IoT and Robotics: A Synergy

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***Abstract*— The Internet of Robotic Things (IoRT) [9] is a concept first introduced by Dan Kara at ABI Research, which talks about augmenting the existing IoT with active sensorization; thereby, opening the doors to novel business ideas, at the intersection of both IoT and Robotics. This position paper considers the synergy between IoT and robotics: it talks about the technologies in IoT that would benefit the robotics domain. The advent of Cloud Robotics and its role in aiding robot functions like sensing, manipulation, and mobility. The paper then discusses the ways in which robots can extend the capabilities of existing IoT infrastructure by acting as a special class of edge device. IoT-aided robotic applications are discussed in various domains like health-care, military, industrial plants and rescue operations. The paper concludes by considering the use case of an Intelligent Transportation System endowed by an IoRT-inspired architecture.**

***Index Terms*— IoT, robotics, IoRT, Cloud Robotics, edge devices, ITS**

I. INTRODUCTION

The Internet of Things has already started playing an important role in our daily lives [1], in industry [2], and society. It is expected that by 2020, the number of internet-connected devices would exceed 50 billion [3], and about a quarter of a billion vehicles [4] would be connected to the internet, giving us new possibilities for in-vehicle services and autonomous driving. The number of wearable devices, smart clothing [5], RFID sensors [6] etc. are all expected to grow in the future. All in all, IoT would have a great impact on the economy, with estimates of $4.6 trillion being generated in the public sector and about $14.4 trillion in the private sector, over the course of next ten years [7].

Robots, on the other hand, will play a major role in tomorrows society, continuing to help humans accomplish many tasks, spanning assistive operations, industrial assembly, rescue management systems, military support, health care and automation systems [8].

At this time, most IoT initiatives are focused on using connected devices with simple, onboard, passive sensors to manage, monitor and optimize systems and their processes. Even though impactful, the potential of IoT solutions could be further unlocked by exploring the more advanced and transformational aspects of ubiquitous connectivity to, and communication among, smart devices.

Robotic systems can aid this transformation because of their inherent ability to sense, think (compute), act (manipulate) and move around (mobility). Internet of Robotic Things (IoRT) [9] is a new concept given by ABI Research, that depicts this synergistic nature between IoT and robotics, where intelligent devices can monitor events, fuse sensor data from a variety of sources, use local and distributed intelligence to determine a best course of action, and then act to control or manipulate objects in the physical world, and in some cases while physically moving through that world.

IoT-aided robotics applications will grow upon a digital ecosystem where humans, robots, and IoT nodes interact on a cooperative basis. In this framework, the actors involved would be free to autonomously agree on secure communication principles, based on the meaning of the information they want to exchange and on the services they intend to provide/access. Thus, the research areas related to IoT-aided robotics applications span from short range communication technologies to semantic oriented services, from consensus theory to protocol design, from application design to information centric networking, from security to whatever is useful to build a smart, pervasive, and secure environment. [10]

The rest of the paper is organized as follows:

- **Section 2** discusses Cloud Robotics and broadly, how it can help robots tap into the IoT ecosystem and enhance their abilities
- **Section 3** talks about the different types of edge devices and how robots are a special class of them; thereby, implying how robots can help augment the IoT ecosystem
- **Section 4** talks about the various application areas of IoT-aided robotics
- **Section 5** concludes the paper by presenting a use case of an Intelligent Transport System governed by an IoRT system

II. CLOUD ROBOTICS

James Kuffner coined the term Cloud Robotics [11] in 2010, to describe a new approach to robotics that takes the advantage of the Internet as a resource for massively parallel computation and real-time sharing of vast data resources.

Googles autonomous cars are cloud robots: they connect to the internet to tap into the enormous database of maps and satellite imagery, and environment models (like Streetview) and use sensor fusion to combine streaming data from its many camera, GPS, and 3D sensors to localize its position within centimeters. Moreover, each of the autonomous cars contribute to this knowledge-loop by learning about the environments, roads, or driving conditions, and sending the information over to the Google cloud, where it can be used to improve the performance of other cars.

