4b)\\
M_3^{CR} &= [Physical\ Layer :\ Heterogenous\ CR\ use\ cases,\\
&\quad Infra.\ Layer\text{-}CR\text{-}Eco\text{-}Sys :\\
&\quad (DMC, GD\text{-}HDFS, MUT, COE, ECB,\\
&\quad MAA\text{-}FE\text{-}ME\text{-}BE, DTMS, ISOW),\\
&\quad Analytical\ Layer : ASC(MAA\text{-}BE)] && (4c)
\end{aligned}$$

As mentioned, we defined the M_1^{CR}, M_2^{CR}, and M_3^{CR}. Regarding the SoS of the UAF, we represent the M_4^{CR} in two ways, which are normative representation and nonnormative representation. We used the term RA for the normative representation of M_4^{CR} and that depicted by Fig. 6. For the nonnormative representation, we used high-level SA, as shown in Fig. 7. We employ the ArchiMate modeling tool to devise the normative representation of the RA for the MNCRP [87]. The ArchiMate is open and the independent enterprise architecture modeling toolkit supports the description, analysis, and visualization of architecture within and across business domains. The normative M_4^{CR} contains three main layers, which are the *physical layer, infrastructure layer*, and *analytical layer.* Here, we give a brief introduction to the respective layers, components, and connectors. All the main and subcomponents of *detail, concreteness*, and *representation* are defined in the *semidetailed, semiconcrete*, and *semiformal* manner, respectively.

TABLE 2. Summarized information of main & subdimensions.

Dimensions			Value		
Main	Sub				
G^{CR}	G_1^{CR} :	Which	Stakeholder:: *Heterogeneous-org*	→	Stage::*Incubation*
	G_2^{CR} :	Whose	Stakeholder:: *Heterogeneous-org*	→	OwnedBy:: *Requirement-specification-provider* OwnedBy:: *Modeling-user*
↓			↓		
C^{CR}	C_1^{CR} :	Where	Heterogenous-org		
	C_2^{CR} :	Who	Requirement-specification-provider	→	Heterogeneous-org
			Modeling-user	→	Heterogeneous-org
	C_3^{CR} :	When	hybrid		
↓			↓		
M^{CR}	M_1^{CR} :	What	Components, Connectors, information-flow		
	M_2^{CR} :	Detailed	Semidetailed		
	M_3^{CR} :	Concrete	Semiconcrete		
	M_4^{CR} :	Represent	Semiformal		

The *physical layer*: This layer maintains heterogeneous robots and end users of the MNCRP. End users described in scenario 2 dominate in this layer. All users use the same MNCRP for their heterogeneous CR requirements.

The *infrastructure layer*: This layer is dominated by *CR-Eco-Sys*. The *CR-Eco-Sys* comprises a collection of framework modules that accomplish dedicated jobs and are defined in a *semiformal* manner. *DMC, GD-HDFS, MUT, COE, ECB, MAA-FE, MAA-ME, DTMS,* and *ISOW* are respective framework modules proposed in the *CR-Eco-Sys*.

The *analytical layer:* This layer is responsible for the operations of *MAA-BE*. The *ASC* is responsible for automating all data science-related workflows involving the analytics in the MNCRP.

DMC: This is responsible for maintaining the decentralized CR ecosystem of the MNCRP. The *DMC* three main subcomponents include edge, fog, and central cloud.

GD-HDFS: This component maintains a fault-tolerant geo-distributed Hadoop distributed file system facility. The *GD-HDFS* provides provisions for cost-effective (due commodity hardware, filesystem shares the hardware with the computation framework as well), scalable, resilient to failure (bounce back effectively), and fault tolerance (operating without interruption) data management.

MUT: This component is responsible for adapting required utility middleware technologies including ROS and tools involving CR to the *GD-HDFS* environment.

COE: This component is responsible for managing the scalability of end users' custom environments (container orchestration) across the geo-distributed DMC environments.

MAA: This component is responsible for managing the automation ability across the platform. In summary, it acts as an interface agent and takes intelligent decisions. To ease the operational factors and characteristics of the overall process, we have divided the *MAA* module into three subcomponents. The front-end operation of the *MAA* managed by the *MAA-FE agent,* the middle-end operation manages by the *MAA-ME agent* and the back-end operation manages by the *MAA-BE agent.* The *MAA-FE* is responsible for dealing with all requests coming from the *physical layer*. Moreover, it activates an adequate waypoint of the *MAA-FE agent* and drives that request to an adequate waypoint of the middle agent. The *MAA-ME* is responsible for automatically managing that given task across the components with respect to their request's inputs and outputs. Then, *MAA-BE* is responsible for automating the required analytical and data science requirements (big data analytics, deep learning, or machine learning) if such is required by the *MAA-ME*.

DTMS: This component is responsible for the digital twin in the MNCRP. It allows users to prepare digital models of physical materials and robots and simulate and analyze them.

ECB: This component guarantees the secured cross communication within components (intra) and systems (inter). It employs an extended crosschain of the blockchain technology.

ISOW: This component is responsible for providing guaranteed privacy awareness of information management in the heterogeneous CR platform. The ontology knowledgebase and web services are the two main provisions proposed.

