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Internet of Robotic Things: Concept, Technologies, and Challenges

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ABSTRACT Internet of Things allow massive number of uniquely addressable ‘‘things’’ to communicate with each other and transfer data over existing internet or compatible network protocols. This paper proposes a new concept which tackles the issues for supporting control and monitoring activities at deployment sites and industrial automations, where intelligent things can monitor peripheral events, induce sensor data acquired from a variety of sources, use *ad hoc*, local, and distributed ‘‘machine intelligence’’ to determine appropriate course of actions, and then act to control or disseminate static or dynamic position aware robotic things in the physical world through a seamless manner by providing a means for utilizing them as Internet of robotic things (IoRT). Although progressive advancements can be seen in multi-robotic systems, robots are constantly getting enriched by easier developmental functionalities, such vertical robotic service centric silos are not enough for continuously and seamlessly supporting for which they are meant. In this paper, a novel concept—IoRT is presented that highlights architectural principles, vital characteristics, as well as research challenges. The aim of this paper is to provide a better understanding of the architectural assimilation of IoRT and identify important research directions on this term.

INDEX TERMS Internet of things, IoRT, robotics, cloud.

I. INTRODUCTION

Robotic system has brought tremendous changes in various socio-economical aspects of human society during the past decades [1]. Per Guoqiang *et al.*, industrial robot manipulators have been widely deployed and used in all sorts of industries to perform repetitive, tedious, critical, and/or dangerous tasks, such as product assembly, car painting, box packaging, and shield welding. These preprogrammed robots have always been very successful at their accomplishments in several structured industrial applications due to their high accuracy, precision, endurance, and speed. Robotic technologies have been integrated with existing network technologies to extend the range of functional values of these robots when deployed in unstructured environments while fostering the emergence of networked robotics during 90’s [2].

IEEE Society of Robotics and Automation’s Technical Committee on Networked Robots has defined the networked robotic system as a collection of robotic devices that are connected via wired and/or wireless communication network [3]. Networked robotic applications can be classified as either *teleoperated* robots i.e., remotely positioned robots controlled by the commands sent by human operator via the communication network, or *multi-robot* system which is a group of networked robots placed in a distributed fashion to perform the given task by exchanging sensing data and information via the communication network by self-cooperative manner. The ‘‘Mars Rover’’ sent to the Mars for exploration is a kind of former type where as *Soccer playing robots* are example of latter case. Networked robotics suffer from inherent physical constraints such as, low speed on-board instruction execution, small size of memory, network latency, variable quality of service, downtime, and lack of intelligence.

The limitations have motivated the researchers to think of new form of efficient robotic systems i.e., ‘‘Cloud Robotics’’. Cloud robotics may be described as a system that relies on the ‘‘Cloud Computing’’ [4] infrastructure to access vast amount of processing power and data to support its operation [5]. That means not all sensing, computation, and memory is integrated into a single standalone system as it was in case of *networked robotics*. *Cloud Robotic* systems often include some portion of its capacity for local processing for low-latency responses when network access is unavailable or unreliable i.e., offline. One example of *Cloud Robotics* is the *Google self-driving car* that indexes the *Google* maps, images, and other relevant information, collected by the satellites and the crowd sourced Clouds to facilitate accurate localization. Although, *Cloud Robotics* is benefited from big data analytics, cloud

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computing, human computation, and collaborative robot learning, it suffers from various issues such as interoperability, heterogeneity, time-varying network latency, security, multi-robot management, common infrastructure design, Quality-of-Service (QoS), and standardization [5], [6]. Due to the IoRT's inherent virtues of qualitative handling of mentioned issues, it is envisaged that it will overcome these constraints, leading to more intelligent, collaborative, heterogeneous, efficient, self adaptive, context aware, and yet cheaper robotic networks.

This article describes Internet of Robotic Things architecture, key concepts, characteristics, and some of the technical challenges. The main aim is (1) to provide a better understanding of the architectural design challenges of IoRT, (2) validation of the proposed concept, and (3) identify important research directions in this fascinating topic.

The rest of the article is organized as follows. Section II describes an overview of Internet of Robotic Things in terms of IoT, including its novel definition. Section III presents the key architecture of IoRT. The feasibility issues of the Internet of Robotic Things are detailed in Section IV. Section V presents the research challenges associated with Internet of Robotic Things. This paper concludes in Section VI.

II. OVERVIEW OF INTERNET OF ROBOTIC THINGS

This section presents a general overview of Internet of Robotic Things. First, concept behind Internet of Things is presented. Later, Cloud Robotics is merged with IoT as Internet of Robotic Things including its novel definition.

A. DEFINITIONS

The main idea behind the Internet of Things or IoT is not a new one. The idea of IoT was conceived by Mark Weiser in his Scientific American article on ubiquitous computing called ''The Computer for the 21st Century''. Later, in the year of 1999, Internet of Things term was coined by Kevin Ashton, the then executive director of the Auto-ID Center. As per Giusto *et al.,* IoT combines people, process, device and technology with sensors and actuators. This overall integration of IoT with human being in respect to communications, collaboration and technical analytics enables to pursue real-time decision. The concept behind this idea is the ubiquitous presence around human being and its socio-economical culture with a variety of smart objects enabled by radio tags, sensors, actuators, smart devices which are disseminated through unique addressing schemes, secure communication channels and standardized architectural frameworks that perform interaction and bridges the cooperation with their neighbors to reach specific goals [7]. Smith [8] describes IoT as a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual ''things'' have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network; often communicate data associate with users and their environments. In this paper, we adopt the definition of Internet of Things provided by The International Telecommunication Union (ITU) [9], as it covers, in my opinion, all the essential aspects of Internet of Things:

1) ITU DEFINITION FOR IoT

A global infrastructure for the information society enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies.

The main reason for the existence of different perceptions, understandings, and definitions of Internet of Things is that Internet of Things, unlike other technical terms, is not a new concept, but rather a new representation of emerging business operations model that brings together a group of available stack of technologies to run business in connected and integrated way. Indeed, most of the technologies used by Internet of Things, such as device identification and heterogeneity, are not new. Instead, Internet of Things leverages these technologies to meet the social, technological, political, and economic requirements of today's societal demand for information technology.

Internet of Robotic Things being a novel concept requires to be defined. Unfortunately, no literature yet has described this term. Here, I propose to merge the IoT and Robotics, especially Cloud Robotics altogether, as IoRT be advanced version of Cloud Robotics.

What is Cloud Robotics? According to the description given by RoboEarth [10], [67], Cloud Robotics may be seen as emerging field of robotics that is rooted in the cloud computing, cloud storage, and other existing Internet technologies, centered around the earned benefits of the converged cloud infrastructure and shared services that allows robots to take benefit from the powerful computational, storage, and communications resources of modern data centers attached with the clouds, while removing overheads for tasks such as, maintenance and updates, and enhancing independence on the custom middleware platforms, entailing additional power requirements which may reduce the operating duration and constrain robot mobility and increase operation costs by covering cloud data transfer rates to offload tasks without hard real time requirements.

Now, we can proceed for defining Internet of Robotic Things by covering the definition of IoT and Cloud Robotics as presented below.