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PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.2760v1 | CC BY 4.0 Open Access | rec: 31 Jan 2017, publ: 31 Jan 2017

Broadly speaking, Cloud robotics can be leveraged to improve the performance of robotic agents in five ways [12]:

- **Big-Data:** harnessing vast amounts of data-sets and knowledge base pertaining objects, maps, and images enriched with mechanical and geometric data.
- **Cloud computing:** taking advantage of the vast processing power of cloud infrastructure to offload expensive offline computations.
- **Collective robot learning:** to reuse and share the knowledge base among robots of different kinds.
- **Open-source and Open-Access:** human sharing of open-source code, data, and designs for programming, experimentation and hardware construction.
- **Crowd-sourcing and Call Centers:** human guidance (call centers) for exception handling and error recovery.

A. Big-Data

The term Big Data describes large data sets that are beyond the capabilities of traditional RDMS in terms of analysis, capture, data curation, and search; that is essential for the growing library of images, maps, and other forms of data relevant to robotics on the Internet.

Ways in which Big-Data could be leveraged is by using data sets that contain information about how to achieve a robot operation like grasping, sensing, localization etc. Examples include the Columbia Grasp dataset [13]. Such a dataset could be consulted by a robot to determine the optimal grasp. Big Data can also facilitate learning in Computer Vision, by matching sensor data to 3D models in an online database. [14]

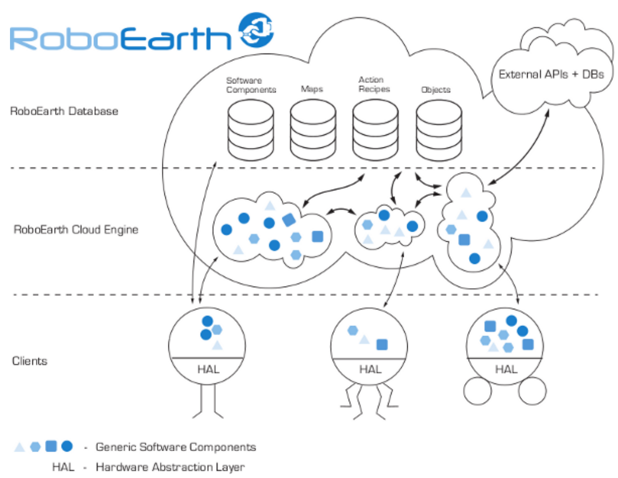

Fig. 1. RoboEarth Architecture [15] - a cloud robotics infrastructure

The RoboEarth project stores data related to objects maps, and tasks, for applications ranging from object recognition to mobile navigation to grasping and manipulation (see Figure 1) [16].

B. Cloud Computing

Cloud Computing services include Infrastructure-as-a-Service and Platform-as-a-Service, for example Amazon Web Services, Google Compute Engine, Microsoft Azure, IBM Watson. These services provide massive gains in terms of parallel computation by renting out a large pool of computing resources that can be used for short-term computing tasks. Originally used primarily by web application developers, scientific and technical high performance computing (HPC) applications have also found a use for them. [17][18][19]

However, cloud computing is challenging when there are real-time constraints [20]; this is an active area of research. However there are many robotics applications that are not time sensitive such as decluttering a room or precomputing grasp strategies.

C. Collective Robot Learning

The Cloud allows robots to share a rich knowledge base comprising of previous operations performed by other robots that have been uploaded on the cloud. Such operations could include various environments, like initial and desired outcomes, associated control policies and trajectories, and most importantly data on performance and outcomes, and thus offer the robot to learn from them and apply the operation on a new environment, thereby, facilitating learning.

One example is for path planning, where previously-generated paths are adapted to similar environments [21] and grasp stability of finger contacts can be learned from previous grasps on an object [22].

D. Open Source and Open Access

Though not directly related to IoT-aided robotic applications, open source hardware and software, can nonetheless lead to the advancement of robotic technologies. The Cloud facilitates sharing by humans of designs for hardware, data, and code. The success of open-source software [23] [24] [25] is now widely accepted in the robotics and automation community. A primary example is ROS, the Robot Operating System, which provides libraries and tools to help software developers create robot applications [26] [27]. ROS has also been ported to Android devices [28]. ROS has become a standard akin to Linux and is now used by almost all robot developers in research and many in industry.

E. Crowdsourcing and Call Centers

We are all used to call centers with automated representatives that help diagnose an issue. However, the same concept can be reversed, wherein, the robot upon detecting errors and exceptions, would access such technical support systems manned by humans. Human skill, experience, and intuition is being tapped to solve a number of problems such as image labeling for computer vision [29] [30] . Amazons Mechanical Turk is pioneering on-demand crowdsourcing that can draw on human computation or social computing systems. Research projects are exploring how this can be used for path planning [31], to determine depth layers, image normals, and symmetry from images [32], and to refine image segmentation [33]. Researchers 4 are working to understand pricing models [34] and apply crowdsourcing to grasping [35].

