

Smart Cloud: Scalable Cloud Robotic Architecture for Web-powered Multi-Robot Applications

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Abstract— Robots have inherently limited onboard processing, storage, and power capabilities. Cloud computing resources have the potential to provide significant advantages for robots in many applications. However, to make use of these resources, frameworks must be developed that facilitate robot interactions with cloud services. In this paper, we propose a cloud-based architecture called *Smart Cloud* that intends to overcome the physical limitations of single- or multi-robot systems through massively parallel computation, provided on demand by cloud services. *Smart Cloud* is implemented on Amazon Web Services (AWS) and available for robots running on the Robot Operating System (ROS) and on non-ROS systems. *Smart Cloud* features a first-of-its-kind architecture that incorporates JavaScript-based libraries to run various robotic applications related to machine learning and other methods. This paper presents the architecture and its performance in terms of CPU power usage, latency, and security, and finally validates it for navigation and machine learning applications.

I. INTRODUCTION

The scope of the robotics industry is immense, and the industry is poised to see huge gains in the coming years. The International Data Corporation estimates the 2019 economic value of robotics and related services will hover around \$135.4 billion, and during the period of 2018 to 2023, the industry is estimated to register a compound annual growth of 24.52 percent [1]. The ubiquitous availability of big data and recent advancements in machine learning can be used to develop smarter and more responsive robots. Most such applications involve processing large quantities of data, which requires high-performing computational resources [2]. However, existing robots come with limited onboard computing capabilities, and once a robot is built, it is not easy to change the hardware configuration. By enabling cloud computing for robotic applications, robots will be able to access increased computational power and storage space as needed to carry out their assigned tasks. With the resources provided by cloud computing services, computationally-intense robotic tasks like object detection, navigation, and others can be solved more efficiently.

Cloud computing is a service-driven paradigm for hosting applications on remote infrastructure, i.e. resources are provided on-demand. Since its inception, cloud computing has helped researchers and business users to host applications by providing access to distributed and shared computing resources over the Internet. In practice, the services provided by the cloud can be categorized into three major types:

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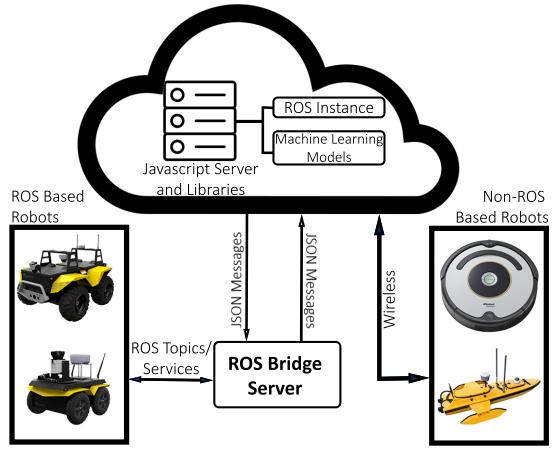


Fig. 1. Schematic overview of *Smart Cloud* architecture.

Software as a Service (SaaS), Platform as a Service (PaaS), and Infrastructure as a Service (IaaS) [3].

SaaS is used to provide access to a completely developed application over the Internet. IaaS refers to the on-demand provisioning of infrastructural resources. In IaaS, the consumer is usually provided with fundamental computing resources, where the consumer can deploy an arbitrary software. PaaS falls between IaaS and SaaS, where cloud service providers provide the consumers with tools like a programming languages, libraries and so on, to help the consumers to develop the applications.

Cloud robotics, first introduced as a term by James J. Kuffner in 2010 [4], can be defined as the wireless connection of robots to external computing resources to support robot operation. Cloud-enabled robots are able to offload computing tasks to remote servers, thus relying less on their onboard computers and instead exploiting the inexpensive computing power and data storage options provided by cloud service providers. The cloud robotics market is estimated to achieve 23.2 percent compound annual growth. The cloud robotics market was valued around \$2.3 billion in 2017, and is expected to reach \$7.9 billion by the year 2023 [1]. To realize the full potential and scope of cloud robotics, however, it is very important to innovate and address the shortcomings currently faced by the field.