2) INTERNET OF ROBOTIC THINGS DEFINITION

A global infrastructure for the information society enabling advanced robotic services by interconnecting robotic things based on, existing and evolving, interoperable information and communication technologies where cloud computing, cloud storage, and other existing Internet technologies are centered around the benefits of the converged cloud infrastructure and shared services that allows robots to take benefit from the powerful computational, storage, and communications resources of modern data centers attached with the clouds, while removing overheads for maintenance and *updates, and enhancing independence on the custom cloud based middleware platforms, entailing additional power requirements which may reduce the operating duration and constrain robot mobility by covering cloud data transfer rates to offload tasks without hard real time requirements.*

In summary, Internet of Robotic Things is envisaged to be positioned on top of the Cloud Robotics paradigm, while leveraging certain aspects of Cloud computing such as virtualization technology, and three service models (i.e., software, platform and infrastructure), while utilizing IoT and its enabling technologies to empower tremendous flexibility in designing and implementing of new applications for networked robotics to achieve the goal of provisioning distributed computing resources as a core utility. It shares certain aspects with Cloud Robotics and Internet of Things but differs from them in other aspects. Therefore, it offers unique benefits and imposes distinctive challenges to meet its requirements.

III. INTERNET OF ROBOTIC THINGS ARCHITECTURE

The architecture of Internet of Robotic Things can be divided into 5 layers such as: (1) the hardware/robotic things layer, (2) the network layer, (3) the internet layer, (4) infrastructure layer, and (5) the application layer, as shown in Fig. 1. Each of these is described in following section.

A. THE HARDWARE LAYER

This is the bottom most layer comprising of various robots and things such as vehicles, sensors, smart phone, defense equipments, under water equipments, weather sensors, personal equipments, home appliances, and industrial sensors. Technically speaking, physical things (real-life components) do cover up this layer of abstraction to leverage information about its periphery to the above layer i.e., the network layer.

B. THE NETWORK LAYER

Several types of network connectivity options are provided into this second bottom most layer. Cellular connectivity such as 3G [11] and LTE/4G [12] are enabled herewith. Few short-range communication technologies, such as WiFi [13], Bluetooth Low Energy (BLE) [14], 6LoWPAN [15], BroadBand Global Area Network (BGAN) [16], and Near Field Communication (NFC) [17] are included for facilitating seam less connectivity between near by robotic things to each other. Medium-Long range communication technologies such as, Worldwide Interoperability for Microwave Access (WiMAX) [18], Z-Wave [19], ZigBee [20], and Low Power Wide Area Network (LoRA) [21] have been incorporated for smooth conduct of information transmission among the robotic network infrastructure positioned in longer distance.

C. THE INTERNET LAYER

Internet connectivity is the central part of the whole communication in the IoRT architecture. Due to its own virtue, IoT specific communication protocols have been selectively added into this layer for energy efficient, resource constraint and light weight information processing in robotic systems. MQTT [22], CoAP [23], XMPP [24], IPv6 [25], UDP [26], uIP [27], DTLS [28], AMQP [29], LLAP [30], and DDS [31] protocols pave the following tasks respectively: publish/subscribe messaging, multicast support, real-time instant messaging, packet switched networking, alternative to TCP, disseminating of networked embed system, providing privacy to datagram protocol, message queuing for middleware environment, lightweight local automation, and directly addressing publish/subscribe based communication for real-time embedded systems.

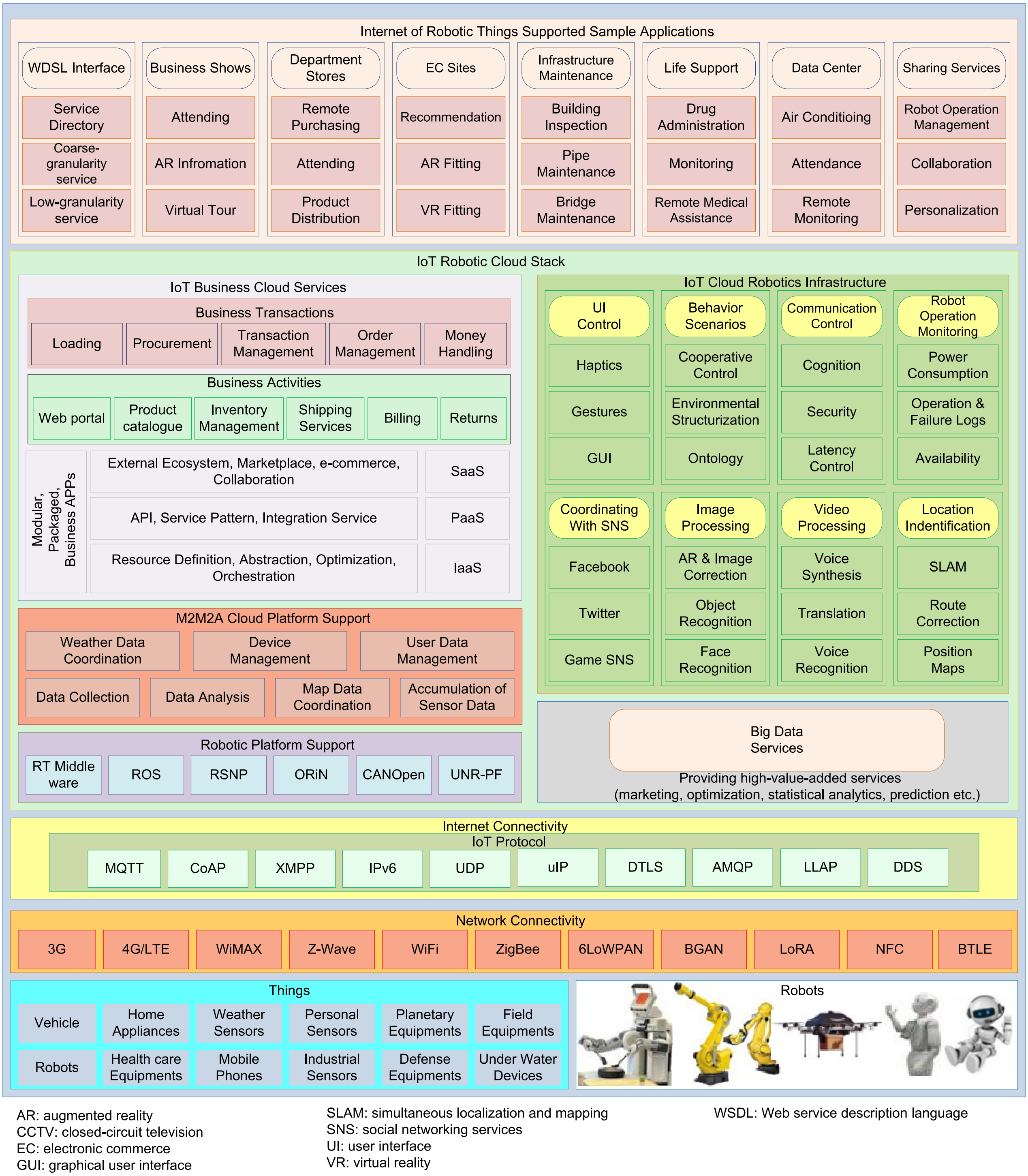
D. THE INFRASTRUCTURE LAYER

IoT based robotic cloud stack revamps this part of architecture to be the most valuable (service centric approaches of cloud, middleware, business process, and big data altogether) layer of all. Truly speaking, this layer is conglomerate of 5 different but related compositions such as, robotic cloud platform, M2M2A cloud platform support, IoT business cloud services, Big Data services, and IoT cloud robotics infrastructure. Let discuss each as below:

Robotic platform support provides robot specific service technologies such as, RT (Robot Technology) middleware [32], Robot Operating System (ROS) [33], Robot Service Network Protocol (RSNP) [34], Open Robot/Resource interface for the Network (ORiN) [35], CANOpen [36], and open source ubiquitous network robot platform (UNR-PF) [37] etc.