ASC: This component is responsible for automating all analytical requirements including data science of the CR of the MNCRP. This is an extended work task of the ASC [75], [76]. ASC process comprises four main stages, which are planning stage for workflow generation [88], selection stage for web service discovery [89] and web service selection [90], [91], verification and refinement for rectifying workflow for uninterrupted execution, and composition stage for service composition.

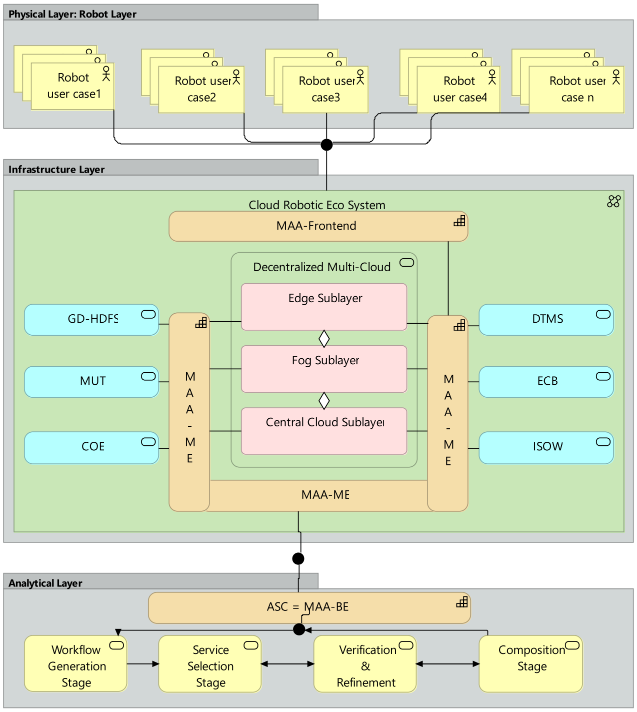


FIGURE 6. **M_4^{CR} abstract normative-view – Reference architecture for framework for MNCRP. DTMS = Digital twin modeling and simulation, DMC = Decentralized multicloud, MUT = Middleware for adapting utility technologies, COE = Container orchestration engine, GD-HDFS = Geo-distributed Hadoop distributed file system, ECB = Extended crosschain for blockchain, ISOW = Information as service based on domain ontology and web services MAA = Multiagent for automation, (FE/ ME/ BE = frontend/ middle end/ backend) ASC = Automatic service composition.**

V. APPLY PROPOSED RA FOR USE CASES AND ABSTRACT SA

This section briefly explains the way that the proposed RA applies with given use cases in scenario 2 and derived abstract nonnormative view for the MNCRP.

Use case 1 – Drone outsourcing company P: The drone outsourcing company provides its drone service for grocery delivering *company R*. In addition, drones of the *company P* recording weather information also provide video streaming and photogrammetry services. Edge devices are used to maintain their raw data and provide permanent metadata storage. Afterward, it drives data into the fog and central cloud according to the requirements. The information collecting shared with (outsourced to) third parties is managed by the *ISOW*. According to the demand of the drone service, the system uses *COE* to scale up or down the drone service CR environment. The *COE* guarantees the secured autonomy of their CR and data in the DMC with the help of *ECB*. Moreover, the *GD-HDFS* provides provisions for cost-effective, fault-tolerant, and seamless connection to the MNCRP despite the geographical location. An automatic and seamless connection between each of the components is maintained by the *MAA-ME.* All types of analytical workflows are automated by the *ASC*, which also acts as *MAA-BE*.

Use case 2 – Company Q is the vendor of self-driving vehicles. Basically, it involves R&D before and after the involvement of real-world physical implementation. Therefore, it employs *DTMS* in the early ages (at the beginning) as well as the fully functional level for creating, simulating digital models, and analyzing. For that, it maintains the digital models of all fleets of self-driving vehicles, physical things involving self-driving vehicles, and testing them with real-world data which are existing sensor data as well as outsourcing data by third parties such as *company P.* Thus, this helps mitigate production-level issues and implement sophisticated production lines. Moreover, its vehicles in the field used by its customers have portable edge devices as their primary data source. With the help of *GD-HDFS*, this helps to maintain a single tenant of their database despite geographical location, enabling a seamless connection of the *CR-Eco-Sys* and flawless data exchanges between edge, fog, and central. In addition, *company Q* employs data outsourced by *company P* to avoid traffic and bad weather; as a definite result, its vehicles enable a comfortable riding experience and minimize makespan.

Use case 3 – C*ompany R* is an e-commerce retail grocery seller company. The factory side of this company is operated autonomously. Customer demand is stochastic, and therefore, *company R* employs big data analytical tools to predict daily, weekly, and monthly demand. To achieve this goal, it employs weather, traffic, and social issues, and other factors that affect demand. All types of analytical and data science requirements are managed by *ASC* as a part of *MAA-BE.* According to that, the company can scale up or down adequate resources and its NFPs (e.g., speed, power supplies, and numbers). C*ompany R* has several factories and warehouses, and then with the help of *GD-HDFS* of the MNCRP, it allows the company to work on the same infrastructure and seamless connection. Moreover, with the help of *ISOW*, it can retrieve third-party data without delay or interruption.