In this paper, we present a new cloud robotic architecture called *Smart Cloud*, outlined in Fig. 1. The architecture includes several novel functionalities that make it the first of its kind. *Smart Cloud* can be used as both SaaS and PaaS depending on the needs of the application. In a SaaS-

based approach, it provides a simple web-based interface by which a robot can make use of several ready-to-use applications, both Robot Operating System (ROS)-based and non-ROS-based. The architecture backend is built on a JavaScript (JS) server. Using JS inherently allows access to open-source libraries, including machine learning libraries like TensorFlow, data compression mechanisms to reduce network load, and more. Additionally, we intend to provide the developed framework as an open-source application for other researchers to modify, as researchers frequently need the flexibility to develop or customize applications to suit their specific requirements. By making the framework open-source, the proposed architecture can also be used in a PaaS implementation.

In this paper, the functionality of the architecture is demonstrated for several application scenarios. Furthermore, the architecture is evaluated in terms of CPU utilization, latency, and security. The remainder of the paper is organized as follows: Section II presents a literature review, while Section III describes the architecture in detail. Section IV discusses its applications and the evaluation of its performance. Finally, Section V presents conclusions and future directions.

II. RELATED WORK

The invention of the World Wide Web in the late 1980's opened up the possibility of connecting a robot to an external machine over the Internet. In 1994, K. Goldberg was amongst the first to successfully connect a robot to the web, teleoperating the robot through an Internet browser [5]. In 1997, Masayuki Inaba at the University of Tokyo worked on a so-called "remote brain;" in the associated publication, the authors described advantages of using remote computing for robots [6]. In 2009, the 'RoboEarth' project was announced with the intent to develop a World Wide Web equivalent for robots [7]. RoboEarth was developed by a team of researchers from Eindhoven University; the idea was to build a large database that allowed robots to share learned information with one another. The RoboEarth project team created a platform for cloud computing, named Rapyuta [8]. Rapyuta is a PaaS-based robotics framework that allows robots to offload all computation-intense tasks to the cloud service. This framework has access to the RoboEarth data repository, which enables robot access to all extant libraries on RoboEarth.

Interest in cloud robotics has led to the development of new vertical research involving architectures that facilitate robot communication with cloud service providers. One of the first architectures in this area was 'DaVinci', which used cloud computing infrastructure to generate 3-D models for robot localization and mapping much faster than possible using on-board hardware [9].

Doriya et al. proposed a robot cloud framework that helps low-cost robots offload computationally-intense tasks to the cloud [10]. The central unit of the framework is equipped with a ROS master node that facilitates all communication. In 2016, Wang et al. proposed a hybrid frame work

called RoboCloud [11]. RoboCloud differs from other cloud robotics architectures by introducing a task-specified mission cloud with controllable resources and predictable resources. For tasks beyond the capability of the mission cloud, the framework opts to utilize public clouds, the same as any other cloud robotics architecture.

In addition to the above-mentioned PaaS architectures, researchers have also worked on SaaS-based frameworks, also called Robot as a Service (RaaS). Notably, SaaS-based architectures can more easily overcome interoperability issues that arise due to differing robot hardware. Frameworks such as C2tam [12] and XBotCloud [13] focus on specific applications or algorithms, for example object recognition or object grasping. Tian et al. [14] proposed a RaaS-based robotics model called Brass, which allows robots to access a remote server that hosts a grasp planning technique. The framework leverages Docker to allow for implementing algorithms by writing simple wrappers around existing code.

In summary, most currently-available architectures are geared towards PaaS models; few of them take a SaaS approach. These architectures are designed to offload robotic applications to the cloud infrastructure. The proposed framework differs from extant frameworks by being built for use in both SaaS-based and PaaS-based applications. A simple web interface will be provided for SaaS usage, and the code will be made publicly available for users to develop applications on top of it in PaaS usage. Furthermore, the proposed framework is the first of its kind to provide access to open-source JavaScript libraries; users are not limited to available packages and do not need to develop applications from scratch, but can make use of available JavaScript libraries for robotic applications.

III. ARCHITECTURE

As shown in Fig. 2, the Smart Cloud architecture consists of two main components: the Robot layer (ROS-based robots and non-ROS-based robots) and the Cloud Service layer. We chose JS for the development of this framework because of its ubiquitous nature, support for ROS, and the vast availability of libraries. In terms of available open-source libraries, JS outnumbers every other programming language. Additionally, the JS library Roslibjs allows interaction with the ROS interface Rosbridge, which is developed for non-ROS users and used to send and receive data in the form of JavaScript Object Notation (JSON) packets. Roslibjs supports essential ROS functionalities such as publishing and subscribing to topics, services, actionlib, and more.

A. Robot Layer

The robot layer consists of a single robot or a multi-robot system that runs on either ROS or any generic robot software. In the next subsection, we discuss how the architecture handles data based on the robot's software and the type of application service requested.