M2M2A cloud platform is envisaged for Machine-to-Machine-to-Actuator paradigm which is suitable for the advanced robot which I predict to be a critical machine that shall contribute in IoRT system. Machine-to-Machine (M2M) system may regarded as collection of multiple machines connected to a network that exchange information without human intervention while providing automated optimum control. M2M2A [38] system is meant for leveraging practical solutions, where various sensors and robotic technologies shall be combined to combine the real and virtual world together. In such kind of solutions, visualized information services generated by the sensors are inter-linked among them selves while formulating respective chain of actions/reactions made to be performed by the robots. Out of many, data collection, analysis, device management, map cum weather data coordination and sensor data accumulation are of most importance.

IoT Business Cloud Services are purely abstracted for manifestation of business specific services for the IoT robotic systems. Here, various business transactions and activities are designed to be served by SaaS, PaaS, and IaaS cloud service models. Modular as well as packed business oriented APIs do ease the performance of e-commerce related operations. At the same time, it performs resource definition, abstraction, optimization, and orchestration of external ecosystem. In short, business clouds do serve the IoRT by allowing organizations and manufacturers of robotic systems to reduce their



AR: augmented reality
CCTV: closed-circuit television
EC: electronic commerce
GUI: graphical user interface
SLAM: simultaneous localization and mapping
SNS: social networking services
UI: user interface
VR: virtual reality
WSDL: Web service description language

FIGURE 1. **Conceptual diagram of Internet of Robotic Things Architecture.**

overhead of operational (business related) activities through a common layered approach where all sorts of necessary supports are provided.

IoT Cloud Robotics Infrastructures is solely included for services. Here regarding this topic, we should have basic idea about IoT cloud. IoT cloud may be described as:

"*a model designed to facilitate the information society, enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies through ennoblement of ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources* *(e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction that leverage the need and heterogeneous connectivity issues of the user centric things in well defined fashion"* [39].

In such scenario, IoT cloud enables robotic systems to be empowered with several services of which few have been presented such as, image processing, video processing, location identification, communication control, coordinating with SNS, robotic behavior scenarios, and UI control as special attention. The described terms are self explanatory as shown in Fig. 1, hence we shall not go into detail of each.

E. THE APPLICATION LAYER

This is the top most layer of IoRT architecture which is designed to disseminate the user experience through exploring the presented sample of applications that can be performed over using robotics. Robots bound with IoT can take active participation while solving numerous problem fields such as heath care, infrastructural maintenance, EC sites, departmental stores, life critical situations, data centers, business shows, WSDL [40] interface, and many more. The possibilities are countless and ever growing, hence its importance and existence.

IV. FEASIBILITY OF THE PROPOSED ARCHITECTURE

This paper may not be concluded without answering this important question: are existing technologies mature enough to let Internet of Robotic Things born?

While answering this question, let us first present the core characteristics (see Section IV.A) of IoRT architecture which is followed by the features of the most diffused robots (robotic system) (see Section IV.B), then IoT processing units (see Section IV.C), and cloud robotics platforms (see Section IV.D) in what follows a use-case scenario, in which IoT and robotics are jointly adopted to manage enhanced services in day-to-day human lifestyle.

A. CHARACTERISTICS OF IoRT ARCHITECTURE

Internet of Robotic Things provides several salient features that are different from traditional robotics services such as cloud robotics and networked robotics, which are summarized as below:

1) COMPOSABILITY

Since the proposed IoRT architecture uses Web Service Description Language (WSDL) interface, it strives to standardize several communication interfaces deployed for the IoRT architecture. WSDL is included to facilitate the overall communication between the individual robots (or robotic systems) and with the other segments of the IoRT. Service directory shall store the information of all the deployed services (coarse and granular) for robotic systems. All the services are published as a web services thus make IoRT easier to compose the complex applications by using basic web based components [41].

2) CONTEXT AWARENESS

Based on the sensed information about the physical and environmental parameters, the sensor nodes attached with IoRT ecosystem gain knowledge about the surrounding context. The decisions that the robotic systems take thereafter are context-aware.

3) VIRTUALIZED DIVERSIFICATION

The proposed IoRT architecture uses a dedicated infrastructure component comprising location identification based mapping layer responsible for mapping virtual robot objects to physical robots. Thus, end user i.e., business, manufacturer, or person only requests desired services without consideration of what actual physical robots are assigned for their requirements. The proposed IoRT architecture would support and validate the heterogeneous robotics where each individual robot (or robotic system) might have completely different hardware architecture and software. For example, some of the deployed robots could be servicing in hospitals, some others in restaurants, few for entertainment purpose, and some as robot-cops or in rescue operations etc. Hence, the IoRT architecture is truly virtualized and diversified by its characteristic.

4) EXTENSIBILITY

The way complete IoRT architecture is designed it would devise the extension of existing robotic services either by adding new forms of robots i.e., drone, butler-robot etc., in M2M2A cloud unit or by updating new services in the IoRT enabled system and which would be easily published as well as subscribed through the developed web interface.

5) INTEROPERABILITY

IoT devices may support several interoperable communication protocols be in internet related or service related, and can communicate with other devices of different genre and with the infrastructure. Hence, the IoRT is interoperable by its own virtue.

6) DYNAMIC AND SELF-ADAPTIVE

IoT devices and systems should have the capability to dynamically adapt with the changing contexts and take actions based on their operating conditions, robot's context, or sensed environment. For example, consider a surveillance system comprising of several automatic surveillance cameras i.e., auto bots. The auto bots can adapt their modes (to normal or infrared night modes) based on whether it is day or night. Auto bots could switch from lower resolution to higher resolution modes when any motion is detected and alert nearby auto bots or other robotic systems to do the similar task. In this example, the auto bots are adapting themselves based on the context and changing (e.g., dynamic) conditions [42].

TABLE 1. Existing robots envisaged for IoRT architecture.