Use case 4 – Company *S* is a military service provider. It engages in variations of military and security operations across the globe. It is highly concerned about the security, fullest level of accuracy, and need to maintain zero faults of its robots and their operational issues. The *GD-HDFS* and *COE* provide provisions for fault-tolerant, seamless, and secure communication for their field robots. Moreover, on the R&D side, it still tests different product models and optimizations. For that, it employs the *DTMS*. In that, it maintains highly secured digital blueprints (models) of its fleets of robots and physical things, and with third-party sensor data and its own data, it can conduct initial R&D operations and virtual warfare exercises before making physical robots of physical equipment. Because of the geo-distributed operations, with the help of the *GD-HDFS*, the company can maintain its own single tenant and seamless connection across its data. Data security, privacy, and autonomy are guaranteed by the *ECW*. All types of requirements related to the data analytics and data science requirements are performed by the *ASC*.

VI. LITRETURE REVIEW AND SURVEY ON CLOUD ROBOTIC ARCHITECTURE

This section is structured into three subsections. First, Section A discusses the background of the survey. Section B then discusses the preparation of literature works and survey matrix. Section C discusses the survey results.

A. BACKGROUND

Our research objective is to propose state of the art heterogeneous CR platform for the Fukushima-RTF complying with benchmarks and norms set by Industry 4.5 (Industry 4.0 and Society 5.0). In the journey of making a comprehensive solution based on the UAF-based SoS, devising a model-based abstract representation (abstract normative: RA; and abstract nonnormative: SA) is a key milestone. Therefore, first, we have performed a thorough survey of the CR architecture domain.

1) REASONING MNCRP AND UAF

The vast majority of studies are dedicated to a domain or specific use case. In addition, architectural solutions for the heterogeneous CR platforms are limited compared with the CR platform. Nevertheless, our objective is to establish a next-generation CR platform for the Fukushima-RTF, which caters to heterogeneous-robotics requirements. In addition,

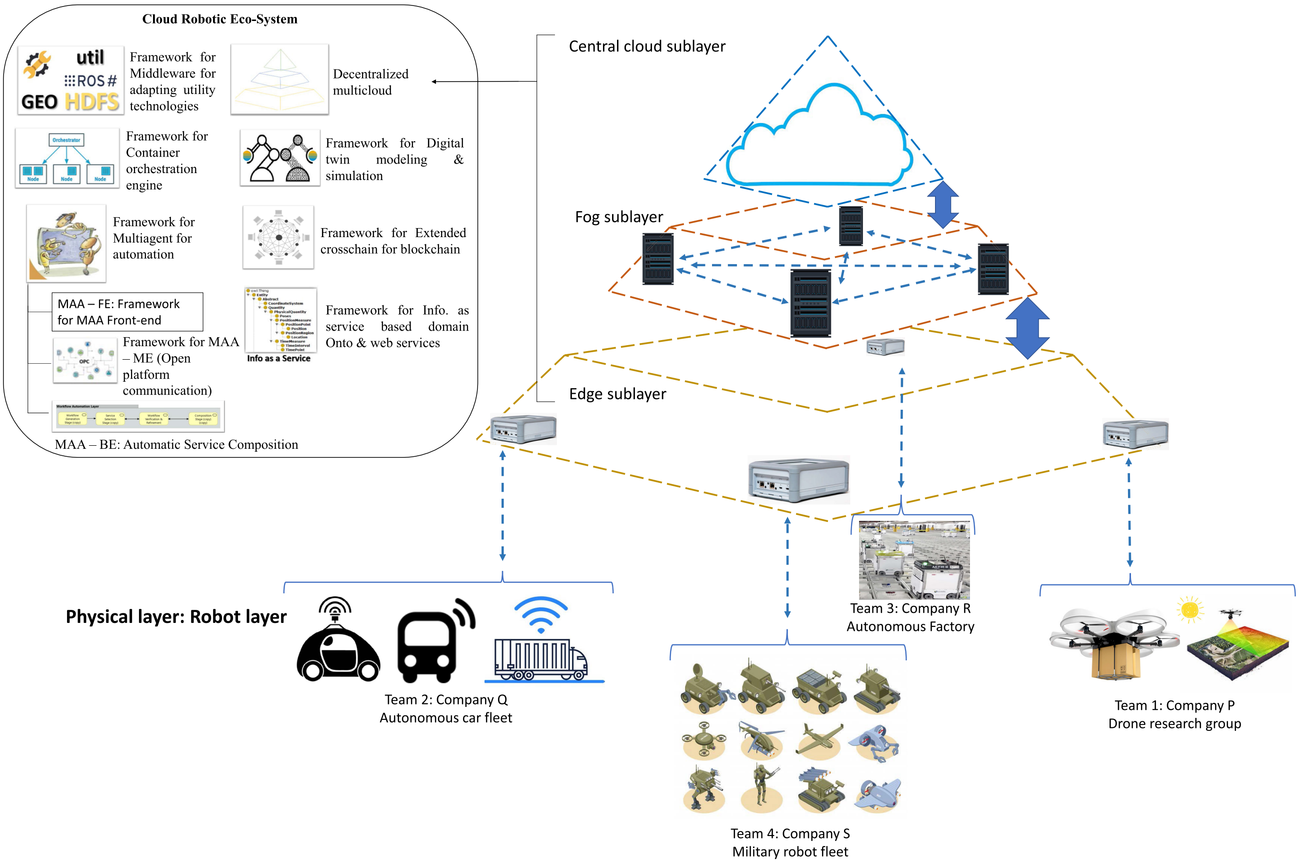


FIGURE 7. M_4^{CR} abstract nonnormative view – Abstract system architecture for MNCRP.