1) ROS Based Robots: ROS is a framework for writing robotic software. The Rosbridge package allows a ROS-based robot to interact with any non-ROS system [15]

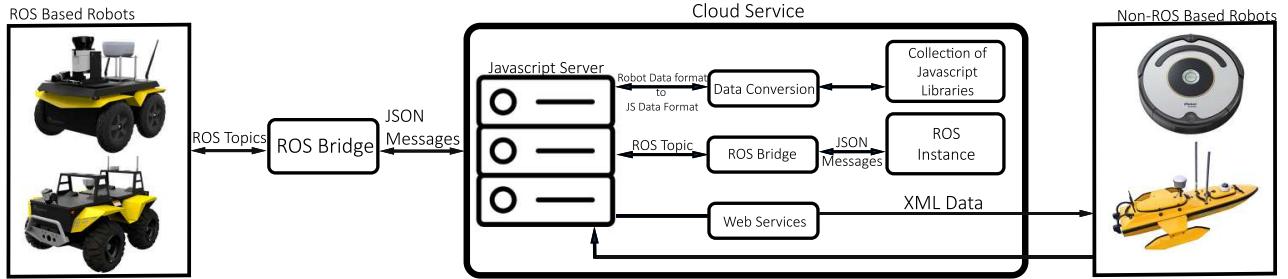


Fig. 2. Smart Cloud architecture. (Middle) Cloud Server: The JS server interacts with JS libraries and ROS. (Left) ROS-Based Robots: Robots interact with the server using the ROSBridge protocol. (Right) Non-ROS-Based Robots: Robots send information through wireless data transfer and receive responses as web services.

through web sockets. In this architecture, we use Rosbridge to establish a communication protocol between robots and cloud services. On the cloud side of the architecture, a master instance of ROS helps the robots to offload computationally intense tasks to the cloud.

Through this framework, robots can access ROS packages and JS libraries; however, to use ROS packages on the cloud, the robots themselves need to run on ROS. Data from the robot is published as ROS topics and received on the cloud side using Rosbridge with the following code:

```
function rosTopics()
{
    var topicsClient = new ROSLIB.Service({
        ros : ros,
        name : '/rosapi/topics',
        serviceType : 'rosapi/Topics'
    });
}
```

Almost every ROS package functions by taking the topics from the robot as input. Once the cloud framework receives the list of topics from the robot, the framework parses through the list of ROS packages available on the cloud, to find the packages that can be used based on the topics available. The list of matched ROS packages (the package that can be used) are displayed on the web interface for the user to choose. The user can pick a package from the list and the result computed by the package is sent back to the robot over the Rosbridge. For example, a ROS gmapping package requires *tf* and *scan* topics to work. The framework after receiving the list of topics from the robot and if it finds *tf* and *scan* topics available, the user will be provided with an option to use gmapping package on the cloud. Fig. 3 shows the web interface displayed to the users.

Almost every ROS package takes topics from the robot as input. Once the cloud framework receives this list of topics, it parses through the list of available ROS packages to find those that can be used with the given input. The list of matching ROS packages are displayed on the web interface for the user to choose between. After the user picks a package, the result is computed and sent back to the robot over the Rosbridge. For example, the ROS gmapping package requires *tf* and *scan* topics. If the framework finds *tf* and *scan* topics available, the user will be provided with the option to

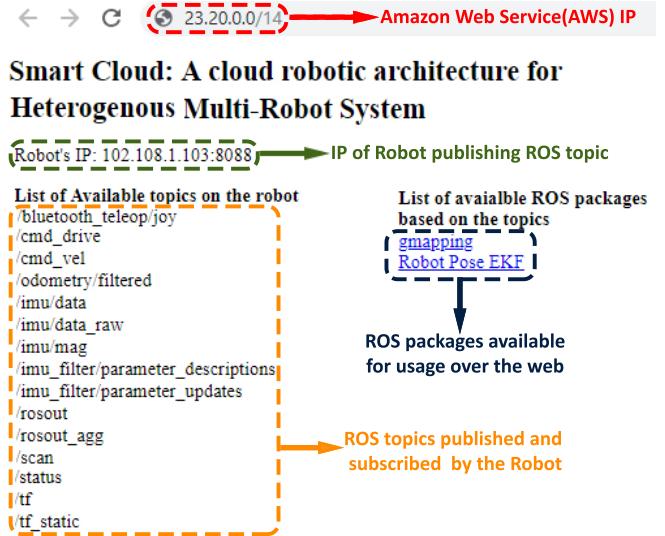


Fig. 3. Smart Cloud: SaaS-based ROS interface. The robot provides a list of topics and the architecture displays corresponding packages that can be used.

use gmapping. Fig. 3 shows the web interface displayed to a user.