Technologies			Applications			
Type	Model	Description	Health	Industrial and Building	Military	Rescue System
Humanoid & Domestic robots	Adept MobileRobots Peoplebot [45]	Support for human-robot interaction activities and other tasks concerning telepresence, robot vision, tourism, monitoring and control, and education	X	X		
	Fraunhofer IPA Care-O-bot 3 [46]	Assistance of humans in their daily life	X	X		
	Willow Garage PR2 [47]	Support of human activities at work and home (including the assistance of disabled and elderly people)	X	X		
	PAL Robotics REEM [48]	Support of human activities in a wide range of indoor environments (i.e., hotels, museums, industry, shopping malls, airports, hospitals, care centers)	X	X		
	Robosoft Robulab family [49]	Control of home infrastructure, recognition of surroundings, communication with medical and public facilities, supervision of vital signs, generation of emergency calls, lifting and carrying of humans	X	X		
Ground mobile robots	Turtlebot [47]	Multi-purpose mobile structure for indoor applications	X	X		
	Neobotix mpo family [50]	Autonomous transportation systems in industrial Environments		X		
	Robotnik Automation Guardian [52]	General purpose robots. They can move on a wide spectrum of surfaces and bear high payloads. Each device can be customized with sensors, grippers, and GPS interfaces			X	X
Flying robots	AscTec Quadrotor [53]	Environment control and monitoring			X	X
Marine robots	Clearpath Robotics Kingfisher [51]	Control of marine areas and transportation of objects and Humans			X	X

7) Geo-DISTRIBUTION AND UBIQUITOUS NETWORK ACCESS

Clouds are generally accessible through the Internet and use the Internet as a service delivery network. Hence any device with Internet connectivity, be it a robotic system, mobile phone, a PDA or any other equipment, can access the distributed cloud services. Additionally, to achieve high network performance and localization, many of today's robots consist of cloud enabled data centers located at many distant geographic locations around the globe. A service provider can easily leverage geo-diversity to achieve maximum service utility [4]. This makes IoRT a geo-distributed ubiquitous network enabler.

B. SUITABLE EXISTING ROBOTS FOR IoRT ARCHITECTURE

Generally, robotics is classified into two categories: Service Robotics and Field Robotics [43]. Service Robotics stands for Humanoid and Domestic robots that execute human oriented supportive tasks. Example includes domestic, office work, personal mobility assistants, room cleaning, and delivery etc. On the other hand, the Field Robotics identifies the robots that work in unconstrained and unstructured environments; especially in outdoors. Field robots may be further classified as three sub categories such as, Aerial, Marine, and Ground robots. These types of robots do pave wide range of operational and environmental conditions. Grieco *et al.,* [44] lists different genre of robots as shown in Table I. Table I presents most important and relevant commercialized products belonging to both the Service Robotics and the Field Robotics categories that can be used in conjugation with IoRT. The table is arranged per the type, model, description, and respective application. A "X" mark is assigned on appropriate application per robotic behavior. The detailed information can be obtained from the datasheets for which references are provided beside each.

Additional equipment such as sensors, RFID, pose estimation, meteorological, and cameras could also be adopted with the above-mentioned robots to gather further information from the environment, such as position, presence of obstacles, humans, environment, and objects (see Table II) [44].

C. IoT PROCESSING DEVICES

Talking about IoT, we should know about the basic building blocks of IoT as shown in Fig. 2. As mentioned by Ray [54], in his mention of relevance of IoT towards smart agriculture, he has cited the fact that IoT is comprised of 5 fundamental building blocks such as, physical layer, link layer, internet layer, transport layer, and applications layer [41]. IoT related

TABLE 2. Available robotic equipment envisaged for IoRT architecture.

Type	Model	Description
2D laser range finder	Hokuyo Scanning range finder	Environment recognition, detection of human body size and position, identification of invaders and obstacles
	SICK Laser LMS-2xx	Area monitoring, identification, classification, and control of size, nature and position of objects
3D sensors	Mesa Imaging SwissRanger	Real-time generation of high quality 3D images through the time-of-flight distance measurement principle
	Microsoft Kinect	Identification of people motion
	Forecast 3D Laser	Detection and avoidance of obstacles during navigation
Cameras	Forecast 3D Laser	Capture and processing of stereoscopic images
RFID	RFID UHF RFID Reader	Identification of objects and people
Pose estimation	Applanix POS-LV imu/GPS interface	Measurement of position and pose, even under the most difficult GPS conditions
LIDAR	RPLIDAR A2 360° Laser Scanner	Measurement of target distance by illuminating a laser light

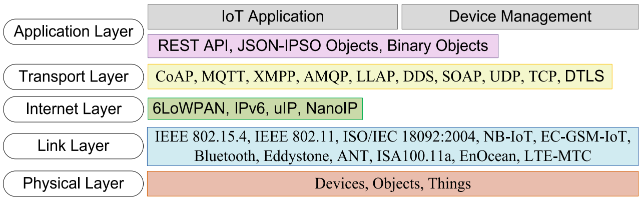


FIGURE 2. Protocol stacks of IoT.

communication technologies that includes protocols, cloud services, and management issues are already presented in IoRT architecture (see Section III B, C, and D). Here, this sub section would point out the appropriate devices (processing modules) that are most suitable for integration of IoT with robotics.

Table III presents various IoT enabled processing units such as, Arduino Uno, Arduino Yun, Intel Galileo Gen 2, Intel Edison, Beagle Bone Black, Electric Imp 003 Raspberry Pi B+, ARM mbed NXP LPC1768, and TelosB. These units have been categorized based on parameters like GPU, clock speed, operating voltage, flash memory, system memory, development environments, programming languages, I/O connectivity, processor type, and bus width. These processing units are most suitable for development of IoRT supported robots as these units are of handling resource constrained environments with ease of seamless heterogeneous connectivity as required for IoT.

D. CLOUD BASED ROBOTICS PLATFORMS

When talk about IoT enabled robotics, cloud platforms play a vital role necessitate data centric, machine centric, environment centric, and system centric meaningful information in a hassle-free condition where maximum portion of computation, communication, and decision making activities are leveraged. Recent development in cloud computing has helps to originate a few cloud-based robotic platforms in the global market. The existence of such robotic platforms gives value wings to the proposed IoRT architectural aspects to become reality in coming years. In this sub section I will elaborate their characteristics in a precise manner. Table IV presents various cloud robotic platforms being used for actual and research purposes. Indeed, most of the platforms support follow Software-as-a-Service (SaaS) model, whereas only Artoo and FIWARE prescribe Platform-as-a-Service. From the information, we can say that most of cloud enabled robotics platforms are still in nascent phase. Rapyuta, FIWARE, and Artoo look promising to go far in the field of IoT and associated domains, whereas others are still striving to reach this goal but it is predicted that IoT shall be incorporated with the rest platforms as a crucial development component.

The section presents that essential components including, advanced robotic systems, additional sensor/actuator based devices, resource constrained but appropriate processing units, and existing cloud supported robotic platforms, may be accumulated to develop the Internet of Robotics Things. As Internet of Things and cloud assisted robotics establishes the foundation of Internet of Robotics Things, it is predicted that Internet of Robotics Things shall arise in a novel formation of robotic world. As of others, the proposed architecture of Internet of Robotics Things is no longer void of worries. The important challenges that may resist its path to grow are elaborated in the next section (see Section V).

V. RESEARCH CHALLENGES

Being a novel area, the research on Internet of Robotic Things is in its preliminary stage. Many issues are to be fully addressed by the scientific communities. This section describes some of the challenging research issues in IoRT which will be followed by few future applications.

A. COMPUTATIONAL PROBLEM

One of the key benefits of IoRT is the capability of shared-offloading of computationally intensive tasks to the IoT cloud

TABLE 3. Existing processing units for IoRT architecture.