Therefore, if robots can become a part of the IoT infrastructure, then it could not only harness the benefits offered by Cloud Robotics, but also exchange and enhance sensory information from its many non-robotic things. Having talked about the ways in which the Internet of Things could benefit robotics, the following section discusses the flip side: how Robots can help enhance the IoT. It starts by talking about the various kinds of edge devices and how robots are a special class of them.

III. Robots as Edge Devices and Gateways

Edge devices in IoT represent the things that form the sensory layer of the architecture. Edge devices are responsible for sensing the environments they are in and send data back to the hub or the gateway device to be sent to the server. Edge devices can include simple instruments like temperature sensors to complex ones like a robot.

There are three types of edge devices:

1) Thin
2) Intelligent
3) Actuated

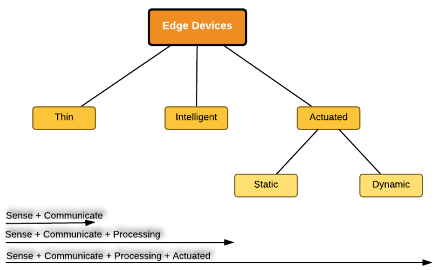

Fig. 2. The 3 types of edge devices [9]. Each of the types has different capabilities in terms of sensing, communicating, processing and having actuation capability.

A. Thin Edge Devices

Thin devices are the bare minimum of edge devices. These devices have the functionality of sensing (example humidity sensor), and communicating that information to its nearby gateway device via wireless or wired technology. Any processing based on the information disseminated is done on distant servers. These devices have limited level of programmability. Examples of such edge devices include an IR temperature sensor, humidity sensor.

B. Intelligent Edge Devices

Intelligent edge devices offer the functionality of having rudimentary processing capabilities, in addition to having sensing and communication abilities. They offer a level of intelligence in terms of processing. They are reprogrammable, sometimes to some degree of autonomy. However, any major processing still occurs at remote servers. Examples of intelligent edge devices include Smart electric meters.

C. Actuated Edge Devices

Actuated edge devices offer the added ability to perform actuation apart from having the abilities of an intelligent edge device. They can be of two types: static actuation and dynamic actuation.

Static actuators are simple in terms of the controls they perform, for example a smart thermostat may have the ability to lower or higher the temperature based on feedback. Static actuated edge devices do however, lack the ability of manipulation, mobility, autonomy, and movement. An example of a static actuated edge device would be the Nest Thermostat. [36]

Dynamic Actuated edge devices can perform much more advanced operations involving manipulation, movement, autonomy, and mobility. In that sense, these are Robotic devices. For example, such a device could be alerted about the need to fetch an object; owing to its abilities it could locate the object, navigate to it, grasp it and navigate back to the intended location to deliver it. An example of a dynamic actuated device could be Willow Garages PR2 robot [37].

Thus, we see that robots form part of a special type of edge device which can extend the abilities of traditional IoT infrastructure. It can be said that the robots provide the arms and legs of an IoT system.

Apart from being an edge device, the robot can also act as a hub or a gateway device. Robots are typically equipped with interfaces to the LAN or WiFi networks, but also Bluetooth, XRF and more. Therefore, robots could intercept information emanating from the other edge devices before sending it to the cloud and other distributed systems, as well as the reverse, that is, allow distributed systems to connect to these devices. These robots could also act to fuse sensor information coming from multiple edge devices, before sending it to the remote servers.

Having looked at how IoT and Robotics complement each other in the previous two sections, the next section talks about the various IoT-aided robotics applications in various domains.

IV. IoT-aided robot applications

The synergy of IoT and robotics remains largely an untapped field of future technology that has the potential to bring about drastic changes to how we live today. IoT based solutions are changing the way we tackle problems. Smart homes, wearables, smart cities, smart grids, industrial internet, connected cars, connected health, smart retail, smart supply chains and smart farming are only a few of the IoT applications in todays times which have impacted how we live as a society. By providing real time, quantifiable and decisive data, IoT has reduced our response time to critical problems and in a few cases made removed the need for human supervision to solve problems. Robotics, on the other hand is a field of science that has been held back the technology of its time. To top it off, the investment required to deploy robotics based solutions is high. This is however changing.