2) *Non-ROS Based Robots*: The data from robots not using ROS will be transferred directly to the cloud using wireless protocols. Once the data is received, the architecture provides a set of JS-based libraries to choose from based on the message type. For example, if the message is in the form of an image, the framework provides libraries related to object detection, object tracking, and the like. If the message is in the format of GPS coordinates, the framework provides various GPS-based applications.

On the server side, the framework implements a RESTful-based web service (Fig. 4) that is used to communicate the results back to the robot

B. Cloud Layer

Robots are connected to the JS server on the remote cloud infrastructure through web sockets. Depending on application requirements, the cloud layer runs a single or multiple instances of Linux-based operating systems. On these instances, JS Server and ROS are deployed. In this

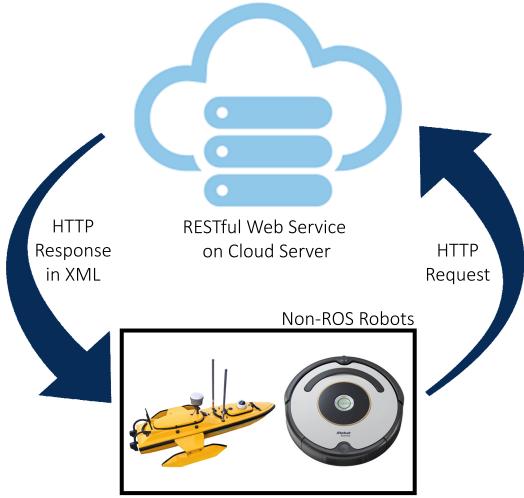


Fig. 4. General flow of information between robot and cloud through the RESTful web service

section, we will look into how data is received and processed by the JS server and how various libraries are used for robotic applications.

1) *JavaScript Server*: In this architecture, we use a JS server based on *Node.js* [16]. *Node.js* is an open-source and cross-platform JS server that runs JS scripts outside a browser. The framework has different mechanisms for handling data from ROS and non-ROS systems.

For ROS-based data, the user has can choose applications from ROS packages or JS libraries. If the user chooses a JS-based library, the framework decodes the data provided by the robot using appropriate JS libraries. We use inherent JS tools like *Data.Type.type()* to classify the type of data and then decode it into an appropriate form. For ROS image formats, we use the *Canvas* library to the convert it to Base64 image format. Figure. 5 illustrates the data flow on the cloud.

2) *JavaScript Libraries*: For the past five years, JS has consistently ranked among the top ten programming languages. It is used everywhere: in web browsers, mobile applications, games, the Internet of Things, robotics, and more. Due to the high usage of JS, the ecosystem around it is growing at a fast pace. Node Package Manager (NPM) is a popular package manager for JS, with more than 35,000 open-source packages. We intend to use some of this vast set of publically-available libraries in our proposed framework, including the popular machine learning library TensorFlow, which has recently been introduced to the JS ecosystem. To demonstrate the working of the architecture, we used TensorFlow.js for object recognition.

IV. APPLICATION AND EVALUATION

We conducted an experiment to demonstrate the working of the architecture and also to evaluate various metrics. This experiment used two robots, a Clearpath Jackal Unmanned ground vehicle (UGV) and an iRobot Roomba powered by

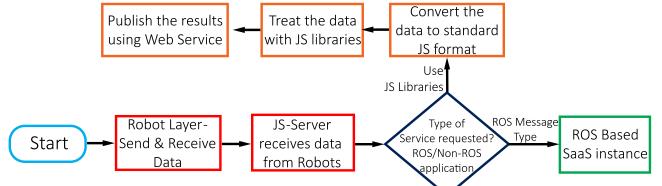


Fig. 5. Flow chart illustrating the data flow between the robot and Cloud.

TABLE I
HARDWARE CONFIGURATION OF THE ROBOTS

	Jackal UGV	ODROID-XU4
CPU	Intel(R) Celeron(R) G1840 @ 2.80 GHz	Samsung Exynos5422 A7 Octa-core CPUs
RAM	2 GB	2 GB

ODROID-XU4. The hardware configurations of the devices are summarized in Table I .

A. Offloading ROS applications to the cloud

For this experiment, we implemented the ROS package gmapping over the cloud and also on the robot. The framework subscribes to topics from the robot and executes the gmapping application on the cloud. We evaluated the performance impact using three metrics: CPU utilization, latency, and security.