Parameters	**Arduino Uno**	**Arduino Yun**	**Intel Galileo Gen 2**	**Intel Edison**	**Beagle Bone Black**	**Electric Imp 003**	**Raspberry Pi B+**	**ARM mbed NXP LPC1768**	**TelosB**
Processor	ATMega328P	ATmega32u4, and Atheros AR9331	Intel® Quark™ SoC X1000	Intel® Quark™ SoC X1000	Sitara AM3358BZCZ100	ARM Cortex M4F	Broadcom BCM2835 SoC based ARM1176JZF	ARM Cortex M3	MSP430 f1161
GPU	-	-	-	-	PowerVR SGX530 @520MHz	-	VideoCore IV® Multi media@ 250 MHz	-	-
Operating Voltage	5V	5V, 3V	5V	3.3V	3.3V	3.3V	5V	5V	3-3.6V
Clock Speed (MHz)	16	16, 400	400	100	1GHz	320	700	96	8
Bus Width (bits)	8	8	32	32	32	32	32	32	16
System Memory	2kB	2.5kB, 64MB	256MB	1GB	512MB	120KB	512MB	32KB	10KB
Flash Memory	32kB	32kB, 16MB	8MB	4GB	4GB	4Mb	-	512KB	48KB
EEPROM	1kB	1kB	8kB	-	-	-	-	-	
Communication Supported	IEEE 802.11 b/g/n, IEEE 802.15.4, 433RF, BLE 4.0, Ethernet, Serial	IEEE 802.11 b/g/n,IEEE 802.15.4, 433RF, BLE 4.0, Ethernet, Serial	IEEE 802.11 b/g/n,IEEE 802.15.4, 433RF, BLE 4.0, Ethernet, Serial	IEEE 802.11 b/g/n,IEEE 802.15.4, 433RF, BLE 4.0, Ethernet, Serial	IEEE 802.11 b/g/n, 433RF, IEEE 802.15.4, BLE 4.0, Ethernet, Serial	IEEE 802.11 b/g/n,IEEE 802.15.4, 433RF, BLE 4.0, Ethernet, Serial	IEEE 802.11 b/g/n,IEEE 802.15.4, 433RF, BLE 4.0, Ethernet, Serial	IEEE 802.11 b/g/n,IEEE 802.15.4, 433RF, BLE 4.0, Ethernet, Serial	CC2420
Development Environments	Arduino IDE	Arduino IDE	Arduino IDE	Arduino IDE, Eclipse, Intel XDK	Debian, Android, Ubuntu, Cloud9 IDE	Electric Imp IDE	NOOBS	C/C++ SDK, Online Compiler	Eclipse IDE
Programming Language	Wiring	Wiring	Wiring, Wyliodrin	Wiring, C, C++, Node.JS, HTML5	C, C++, Python, Perl, Ruby, Java, Node.js	Squirrel	Python, C, C++, Java, Scratch, Ruby	C, C++	C, NesC
I/O Connectivity	SPI, I2C, UART, GPIO	SPI, I2C, UART, GPIO	SPI, I2C, UART, GPIO	SPI, I2C, UART, I2S, GPIO	SPI, UART, I2C, McASP, GPIO	SPI, I2C, UART, GPIO	SPI, DSI, UART, SDIO, CSI, GPIO	SPI, I2C, CAN, GPIO	USB Serial, GPIO

for execution. However, the decision to shared-offloading of a specific task requires a more stringent and unified architectural framework that can handle a collection of complex issues. To solve this problem, firstly, shared-pool of robotic and allied resources shall be leveraged together where novel shared-offloading strategy should consider various factors such as large amount of data exchanged due to huge number of robotic systems in IoT paradigm, and the real-time delay deadline to complete the selected tasks in order. Secondly, the IoRT should be capable enough to take decide whether it is more advantageous to execute the tasks within the IoRT or not. Finally, given a pool of IoT cloud resources spread across geographically different data centers, it is a difficult challenge to allocate and assign the virtual machines optimally to execute the–shared-offloaded tasks while managing the real-time VM migrations among the IoT cloud platforms.

B. OPTIMIZATION

Computational challenge would get worse if we do not consider optimization. Normally, the processing of task through offloading is decided among three execution strategies, including: standalone computation by individual robotic system, collaborative computation by group of robotic system connected through a network, and cloud computation [2]. Sometimes, a hybrid cloud model includes partial computation taking all these strategies together. I advocate for developing of an IoRT based optimization framework that shall involve all computation modes along with available communication technologies and pre-set computation costs included, so as IoRT shall find the optimal computation strategy. Ordinarily, the optimal strategy should take into consideration the time-varying nature and IoT protocol introduced latency of the M2M2A communication network. It is advised to communicate minimal amount of data as possible, through it depends on the application scenario. It shall be of interest to investigate what type of information in which amount and what speed should be stored in IoT cloud. This obviously points our interest towards the Big Data problem which should in this case be well suited.

C. SECURITY ISSUES

Security and trust are the major issues in robotics. Especially, when it is the case of IoRT where cloud involvement is a must we shall face two major security challenges.

TABLE 4. Emerging cloud based robotics platforms evaluated for conglomeration with IoRT architecture.

Cloud Robotic Platforms	Cloud Type	Purpose	Description	Implementation Technology
DAvinCi [55]	Software-as-a-Service	Research	Provides the scalability and parallelism advantages of cloud computing for service robots in large environments as well as share data co-operatively across the robotic ecosystem.	Hadoop cluster, ROS, WiFi, ZigBee
Rospeex [56]	Software-as-a-Service	Research/ Practical	Designed for multilingual spoken dialogues with robots can be used without payment or authentication.	HTML5, JSON [65], Smart Phone,
CRALA [57]	Software-as-a-Service	Research	Provides a domain-specific architecture description language for architecture-centric Cloud robotics, by showing an linkage between architectural descriptions with cloud deployments.	Eclipse modeling Framework (EMF)
Robot Web Tools [58]	Software-as-a-Service	Research/ Practical	Enables interoperability and portability across heterogeneous robot systems, devices, and front-end user interfaces. It is meant for messaging ROS topics in a client-server paradigm suitable for WAN, and web based human-robot interaction.	Rosbridge protocol, ROS, JSON
CORE [59]	Software-as-a-Service	Research	It is a cloud-based object recognition engine for robotics. It provides access to large-scale datasets for training machine learning classifiers, offers the capability to load different feature detector and classifier combinations, and intelligently throttles sensor data within a robotic network.	CloudLab [60], ROS, TCP, UDP
UNR-PF [61]	Software-as-a-Service	Research/ Practical	Enables robots and sensors to contribute their abstracted functions to a pool on cloud robotics where applications can access diverse resources through APIs to build device-independent, multi-area ubiquitous services for supporting daily activities, especially of the elderly and disabled.	Robotic Interaction Service (RoIS) Framework [62], C++
GOBOT [63]	Software-as-a-Service	Practical	Provides a framework for robotics, physical computing, and the Internet of Things in form of device drivers and adapters for controlling a wide variety of robots, a software abstraction, and external control interface for individual or groups on a shared network.	Go [64], JSON
Rapyuta [66]	Platform-as-a-Service	Practical	Provides a secured computing environment to the robots enabling them to move their heavy computation into the cloud. It also provides a high bandwidth connectivity to the RoboEarth [67] knowledge repository.	Linux Containers [68]
FIWARE [69]	Platform-as-a-Service	Research/ Practical	Provides context broking services to publish/subscribe the connected robot's data to other robots by using FIROS [70].	Openstack Swift [71] and other enables.
Artoo [72]	Platform-as-a-Service	Practical	It is a micro-framework for robotics implemented using Ruby. It provides Domain-Specific Language (DSL) for robotics and physical computing for various IoT enabled devices.	Ruby [73]