Robotics based solutions to challenges are quickly emerging. Industrial robots, used in the manufacturing and automobile industry have reduced production time, reduced degree of error and improved quality produce. Robots are used for deep underwater explorations and unchartered space explorations. In this section, I'll be focussing on the amalgamation of IoT and robotics applications/solutions in healthcare, industry, military and search and rescue operations[38].

A. Healthcare applications

IoT applications in the healthcare industry range from remote monitoring of patients. Wireless devices that monitor the patient's vitals are connected together in Wireless Body Area Network, that deliver the collected data to a remote device for monitoring, tracking and analysis. Edge devices that gather timely data of the patient, allow healthcare providers to remotely monitor, assist and if possible provide medication to those patients for whom it may not be feasible to meet their healthcare provider[39]. Robotics in healthcare is mostly seen in literature and there is little widely in practice today[40][41][42][43]. IoT and robotics solutions can deployed to provide assistance to disabled, elderly patients and those with locomotory issues[44] [45]. Monitoring and tracking of medical equipment or lack of can greatly improve management of hospitals and medical equipment so that less amount of time goes into maintaining infrastructure. This can greatly improve the quality of medical service that is dispensed to patients[46].

B. Industrial Applications and Personal Applications

IoT solutions solve a wide range of problems in industry from electrical grid system monitoring, temperature monitoring, power consumption, lubricant status, etc[47][48]. IoT applications are also often used in perimeter intrusions detection systems at airports, railway stations and ship ports. Smart objects are used to manage parking places. Smart objects comprising the wireless sensor network (WSN)[49] are used enable automation, energy monitoring and control and surveillance systems. Robots in industry are largely used in large assembly lines to speed up the production process. Robotic perception along with artificial intelligence are used for efficient human robot interaction. Moving toward the vision of a robot in the personal space, cleaning and servicing robots are increasingly becoming common trend. Efforts are being made to deploy robots in the public space for surveillance and monitoring activities[50]. IoT aided robotics are most suitable for scenarios where real time data is required from inhospitable environments for long durations of time. IoT aided robots can be strategically deployed to get high quality real time data which would not have possible from disconnected robots.

C. Military Applications

IoT in the military is used to detect presence and intrusion of unwanted chemical agents, signals, radiations etc though photoelectric, laser and acoustic sensors. They are used to uncover hidden areas of danger, track enemy movements, detect snipers and perform perimetric surveillance in sensitive areas[51][52]. The most common type of robotic military application would be the unmanned aerial, ground, and underwater vehicle. These robots are use to cover areas which would normally put the life of many soldiers at risk. Using these, remote surveillance and attack can be carried out over crucial strategic zones. IoT aided robot applications can include the co-ordination of smart objects with UAVs, UGvs and UUVs[53]. Smart objects can detect and uncover chemical agents, hazard zones and nuclear/biological weapons in the given environment, these can then be traversed by UGV/UAV/UUV to further evaluate and monitor the environment.

D. Rescue Applications

Smart objects in are used to collect emergency information and distribute the captured data to the required sources in the least amount of time as possible. IoT devices operating in a wireless sensor network are ideal in disaster scenarios to relay critical information as the default communication infrastructure may be damaged. They are used to monitor the relief and rescue operations of the affected site. This information can be used to organize and direct ground rescue forces to critical areas. Robot applications in recure are used in search and rescue, where it is too dangerous or not physically possible for rescue and relief forces to save people. IoT aided robot applications can be used to coordinate with relief and rescue forces on the ground to prioritize operations according to risk and damage to the environment and then to deploy robot applications to perform search [54] and rescue operations on high priority locations[55].

The following section discusses the use case of an Intelligent Transportation System within an IoRT architecture.

V. Use Case: Intelligent Transportation System

Intelligent transportation systems (ITS) are advanced applications which, without embodying intelligence as such, aim to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer, more coordinated, and 'smarter' use of transport networks [56].

ITS applications mostly have to deal with communication technologies, more so on short range communications. Moreover, ITS applications involve a myriad of sensors for detecting vehicles, in automated-toll collection booths etc. and these sensors can tap into the existing IoT infrastructure. In other words, protocols that govern IoT applications can be brought into play for ITS, and since both these concepts: IoT and ITS are suffering from a lack of standardisation, it is ideal to look at them collectively, to better complement each other. Also, the development of technology in one domain can also benefit the other, for example, the introduction of 5G can help in communications between the different types of sensors.