1) *CPU Utilization*: Execution of the ROS gmapping package onboard the Jackal was compared against using the cloud architecture to observe differences in CPU utilization. CPU utilization was measured using the open-source tool netdata, which is a real time performance monitoring tool for Linux-based systems. We were able to demonstrate that by offloading gmapping computation to the proposed architecture the, CPU utilization of the robot decreased by an average of ten-fold compared to running the package on the robot. Fig. 6 and Fig. 7 show the difference in the CPU utilization on the robot. When offloading applications, the architecture subscribes to topics published by the robot and executes all back-end computation related to ROS packages. By using the architecture, no load associated with ROS packages is incurred by the onboard CPU, hence the dramatic decrease in CPU utilization.

2) *Latency*: Latency is the term used to describe any kind of delay that occurs during data communication over a network. As the Smart Cloud architecture requires an exchange of information between robot and cloud service provider, some latency exists between robot requests and cloud service responses. For this experiment, we used an Amazon Web Services (AWS) server located in North Virginia. We measured the latency at various time periods throughout a given day and recorded an average latency of 28 to 33 milliseconds.

To measure the time delay between robot requests and cloud service responses, we implemented a simple ROS service to exchange information and recorded the message timestamps. On average, we observed a time delay of around

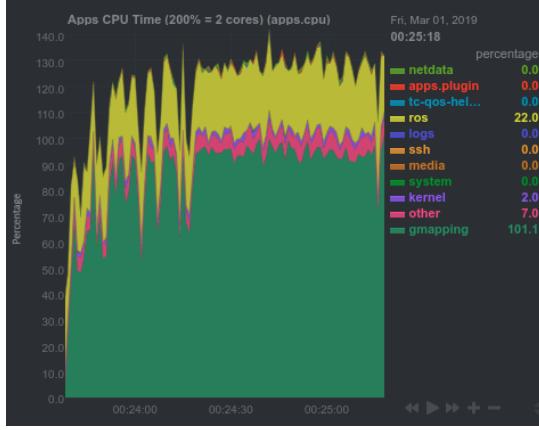


Fig. 6. CPU utilization with gmapping deployed on the robot (Jackal). On balance, gmapping fully consumes one processor core.

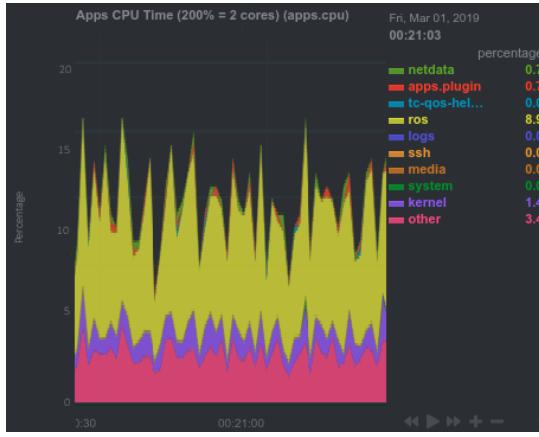


Fig. 7. CPU utilization with gmapping deployed on the cloud. Demand on the robot CPU is significantly decreased.

35 milliseconds, of which an average of 32 milliseconds was associated with AWS. Thus, the time delay contributed by the framework is approximately three milliseconds.

3) Security: Using a commercial cloud service inherently provides the architecture with robust security measures [17]. AWS offers comprehensive security measures to protect data from theft, data leakage, and deletion, including measures such as a firewall, intrusion prevention, a certificate manager, and web application security. Furthermore, an AWS user can set up a security group that allows architecture users to define security measures based on the sensitivity of their data. Hence, using cloud services makes the architecture less susceptible to hacking and intrusion than using traditional in-house security.

B. Object Detection using Tensorflow JS library with Odroid

In this experiment, we streamed video from a Roomba equipped with an ODROID-XU4 computer to the architecture. The architecture then identified objects in the video stream using the TensorFlow.js library with an ImageNet dataset and generated XML-based web services to report the results (Fig. 9). Between the robot publishing a frame and the resultant web service feedback, we observed an average

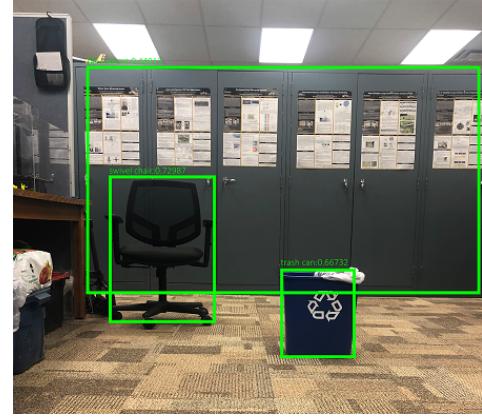


Fig. 8. Object (i.e. cabinet, swivel chair, and trash can) detected using TensorFlowJS.

time delay of 34 milliseconds. The same functionality can be implemented for ROS Image messages by converting the image to base64 format.