we observed that even though those followed top-down architectural processes, ad hoc architectural design policy is the key concern of both cases (CR and heterogeneous CR). However, those solutions have not undergone adequate modeling. Therefore, such solutions are suffering from inherent drawbacks of ad hoc approaches. Common drawbacks are strictly domain specific; moreover, the customizability, adaptability, and extendibility are minimized. To address these concerns, we propose a model for the ADP. That means, our solution is MNCRP.

Moreover, because of the complexity of the diverse CR, the requirements of the total solution of the MNCRP become the SoS. Nevertheless, it needs a UAF approach for assembling systems in the SoS, i.e., MNCRP [72], [92]–[95]. These systems are called the modules of the framework. In addition, the complexity of the MNCR architectures limits the number of available solutions for heterogeneous approaches. The RA is one of the well-known approaches to address the architectural designing issues of SoS, which are technically large and systematically complex problem domains [20], [23], [27], [31], [85], [86], [96]. Therefore, to alleviate the constraints in the architectural designing process, first, we propose an adequate model for the MNCRP. We employed the design principles proposed by Angelov *et al.* of developing a model and adapting it as necessary [86]. Next, we proposed UAF, which is derived based on abstract normative and nonnormative perspectives. Here, we called the abstract normative view the RA for the MNCRP and called the abstract nonnormative view the abstract SA. We employed ArchiMate [87] to develop the RA.

2) LITURETURE REVIEW RELATED TO THE SURVEY OF CR ARCHITECTURE

To date, recent CR architectural surveys published in the last decade are [97]–[100]. The respective authors have focused on contributions up to 2015, 2016, 2018, and 2019. Ben K. *et al.* [97] focused on work before 2015 and mainly focused on automation. In that, they focused on big data, cloud computing parallel processing, collective learning, and crowdsourcing. Moreover, they did not focus on both the model-driven SA for ADP and PSH to cope with industrial evolution; however, they merely discussed PIE. Jiafu W. *et al.* [98] discussed works up to 2016. They mainly focused on areas of robotics involving cloud computing, big data, open-source resources, robot cooperative learning, and network connectivity. They discussed cloud security and heterogeneity. They emphasized the importance of involving multirobot systems. However, they did not discuss ADP and PIE. The level of their discussion of PSH does not cover managing challenges that tend to be caused by industrial evolution. Olimpiya S. and Prithviraj D. [99] discussed the trend of CR architectures and applications up to 2018. Most of their discussion focused on application-related contributions and issues, and there was also some limited discussion on an architectural level. They did discuss some security issues but without focusing on the aspects of industrial evolution. In addition, they offered no adequate discussion of either ADP or PIE. Yara R. *et al.* [100] surveyed and discussed more works up to 2019. More specifically, they discussed the heterogeneous multirobot system and their involvement. Moreover, they discussed MAS for heterogeneous multirobots and UAF for architectural designs; theirs is a unique contribution compared with the previous discussion. However, they did adequately discuss either PIE or PSH.

This implies that there are good survey works for the CR domain; however, none of them focused on ADP, PIE, and PSH together. Nevertheless, our objective is proposing a model-driven ADP for the CR to also cope with next-generation requirements. Consequently, it is essential to survey existing works and their limitations with respect to the ADP, PIE, and PSH together. Therefore, in this survey, we made our survey matrix as discussed in Subsection B. Literature works are selected key contributions for more specifically to comply with our three main dimensions of the survey matrix. In that, we classified all contributions under five levels as stated in the introduction. Levels are L1, L2, L3, L4, and L5. To the best of our knowledge, ours is the first survey work that focuses on the aforementioned three dimensions (ADP, PIE, and PSH) with respect to the heterogeneous CR.

B. SURVEY MATRIX

1) DATA PREPARATION

We selected literature works mainly from 2010 and up to the present. Moreover, according to the importance, we selected some of the works even before that. Next, we classified all the works into five main levels, L1, L2, L3, L4, and L5.

As mentioned, the three main dimensions are ADP, PIE, and PSH. Then, we further divide each dimension into five levels as shown in Table 3. Table 3 gives a summary of the marking scheme for the three main dimensions and their subcategories.

First, we categorized ADP, considering unmodeled to comprehensive modeled behavior. Those categories are "ad hoc architectures," "architecture works either SA or RA with relevant reasoning/modeling," "architecture works, SA or RA with reasoning/modeling," and "architecture works for UAF grid (framework, metamodel, profile) modeling." Next, we awarded the marks respectively 0.25, 0.5, 0.75, and 1 for the mentioned subcategories.

TABLE 3. Subdimensions of the ADP, PIE, and PSH marking schemes.