Firstly, the IoRT-VM environment should be trust-worthy. Otherwise, a malicious IoRT-VM can easily sabotage a crucial task without the intervention of actual robot. For example, in military applications, the IoRT enabled robotic things have to be capable enough to identify the trust-worthy IoRT-VM infrastructure out of many so that they can connect to the respected infrastructure and avoid the known malicious IoRT-VM infrastructure. Trust establishment, trust measurement, and reputation based trust; these three approaches can be adopted to tackle this problem. Secondly, the future robotic systems shall need to trust to initiate computational task on IoRT based clouds where the cloud should be in position so that verification van be done by the owner or controller of that robotic system. Here, we must ensure that there is no malicious code running behind these delegated tasks. At the same time, confidential data may be permanently stored in the IoT enabled cloud servers, while cloning the logical shadow of data to private cloud servers. Hence, rigid methodologies are needed to protect integrity, trust, and confidentiality to secure IoRT data.

D. ETHICAL ISSUES

This is another key issue where robotics is striving to bet through since its inception. Robotics should be governed by the three famous laws given by Sir Isaac Asimov. The law states that:

"*A robot may not injure a human being or, through inaction, allow a human being to come to harm. A robot must obey orders given it by human beings except where such orders would conflict with the First Law. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law*" [74].

Recent development in the field of the Affective Computing [75] – which is about fostering emotional attachment among human and robotic systems through intervening of the design and development of the "*emotional robots*" e.g., "Pepper" [77] – is gradually advancing to such a point of interaction where artificial software agents or "*bots*" and the similar ones, are going to pave those emotional relationships into reality [76].

As we know that "Chatter bots" [78] do engage its people active in online-chats very often to solicit the persons' personal information. In such circumstances, ethics becomes important not only for the robotic things but also the robot manufacturer, owner, user, and the governments. Effective policies should be devised by the country heads around the globe so that misuse of robotic things may be minimized. As IoRT does not comprise of ethical implications, it should be the challenge for the relevant society to come up with novel practices in near future.

VI. CONCLUSION

This paper has proposed an IoT based robotics architectural concept – Internet of Robotic Things (IoRT), as an advancement of current cloud networked robots. Internet of Robotic Things allows robots or robotic systems to connect, share, and disseminate the distributed computation resources, business activities, context information, and environmental data with each other, and to access novel knowledge and specialized skills not learned by them selves, all under a hood of sophisticated architectural framework. This opens a new horizon in the domain of connected robotics that we believe shall lead to fascinating futuristic developments. It indeed allows adapting into connected ecosystem where resource constraint deployment of inexpensive robots shall be leveraged by heterogeneous technologies, be it, communications network, processing units, different genre of devices, or clouds services. Enormous developments could be foreseen to get benefited from the IoRT approach such, SLAM, grasping, navigation, and many more that are beyond the discussion. In this paper, a novel Internet of Robotic Things architecture is proposed considering conjugation between recently grown IoT and robotics together. Feasibility of the proposed architecture has been validated by showing the presence or possibilities of emergence of few components, including existing robotic systems, their peripheral devices, IoT processing units, and cloud enabled robotic platforms. Key characteristics are also elaborated. Research challenges are presented in precise manner so that enthusiasts can get involved into this novel concept in recent future.

REFERENCES

[1] B. Siciliano and O. Khatib, Eds., *Springer Handbook of Robotics*. Berlin, Germany: Springer, 2008.

[2] G. Hu, W. P. Tay, and Y. Wen, "Cloud robotics: Architecture, challenges and applications," *IEEE Netw.*, vol. 26, no. 3, pp. 21–28, May/Jun. 2012.

[3] *IEEE Society of Robotics and Automation's Technical Committee on Networked Robots*. [Online]. Available: http://www-users.cs.umn.edu/~isler/tc/

[4] Q. Zhang, L. Cheng, and R. Boutaba, "Cloud computing: State-of-the-art and research challenges," *J. Internet Services Appl.*, vol. 1, no. 1, pp. 7–18, 2010.

[5] B. Kehoe, S. Patil, P. Abbeel, and K. Goldberg, "A survey of research on cloud robotics and automation," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 2, pp. 398–409, Apr. 2015.

[6] K. Kamei, S. Nishio, N. Hagita, and M. Sato, "Cloud networked robotics," *IEEE Netw.*, vol. 26, no. 3, pp. 28–34, May 2012.

[7] D. Giusto, A. Iera, G. Morabito, and L. Atzori, Eds., *The Internet of Things: 20th Tyrrhenian Workshop on Digital Communications*. New York, NY, USA: Springer, 2010.

[8] I. G. Smith, *The Internet of Things 2012: New Horizon*. Halifax, U.K.: IERC-Internet of Things European Research Cluster, 2012.

[9] *IoT Definition*, accessed on Jul. 4, 2012. [Online]. Available: http://www.itu.int/ITU-T/newslog/New+ITU+Standards+Define+The+Internet+Of+Things+And+Provide+The+Blueprints+For+Its+Development.aspx

[10] J. Wan, S. Tang, H. Yan, D. Li, S. Wang, and A. V. Vasilakos, "Cloud robotics: Current status and open issues," *IEEE Access*, vol. 4, pp. 2797–2807, 2016.

[11] H. Karjaluoto, "An investigation of third generation (3G) mobile technologies and services," *Contemp. Manage. Res.*, vol. 2, no. 2, pp. 91–104, 2006.

[12] K. Q. Henderson, S. I. Latif, and G. Y. Lazarou, "A microstrip line-fed multi-resonant slot antenna in the 4G/LTE band for smartphones," in *Proc. IEEE Military Commun. Conf. (MILCOM)*, Nov. 2016, pp. 208–212.

[13] H. Peng, "WIFI network information security analysis research," in *Proc. 2nd Int. Conf. Consumer Electron., Commun. Netw. (CECNet)*, 2012, pp. 2243–2245.

[14] L. F. D. Carpio, P. Di Marco, P. Skillermark, R. Chirikov, K. Lagergren, and P. Amin, "Comparison of 802.11ah and BLE for a home automation use case," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–6.

[15] X. XMa and W. Luo, "The analysis of 6LowPAN technology," in *Proc. IEEE Pacific–Asia Workshop Comput. Intell. Ind. Appl.*, Wuhan, China, Dec. 2008, pp. 963–966.

[16] P. Fines, E. Christofylaki, P. Febvre, and A. H. Khan, "BGAN radio interface enhancements for SatCom-on-the-move," in *Proc. IEEE 77th 4G Veh. Technol. Conf. (VTC Spring)*, Jun. 2013, pp. 1–5.

[17] N. A. Chattha, "NFC—Vulnerabilities and defense," in *Proc. Conf. Inf. Assurance Cyber Secur. (CIACS)*, 2014, pp. 35–38.