The following lines of code can be used to convert a ROS Image to JPEG format:

```
var imgResponse = new Image();
var byteCharacters = atob(message.data);
var abc = "data:image/jpeg;base64,"+byteCharacters;
imgResponse.src = abc;
```

The following XML file is the web service output generated for Fig. 8:

```
<?xml version="1.0"?>
<Response>
  <Message>
    <MessageID>1</MessageID>
    <ReferenceID></ReferenceID>
    <Result>
      <Class>Trash Can</Class>
      <Probability>0.66</Probability>
    </Result>
    <Result>
      <Class>Swivel Chair</Class>
      <Probability>0.72</Probability>
    </Result>
    <Result>
      <Class>File Cabinet</Class>
      <Probability>0.44</Probability>
    </Result>
  </Message>
</Response>
```

C. Application scenario using a heterogeneous multi-robot

In this section, we demonstrate a scenario applying a heterogeneous multi-robot system to search and rescue that can be implemented using the proposed architecture. The multi-robot system consists of a non-ROS-based iRobot Roomba equipped with a Microsoft Kinect Camera and a ROS-based Clearpath Jackal equipped with Velodyne 3D LiDAR. Data from the camera is continuously streamed to the cloud service using wireless protocol, and TensorFlow.js is used to detect objects in the video stream. The results are continuously streamed back using the web service. Meanwhile, the ROS-based Jackal subscribes to the web service

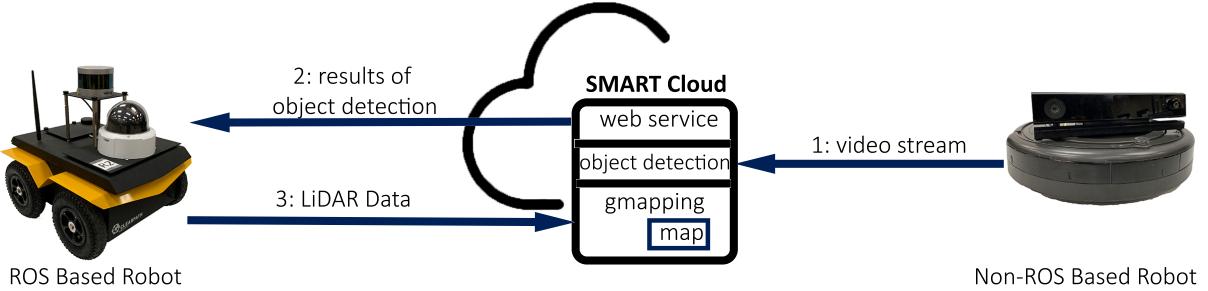


Fig. 9. Heterogeneous multi-robot setup.

results and waits for the Roomba to find an object of interest. When such an object is found, the Jackal uses its LiDAR to create a map of the area. Figure. 9 demonstrates this heterogeneous setup.

A video of the simulations is available for reference at: <https://youtu.be/zImysVWLlFs>.

V. CONCLUSIONS

In the paper, we present the *Smart Cloud* architecture, which is the first of its kind to incorporate JavaScript-based libraries for running diverse robotic applications related to machine learning and more. *Smart Cloud* also leverages the resources provided by cloud service providers for use with robotic applications. The architecture can be used with heterogeneous and homogeneous multi-robot systems as well as single-robot systems. We additionally demonstrate the working of ROS and non-ROS based robot systems with the architecture and the incorporation of JS libraries for robotic applications. We measured the performance of the architecture in terms of onboard CPU usage, latency, and security. We were able to show significant reduction in onboard CPU usage and achieved an average latency of 35 milliseconds.

Our future work will focus on the development of tools and mechanisms to lower latency further. We are also working on designing an offloading schema that will facilitate the dynamic offloading of applications based on application memory requirements and criticality. We are also developing a pipeline of tools to improve overall performance of the architecture in terms of metrics such as latency, scalability, interoperability, availability, and security.

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