SCORES / DIMENSION	0	0.25	0.5	0.75	1
ADP	No architecture	Ad-hock RA or SA	Either SA or RA with modeling	Both SA & RA with modeling	UAF grid
PIE	No provisions for Industrial evolution	Limited provisions for Industry 4.0	Adequate provisions For Industry 4.0	Adequate provisions for Industry 4.5	Discussion for Industry 5.0
PSH	No mention about Heterogeneity	Default cloud security provision + Heterogeneity	Cloud security provision + Heterogeneity	Cloud security provision for Industry 4.5 + Heterogeneity	Cloud security provision for Industry 5.0 + Heterogeneity

PIE means that the given proposal supports the achievement of norms or benchmarks set by industrial evolution. We considered Industry 4, Industry 4.5, and Industry 5.0. We examined the provisions for the respective industrial evolutionary stage by appropriate literature works. Then, we categorized this dimension into four subcategories, including literature works "without provisions for Industry 4.0," "with limited provisions for Industry 4.0," "adequate provisions/discussion for Industry 4.0," "adequate provisions/discussion for Industry 4.5," and "adequate discussion for Industry 5.0". Then, we award marks of 0.25, 0.5, 0.75, and 1 for the respective subcategories mentioned.

Moreover, the PSH dimension was also divided into four subcategories: "default security provisions provided by cloud provider + heterogeneity," "adequate security provisions for Industry 4.0 + heterogeneity," "adequate security provisions for Industry 4.5 + heterogeneity," and "adequate security provisions for Industry 5.0 + heterogeneity." Then, we awarded marks of 0.25, 0.5, 0.75, and 1, respectively, for the subcategories mentioned.

Next, we prepared a score table based on the marking scheme in Table 3. Afterward, we drew graphs of ADP, PIE, and PSH and considered them as the x-, y-, and z-axes, respectively.

First, we prepared the graph shown in Fig. 8, which is drawn against ADP (x) vs PIE (y). Next, we prepared the graph shown in Fig. 9, which is drawn against ADP (x) vs PSH (z), and then prepared the graphs shown in Fig. 10 and Fig. 11. Fig. 10 is drawn against PIE (y) vs PSH (z) and Fig. 11 is drawn using ADP (x), PIE (y), and PSH (z). Fig. 8, Fig. 9 and Fig. 10 distributions are circled based on their distributions. Then, each circled group is considered a cluster group. Respective cluster groups are numbered with the prefix C. In addition, sample $C_{1.m}(n)$ implies that the m^{th} cluster of the C_1 group contained n number of items (literature works).

Moreover, we prepared Table 4, Table 5, and Table 6 based on the distributions of the clusters presented in Fig. 8, Fig. 9, and Fig. 10, respectively, and the levels those numbers represent.

2) SURVEY RESULTS

This section comprises three subdiscussions. First, we discuss "ADP (x) vs PIE (y)," shown in Fig. 8 and Table 4. Next, we discuss "ADP (x) vs PSH (z)," shown in Fig. 9 and Table 5. Afterwards, we discuss "PIE (y) vs PSH (z)," shown in Fig. 10 and Table 6. Finally, we discuss "ADP (x), PIE (y), and PSH (z)," shown in Fig. 10.

a: ADP (x) VS PIE (y): FIG. 8 AND TABLE 4

As shown in Fig. 8, ADP (x) vs PIE (y) produced 11 clusters. The first part of this subsection's discussion is mainly based on Fig. 8.

The distribution of studies along the x-axis implies that most of the research works examined architectural works (either for RA or SA) with a model (20) and ad hoc architecture (19). In addition, our contribution is one of those that have adequate modeling with RA for CR. The highest number of distrusted works are the "ad hoc" (19 – $C_{1.4}$, $C_{1.5,}$ and $C_{1.6}$) and "Mod-RA/SA" (20 – $C_{1.7}$, $C_{1.8}$, $C_{1.8}$, $C_{1.9,}$ and $C_{1.10}$) works.

Moreover, the distribution of studies along the y-axis implies that most of the research works examined limited components for Industry 4.0 (23) and no-provisions Industry 4.0 (14). In addition, the proposed method is the only contribution that provides provisions for Industry 4.5. For that, the highest number of distrusted works are the "no provisions for Industry 4.0" (14 – $C_{1.1}$, $C_{1.4,}$ and $C_{1.7}$) and "limited provisions for Industry 4.0" (23 – $C_{1.2}$, $C_{1.5,}$ and $C_{1.8}$) works.

In addition, with respect to the x against y, most of the research works comprise some sort of architecture that is either RA or SA with or without modeling; however, they comprise either limited provisions for Industry 4.0 or no provisions at all. Given that, 32 literature works lie within $C_{1.4}$, $C_{1.5}$, $C_{1.7}$, and $C_{1.8}$ clusters. Only three literature works possess adequate models either for RA or SA and provisions for Industry 4.0 given by the $C_{1.9}$ cluster.

The second part of this subsection's discussion is mainly based on Table 4.

The ADP vs PIE L1, i.e., SA works published before 2017, section mostly examined ad hoc architectures without PIE given that $C_{1.4}$(5) shows the increased Big Tech involvement around 2015. Then, most of the CR SA works published before 2017 minimally focused on both the model for architecture and PIE.