In the context of ITS, an IoRT architecture could be implemented, wherein the following could be its components:

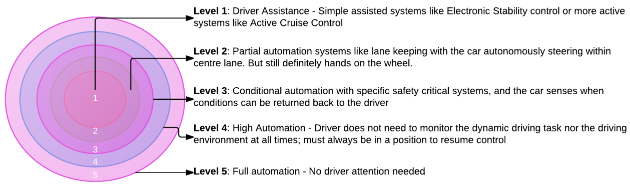

Fig. 3. Five levels of autonomy in vehicles.

1) **Vehicles:** These would be the robotic components in the IoRT-inspired architecture. The vehicles could be connected [57], or fully-autonomous; bringing into play its various sensors, and its ability to be mobile and showcase dynamic actuation. The vehicles would also have the ability to communicate to other vehicles, hence, communicate among the things (V2V communication) and also its environment, for example the Road Side Units (RSU) (V2I communications).
2) **Sensors:** These would be deployed on the road or near intersections. Their functionality could differ: some could be used to detect vehicles, some to measure the amount of wetness of the roads, etc. These things would eventually communicate with gateways placed near their communication range.
3) **Data Centers and Gateways:** RSUs could act as the gateway devices for the nearby sensors. These RSUs could then relay their information back to local data centers. The data centers could take decisions based on local information like traffic decongestion, and also share its information with other data centers for more global decision making. The vehicles, in lieu of being connected would constantly be sending back data to the cloud, however, this information may not be made public by the OEMs to the data centers of the ITS. Thus, such information could be sieved by the private cloud and sent back to the data centers.

All in all facilitating a network of data sharing, which could be used to supplement the various applications of the ITS. Figure 4 depicts the envisioned use case.

VI. Conclusion

In this position paper we have investigated the synergy between IoT and Robotic systems. We have looked into how IoT systems - via cloud robotics - could benefit robotic operations like sensing, manipulation, localization, grasping etc. The paper also discussed the ways in which robots could act as an extension to the things in IoT; how they act as the arms and legs of IoT, and also as enhanced edge devices and gateways/hubs. IoT-aided robotic application were also explored with an emphasis on healthcare, military, rescue operation and industrial applications. The paper culminates by taking the use case of an Intelligent Transportation System viewed in light of an IoRT architecture, thereby highlighting the immense potential such an architecture has on future technologies.

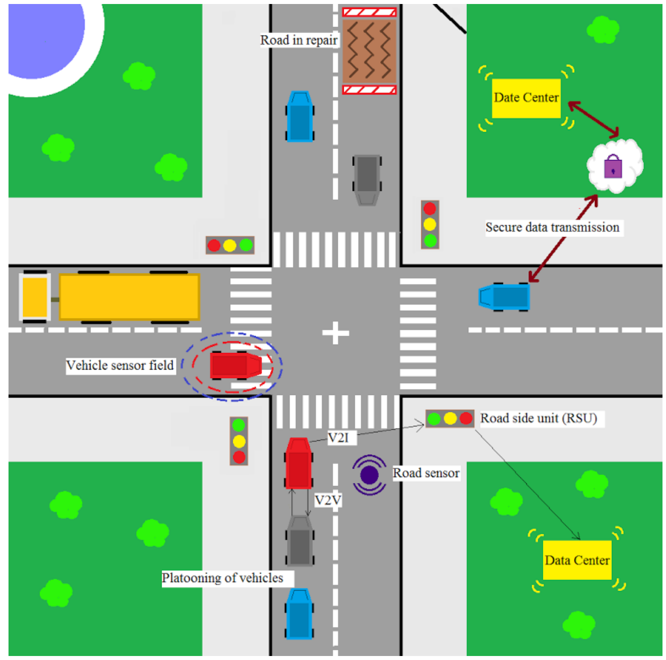

Fig. 4. ITS within an IoRT-inspired architecture.

VII. Acknowledgements

This research was carried out as part of the Advanced Solutions Group initiative at Lochbridge, Gurgaon. I would like to thank Mohan Jayaraman (Chief-Technologist, Lochbridge - Detroit) for mentoring my efforts and for providing valuable insights into the field of IoT.

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