[18] A. Yarali and S. Ffahman, "WiMAX broadband wireless access technology: Services, architecture and deployment models," in *Proc. Can. Conf. Elect. Comput. Eng. (CCECE)*, 2008, pp. 000077–000082.

[19] M. B. Yassein, W. Mardini, and A. Khalil, "Smart homes automation using Z-wave protocol," in *Proc. Int. Conf. Eng. MIS (ICEMIS)*, 2016, pp. 1–6.

[20] H. R. Chi, K. F. Tsang, C. K. Wu, and F. H. Hung, "ZigBee based wireless sensor network in smart metering," in *Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2016, pp. 5663–5666.

[21] W. K. Xue, B. P. Xiao, and L. Ma, "Joint optimization of LORA and spares inventory with fuzzy parameters," in *Proc. IEEE Int. Conf. Ind. Eng. Eng. Manage. (IEEM)*, Dec. 2016, pp. 1640–1645.

[22] A. D. Campo, E. Gambi, L. Montanini, D. Perla, L. Raffaeli, and S. Spisante, "MQTT in AAL systems for home monitoring of people with dementia," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–6.

[23] B. Schütz and N. Aschenbruck, "Adding a network coding extension to CoAP for large resource transfer," in *Proc. IEEE 41st Conf. Local Comput. Netw. (LCN)*, Nov. 2016, pp. 715–722.

[24] A. Stanik and O. Kao, "A proposal for REST with XMPP as base protocol for intercloud communication," in *Proc. IEEE 7th Int. Conf. Inf., Intell., Syst. Appl. (IISA)*, Jul. 2016, pp. 1–6.

[25] P. Pierleoni, L. Pernini, A. Belli, L. Palma, L. Maurizi, and S. Valenti, "Indoor localization system for AAL over IPv6 WSN," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–7.

[26] M. Masirap, M. H. Amaran, Y. M. Yussoff, R. A. Rahman, and H. Hashim, "Evaluation of reliable UDP-based transport protocols for Internet of Things (IoT)," in *Proc. IEEE Symp. Comput. Appl. Ind. Electron. (ISCAIE)*, May 2016, pp. 200–205.

[27] J. Hu, W. Huang, T. Lu, W. Chen, and X. He, "Automate green coverage measure using a novel DIA method: UIP-MGMEP," in *Proc. 19th Int. Conf. Geoinformat.*, 2011, pp. 1–5.

[28] Y. Maleh, A. Ezzati, and M. Belaissaoui, "An enhanced DTLS protocol for Internet of Things applications," in *Proc. IEEE Int. Conf. Wireless Netw. Mobile Commun. (WINCOM)*, Oct. 2016, pp. 168–173.

[29] J. L. Fernandes, I. C. Lopes, J. J. P. C. Rodrigues, and S. Ullah, "Performance evaluation of RESTful Web services and AMQP protocol," in *Proc. IEEE 5th Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Jul. 2013, pp. 810–815.

[30] *LLAP*, accessed on Dec. 30, 2016. [Online]. Available: http://openkontrol.org/llap/index.php/openkontrol/69-LLAP%20-%20Lightweight%20Local%20Automation%20Protocol

[31] L. Zhao, X. Meng, and F. Liu, "Resonant frequency measurement of quartz crystal based on DDS and real-time peak searching," in *Proc. 6th Int. Conf. Instrum. Meas., Comput., Commun. Control (IMCCC)*, 2016, pp. 513–516.

[32] N. Ando, T. Suehiro, K. Kitagaki, T. Kotoku, and W.-K. Yoon, "RT-middleware: Distributed component middleware for RT (robot technology)," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Aug. 2005, pp. 3933–3938.

[33] Y. Saito, T. Azumi, S. Kato, and N. Nishio, "Priority and synchronization support for ROS," in *Proc. IEEE 4th Int. Conf. Cyber-Phys. Syst., Netw., Appl. (CPSNA)*, Oct. 2016, pp. 77–82.

[34] T. Arai, M. Yasuda, and N. Matsuhira, "Development of a teleoperated robot arm system using RSNP: Precise tasks performed using a predictive display," in *Proc. IEEE 13th Int. Conf. Ubiquitous Robots Ambient Intell. (URAI)*, Aug. 2016, pp. 128–131.

[35] M. Mizukawa *et al.*, "ORiN: Open robot interface for the network—The standard and unified network interface for industrial robot applications," in *Proc. IEEE 41st SICE Annu. Conf. (SICE)*, Aug. 2002, pp. 925–928.

[36] M. Postolache, "Time-triggered CANopen implementation for networked embedded systems," in *Proc. IEEE 20th Int. Conf. Syst. Theory, Control Comput. (ICSTCC)*, Oct. 2016, pp. 168–173.

[37] J. Furrer, K. Kamei, C. Sharma, T. Miyashita, and N. Hagita, "UNR-PF: An open-source platform for cloud networked robotic services," in *Proc. IEEE/SICE Int. Symp. Syst. Integr. (SII)*, Dec. 2012, pp. 945–950.

[38] T. Kagaya, "Strategy and efforts for robotics integration aiming at combining information and communications technology with robots," *NTT Tech. Rev.*, vol. 10, no. 11, pp. 1–7, 2012. [Online]. Available: https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201211fa10.html

[39] P. P. Ray, "Creating values out of Internet of Things: An industrial perspective," *J. Comput. Netw. Commun.*, vol. 2016, Sep. 2016, Art. no. 1579460.

[40] S. Gao, Z. Gui, and H. Wu, "Extending WSDL for describing complex geodata in GIS service," in *Proc. IEEE 3rd Int. Conf. Agro-Geoinformat. (Agro-Geoinformatics)*, Aug. 2014, pp. 1–6.

[41] (2016). *Simon Ford, ARM and the Open Internet of Things*, accessed on Dec. 30, 2016. [Online]. Available: https://www.slideshare.net/slideshow/embed_code/45755086

[42] P. J. Vashi. (2011). Cloud robotics: An emerging research discipline. Mälardalen University. [Online]. Available: http://www.idt.mdh.se/kurser/ct3340/ht11/MINICONFERENCE/FinalPapers/ircse11_submission_20.pdf

[43] O. Siciliano and B. Khatib, *Springer Handbook of Robotics*. Berlin, Germany: Springer, 2008.

[44] L. A. Grieco *et al.*, "IoT-aided robotics applications: Technological implications, target domains and open issues," *Comput. Commun.*, vol. 54, no. 1, pp. 32–47, 2014.

[45] E. Ackerman, "CMU's AndyVision Robot is in your store, doing your inventory," *IEEE Spectrum*, 2012. [Online]. Available: http://spectrum.ieee.org/automaton/robotics/industrial-robots/cmu-andyvision-inventory-robot

[46] M. Marcus *et al.*, "Semi-autonomous domestic service robots: Evaluation of a user interface for remote manipulation and navigation with focus on effects of stereoscopic display," *Int. J. Soc. Robot.*, vol. 7, pp. 183–202, Nov. 2015.