L2, i.e., SA works published after 2017, still mainly examined ad hoc architectures; however, those comprise at least either limited provisions for Industry 4.0 or adequate provisions for Industry 4.0 given that $C_{1.2}$(2), $C_{1.5}$(3), and $C_{1.6}$(2). Here, L2 shows significant progress compared with L1. This shows that the L2 works had a significant impact on the rise of Big Tech.

With respect to the L3, the RA works mostly worked on model and limited PIE given that $C_{1.8}$(9). Thus, signals when authors working on RA for the CR domain, were more concerned about future requirements as well as adaptability for future works. Nevertheless, the L3 of $C_{1.7}$(3) and $C_{1.8}$(9) imply they used the RA model compared with the SA model.

Regarding the L4, research works that correlated Robo Earth and Rapyuta comprise modeling for their solution and either limited provision for Industry 4.0 or adequate provisions for Industry 4.0. Consequently, even though L4 works were published before the rise of Big Tech, the authors had a vision for future trends.

Overall, the MNCRP is the only contribution that provides adequate provisions for Industry 4.5 as well as modeling for RA. Nevertheless, the other documents of the other contributions create some joint-cluster groups ($C_{1.4}$, $C_{1.4}$, $C_{1.6}$, $C_{1.7}$, $C_{1.8}$, $C_{1.9}$), that all of them possess either SA/RA with and without modeling; however, none of them provide PIE beyond Industry 4.0.

b: ADP (x) VS PSH (z): FIG. 9 AND TABLE 5

Fig. 9 shows four clusters with respect to their distribution along the z-axis. The first part of this subsection's discussion is mainly based on Fig. 9.

Nearly a quarter of the literature works do not possess adequate PSH given by the $C_{2.1}$ cluster. Nearly half of the literature works possess default cloud security and heterogeneity given $C_{2.2}$, and nearly a quarter of the literature works possess security provisions to cope with Industry 4.0 and heterogeneity. The MNCRP is the only contribution possessing adequate PSH to cope with Industry 4.5. This observation gives an insight that there is no contribution that copes with next-generation security requirements while maintaining the heterogeneity. Nevertheless, half of the literature works limited their study to default securities provided by the classical cloud. Moreover, relatively equal quarter proportions focused either on PSH or no PSH to cope with Industry 4.0.

The second part of this subsection's discussion is mainly based on Table 5.

Both L1 and L2, i.e., literature works discussing CR SA before and after 2017, focused either on default cloud security and heterogeneity or security to cope with Industry 4.0 and heterogeneity. This is a good sign with respect to the SA works, which possess minimal security in their backends.

Moreover, L3 shows the RA works were limited within either no PSH or default cloud security and heterogeneity. This implies that PSH SA works were more concerned about PSH compared with the RA works.

With respect to the L4, i.e., Robo Earth and Rapyuta, the studies were almost equally distributed across $C_{2.1}$, $C_{2.2}$, and $C_{2.3}$.

Overall, compared with the results of Subsection A, even though literature works focused on PIE (L3 and L4), they have a lack of concern for PSH. However, regarding the literature works of SA that possess minimal PIE and those that possess minimal security provisions for their works, we believe this means they did not use the SA model, but they were more concerned with security because they were more application-oriented works. Meanwhile, the MNCRP is the only contribution that focused on modeling for ADP as well as security beyond the default and it complies with Industry 4.5.

TABLE 4. Summarized data based on Fig. 8.

C#	Literature works					
	Total	L1	L2	L3	L4	L5
C1.1	2	[5]		[26]		
C1.2	3	[4]	[16, 17]			
C1.3	2					[45, 46]
C1.4	7	[2, 3, 6, 8, 11]		[27, 33]		
C.1.5	9	[1, 7]	[13, 14, 18]	[28. 32]	[38, 40]	
C1.6	3		[12, 15]		[42]	
C1.7	5	[9, 10]		[21, 24, 25]		
C1.8	11			[20, 22, 23, 29, 30, 31, 34, 35, 36]	[39, 41]	
C1.9	3		[19]		[43, 44]	
C1.10	1					MNCRP
C1.11	1			[37]		

c: PIE (y) VS PSH (z): FIG. 10 AND TABLE 6

Fig. 10 shows five cluster groups with respect to their distribution along the y-axis. The first part of this subsection's discussion is mainly based on Fig. 9.

Half of the contributions possess limited PIE for Industry 4.0, as given by the $C_{3.2}$ cluster group. In addition, nearly a quarter of contributions do not possess PIE, as given by $C_{3.1}$. These two observations are equal compared to the previous subsections $C_{2.1}$ and $C_{2.2}$ given by Fig. 9. These observations imply that most of the authors/contributors paid little attention to a solid platform for the next-generation CR complying with PSH and PIE.

Even though next-generation CR with security is provisionally discussed in the L5 literature works, the MNCRP is the only work that provides adequate PSH and PIE.

The second part of this subsection's discussion is mainly based on Table 6.

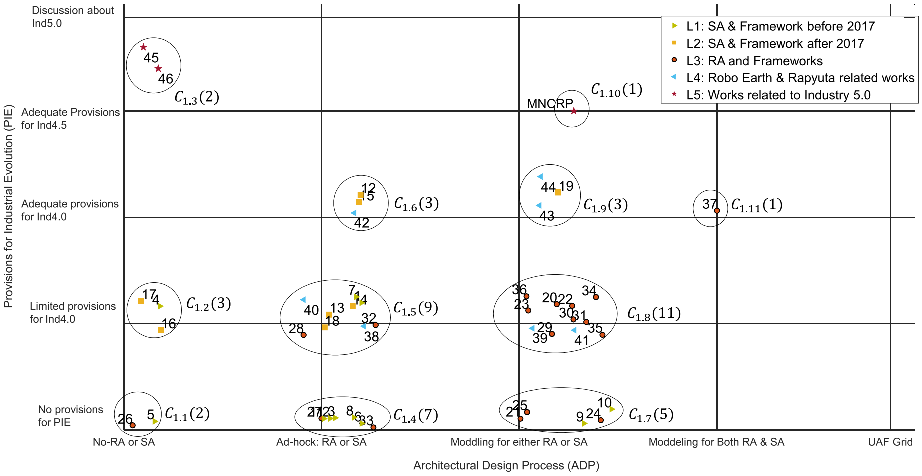


FIGURE 8. X vs Y: Relationship between ADP vs PIE.

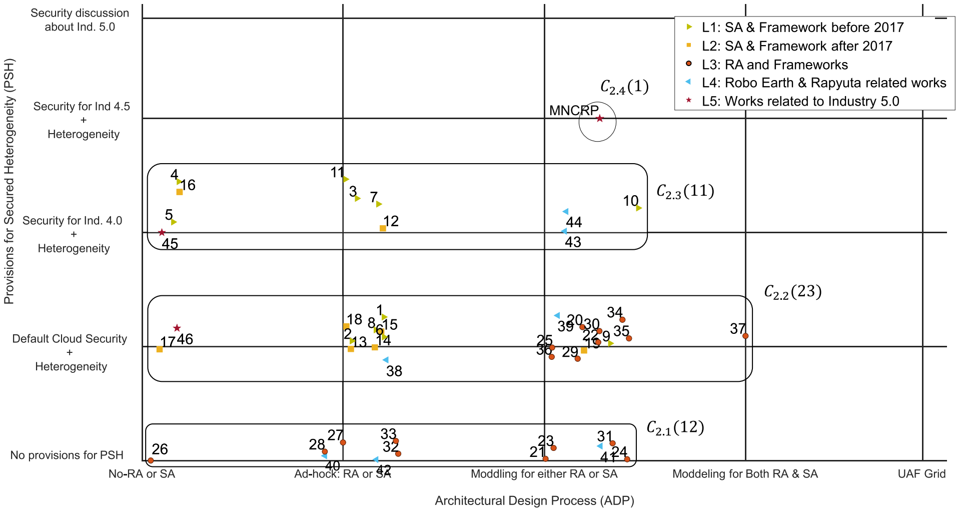


FIGURE 9. X vs Z: Relationship between ADP vs PSH.

TABLE 5. Summarized data based on Fig. 9.

C#	Literature works					
	Total	L1	L2	L3	L4	L5
C2.1	12			[21,23,24,26,27,28,31,32,33]	[40,41,42]	
C2.2	23	[1,2,6,8,9]	[13,14,15,17,18,19]	[20,22,25,29,30,34,35,36,37]	[38,39]	[45]
C2.3	11	[3,4,5,7,10,11]	[12,16]		[43,44]	[46]
C2.4	1					MNCRP

With respect to L1, i.e., SA works before 2017, those works did not examine having PIE, as given by $C_{3.1}$. In contrast, L2, i.e., SA works after 2017, shows some significant progress compared with the works before 2017 by possessing limited PIE given by $C_{3.2}$ and adequate PIE given by $C_{3.2}$. L3 works, i.e., RA works, mostly had limited provisions for PIE, as given by $C_{3.2}$; however, some works still do not possess PIE. When compared to the all-time RA vs SA works after 2017, their preferred model was similar. L4 works, i.e., Robo Earth and Rapyuta, show the same observation as SA works after 2017.

TABLE 6. Summarized data based on Fig. 10.

C#	Literature works					
	Total	L1	L2	L3	L4	L5
C3.1	14	[2,3,5,6,8,9,10,11]		[21,24,25,26,27,33]		
C3.2	23	[1,4,7]	[13,14,16,17,18]	[20,22,23,28,29,30,31,32,34,35,36]	[38,39,40,41]	
C3.3	7		[12,15,19]	[37]	[42,43,44]	
C3.4	1					MNCRP
C3.5	2					[45,46]

d: ADP (x) VS PIE (y) VS PSH (z): FIG. 11

Fig. 11 shows the distribution of literature works over all three dimensions with respect to the ADP, PIE, and PSH. MNCRP is the only work that made a significant contribution to both PIE and PSH. In addition, with respect to the ADP, MNCRP is second only to the L. Gherardi and D. Brugli [37] contribution. They provide adequate ADP for both RA and SA, while we provide ADP for RA. However, they were neither focused on UAF perspective modeling for the CR domain nor possessed adequate PIE and PSH. To the best of our knowledge, we are the first to