[47] R. Bauer. (2016). *Willow Garage Selects Clearpath Robotics to Service and Support the PR2 Robot Through*, accessed Dec. 30, 2016. [Online]. Available: http://www.willowgarage.com/blog/2014/01/17/willow-garage-selects-clearpath-robotics-service-and-support-pr2-robot-through-2016

[48] J. Viladomat. (2016). *TIAGo ROS Simulation Tutorial 2—Autonomous Robot Navigation*, accessed on Dec. 30, 2016. [Online]. Available: http://blog.pal-robotics.com/blog/tiago-ros-simulation-tutorial-2-autonomous-robot-navigation/

[49] *Timelapse Video of the Assembling of STACY*, accessed on Dec. 30, 2016. [Online]. Available: http://robosoft.com/timelapse-video-of-the-assembling-of-stacy/

[50] *Detailed Overview and Comparison Table of All Basic Robot Platforms, Neobotix Robotics and Automation*, accessed on Dec. 30, 2016. [Online]. Available: http://www.neobotix-robots.com/fileadmin/files/downloads/Allgemeines/Technical-Data-Platforms.pdf

[51] C. Bogdon. (2016). *Clearpath Among Fastest Growing Technology Companies in North America*, accessed on Nov. 16, 2016. [Online]. Available: https://www.clearpathrobotics.com/2016/11/clearpath-among-fastest-growing-technology-companies-north-america/

[52] Robotnik. *Radio Project Eu progresses in Ambient Assisted Living*, accessed on Dec. 30, 2016. [Online]. Available: http://www.robotnik.eu/radio-project-eu-progresses-in-ambient-assisted-living/

[53] Astech. *500 Drohnen Setzen Neuen Weltrekord*, accessed on Dec. 30, 2016. [Online]. Available: http://www.asctec.de/500-drohnen-setzen-neuen-weltrekord/

[54] P. P. Ray, "Internet of Things for smart agriculture: Technologies, practices and future road map," *IOS J. Ambient Intell. Smart Environ.*, 2017.

[55] R. Arumugam *et al.*, "DAvinCi: A cloud computing framework for service robots," in *Proc. IEEE Int. Conf. Robot. Autom.*, May 2010, pp. 3084–3089.

[56] S. Komei and Z. Koji, "Rospeex: A cloud robotics platform for human-robot spoken dialogues," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep./Oct. 2015, pp. 6155–6160.

[57] H. Zhang, L. Zhang, Z. Fang, H. Trannois, M. Huchard, and R. Zapata, "CRALA: Towards a domain specific language of architecture-centric Cloud robotics," in *Proc. IEEE Int. Conf. Inf. Autom.*, Aug. 2015, pp. 456–461.

[58] R. Toris *et al.*, "Robot Web tools: Efficient messaging for cloud robotics," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep./Oct. 2015, pp. 4530–4537.

[59] W. J. Beksi, J. Spruth, and N. Papanikolopoulos, "CORE: A cloud-based object recognition engine for robotics," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep./Oct. 2015, pp. 4512–4517.

[60] R. Ricci and E. Eric, "Introducing CloudLab: Scientific infrastructure for advancing cloud architectures and applications," *Usenix*, vol. 39, no. 6, pp. 36–38, 2014.

[61] J. Furrer, K. Kamei, C. Sharma, T. Miyashita, and N. Hagita, "UNR-PF: An open-source platform for cloud networked robotic services," in *Proc. IEEE/SICE Int. Symp. Syst. Integr.*, Dec. 2012, pp. 945–950.

[62] (2012). *Robotic Interaction Service (RoIS) Framework, Object Management Group*. [Online]. Available: http://www.omg.org/spec/RoIS/Current

[63] H. B. Pandya and T. A. Champaneria, "Internet of Things: Survey and case studies," in *Proc. IEEE Int. Conf. Elect., Electron., Signals, Commun. Optim. (EESCO)*, Jan. 2015, pp. 1–6.

[64] F. Schmager, M. Cameron, and J. Noble, "GoHotDraw: Evaluating the go programming language with design patterns," in *Proc. ACM/SPLASH Workshop Eval. Usability Programm. Lang. Tools (PLATEAU)*, 2010, Art. no. 10.

[65] H. Cho, H. Shiokawa, and H. Kitagawa, "JsFlow: Integration of massive streams and batches via JSON-based dataflow algebra," in *Proc. 19th Int. Conf. Netw.-Based Inf. Syst. (NBiS)*, 2016, pp. 188–195.

[66] G. Mohanarajah, D. Hunziker, R. D'Andrea, and M. Waibel, "Rapyuta: A cloud robotics platform," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 2, pp. 481–493, Apr. 2015.

[67] L. Riazuelo *et al.*, "RoboEarth semantic mapping: A cloud enabled knowledge-based approach," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 2, pp. 432–443, Apr. 2015.

[68] J. Claassen, R. Koning, and P. Grosso, "Linux containers networking: Performance and scalability of kernel modules," in *Proc. IEEE/IFIP Netw. Oper. Manage. Symp. (NOMS)*, Apr. 2016, pp. 713–717.

[69] S. Sotiriadis, L. Vakanas, E. Petrakis, P. Zampognaro, and N. Bessis, "Automatic migration and deployment of cloud services for healthcare application development in FIWARE," in *Proc. IEEE 30th Int. Conf. Adv. Inf. Netw. Appl. Workshops (WAINA)*, 2016, pp. 416–419.

[70] *FIROS*, accessed on Dec. 30, 2016. [Online]. Available: https://github.com/Ikergune/firos

[71] K. Nomura, Y. Taniguchi, N. Lguchi, and K. Watanabe, "A system for supporting migration to overlay OpenFlow network using OpenStack," in *Proc. IEEE 10th Int. Conf. Complex, Intell., Softw. Intensive Syst. (CISIS)*, Jul. 2016, pp. 595–598.

[72] *Artoo*, accessed on Dec. 30, 2016. [Online]. Available: www.artoo.io

[73] T. Yamamoto, H. Oyama, and T. Azumi, ‘‘Lightweight ruby framework for improving embedded software efficiency,’’ in *Proc. IEEE 4th Int. Conf. Cyber-Phys. Syst., Netw., Appl. (CPSNA)*, Oct. 2016, pp. 71–76.

[74] S. L. Anderson, ‘‘Asimov’s ‘three laws of robotics’ and machine metaethics,’’ *AI SOCIETY*, vol. 22, no. 4, pp. 477–493, 2008. [Online]. Available: www.aaai.org/Papers/Symposia/Fall/2005/FS-05-06/FS05-06-002.pdf

[75] S. Greene, H. Thapliyal, and A. C. Holt, ‘‘A survey of affective computing for stress detection: Evaluating technologies in stress detection for better health,’’ *IEEE Consum. Electron. Mag.*, vol. 5, no. 4, pp. 44–56, Apr. 2016.

[76] J. Zhu, G. Lin, F. You, H. Liu, and C. Zhou, ‘‘Multiway dynamic trust chain model on virtual machine for cloud computing,’’ *China Commun.*, vol. 13, no. 7, pp. 83–91, 2016.

[77] *Pepper—Aldebaran Robotics*, accessed on Dec. 30, 2016. [Online]. Available: https://www.aldebaran.com/en/cool-robots/pepper

[78] B. A. Shawar and E. Atwell, ‘‘Chatbots: Are they really useful?’’ *LDV-Forum 2007-Band*, vol. 22, no. 1, pp. 31–50, 2007.

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