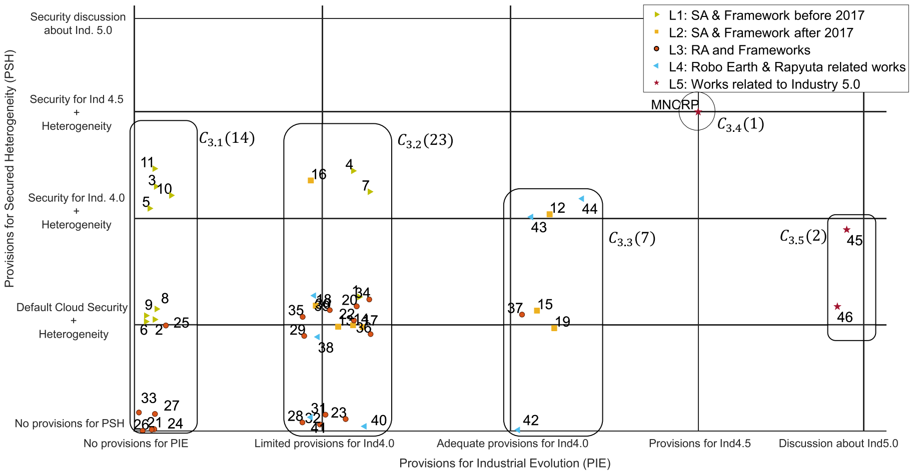


FIGURE 10. Y vs Z: Relationship between PIE vs PSH.

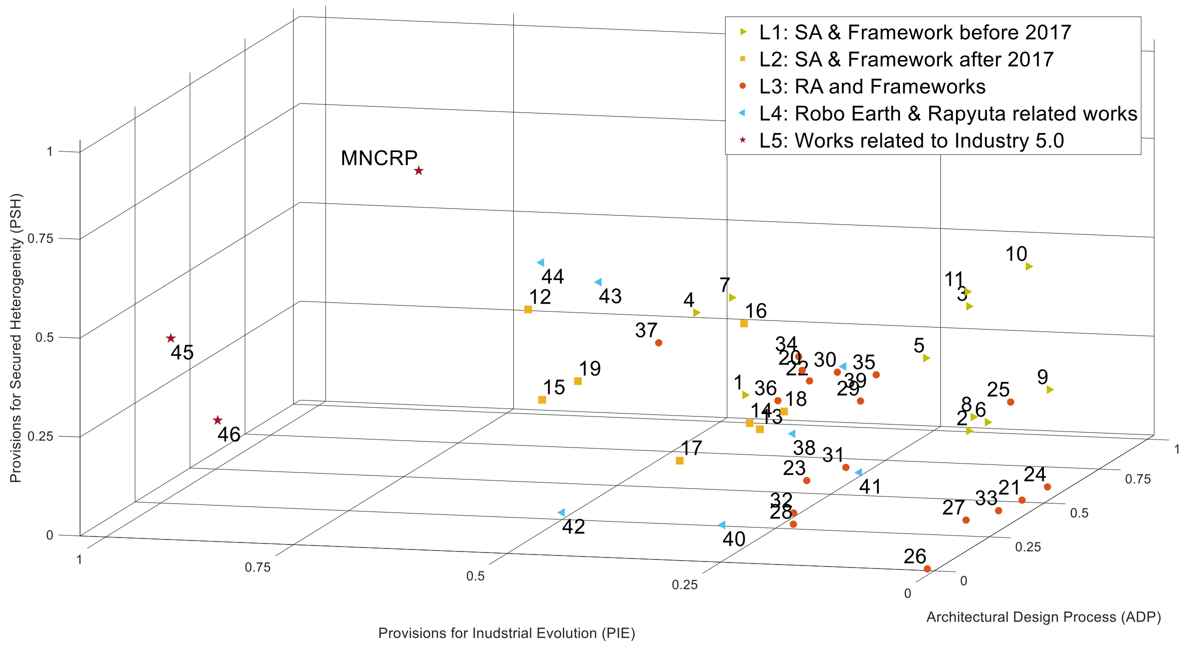


FIGURE 11. X, Y, vs Z: ADP vs PIE vs PSH.

proposed modeling solutions for RA and abstract SA views of the MNCRP.

VII. CONCLUSION

The Fukushima-RTF is a heterogeneous-robotics R&D and testing field. One of the main requirements of the RTF is MNCRP. The UoA robotic research group is one of the key partners of the RTF. Therefore, our key objective is commissioning a sophisticated heterogeneous CR platform that complies with Industry 4.0 and Society 5.0 for the RTF.

According to our survey, we learned that existing works lack ADP, PIE, and PSH dimensions, which are essential when working toward sustainable next-generation solutions. In addition, according to the survey results, studies, and experiences in the CR domain, we learned that there is a gap in the top-down approach for the UAF for MNCRP that complies with standards and norms. To address that issue, we proposed modeling for the MNCRP and derived RA and abstract SA for the MNCRP. When compared with existing works, the proposed method reasonably addressed our problem domain and achieved our research objective.

Moreover, regarding future works, we are working on the completion of the UAF grid that comprises end-to-end ADP to the implementation plan, scheduling work for the MNCRP, and finally commissioning MNCRP for the Fukushima-RTF.

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