Hybrid Cloud Robotics

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***Abstract*— Since its official launch in 2010, cloud robotics has been the major trend in todays robotics, however, there are hard-real time robotics applications that are not able to use this concept due to their sensitive latency requirements. In this paper, we propose the concept of *hybrid cloud robotics* where the computation of any application is dynamically distributed among the computation available on-board, on the edge computing and on the cloud. We show the applicability of this model for a deep learning-based object recognition and a SLAM algorithm.**

I. INTRODUCTION

With the development of artificial intelligence (AI), new computation-heavy applications have been proposed in robotics such as deep learning based object recognition (OR) [3], simultaneous localization and mapping (SLAM) [4] [5], that have been extensively gained attractions.To process such considerable computations, mobile robots by themselves need to overcome some real-time constraints such as their limited on-board compute capability and storage capacity.

Cloud robotics has enabled network-connected robots offloading the intensive and complex computation tasks to take advantage of parallel computation and data sharing available in a centralized location [1]. By utilizing cloud robotics, not only individual robots can become more intelligent and autonomous, but also multiple robots can overcome individual inaccuracies due to observation noise or lack of global view while learning cooperatively.

From the application point of view, two types of robotics applications can be defined, hard vs. soft real-time. While soft real-time applications such as OR can stand a latency in the order of hundreds milliseconds, the hard-real time applications such as collision avoidance can only tolerate a latency of less than ten milliseconds.

Though a lot can be achieved by employing cloud robotics, the need of having constant connection to the cloud infrastructure cannot always be delivered [2]. Moreover, other issues such as network traffic or reliability issues can lead to higher latency that again degrades the real-time performance. The concept of edge computing [8], recently has been proposed in domains such as Internet-of-Things (IoT) to fill the latency and network incompetency gap in real-time applications [9], [10], [11]. In edge computing, the processing is allocated at the edge of the network in a distributed manner, i.e., smaller local servers such as computing base-stations and WiFi access points [8] to provide a required response time for hard real-time applications.

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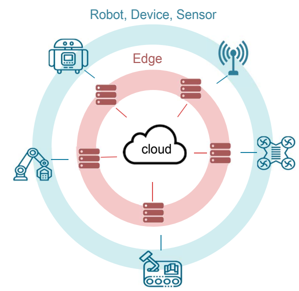

Fig. 1. The proposed *Hyrbid Cloud Robotics* computation model.

However, despite the benefit of edge computing for real-time applications in robotics the computation and storage capacity of the edge nodes are pretty limited. Therefore, the need for cloud computing and storage is still persistence but can be considered more for computation-heavy or accumulative data-intensive applications. The contribution of this paper is proposing *hybrid cloud robotics*, where the computation dynamically is distributed among the on-board computing of the robot (i.e., device), available computation on the edge, and the unlimited computation on the cloud.

II. HYBRID CLOUD ROBOTICS

Although clouds will continue to grow and will include more use cases, the concepts of edge computing is adding an additional dimension to cloud computing. As discussed, robotics applications include hard and soft real-times. While cloud robotics can truly empower the application of AI in robotics, it is still limited to soft real-time applications. This work proposes a *hybrid cloud robotics* paradigm in which the power of cloud robotics can be extended to all types of robotics applications. Fig. 1 depicts the proposed model where three computation layers are involved as follows:

(i) The first computation level is usually light and is done on the device. This include a quick control reaction of the robot in an environment via a closed control loop. The basic functionality of a robot is mainly included in this level; (ii) The second level of computation is pushed to the edge of the network, where edge nodes can be considered as hosting infrastructure [2]. Interestingly, an edge node in our model can be a master robot among a swarm of robots that has a more powerful computation capabilities. This level basically perform the hard-real time use cases where the computation is not light enough to be run on the robot, and the latency tolerance is low so that relying on the network to transmit the sensor data to the cloud and receiving the results can not be tolerated; (iii) The last level covers the delay tolerant processing that are sent to the cloud for either soft real-time or off-line processing. This includes data- or computation-intensive processing that needs to be accumulated in a centralized manner, or the queries that needs to be assessed based on global knowledge.

In such a hybrid computing paradigm, event driven computing is becoming dominant so that each data generated by a sensor can be considered as an event of a robot, edge, or cloud [12]. Therefore, to realize the idea of *hybrid cloud robotics*, dynamic allocation and scheduling of computing tasks is key.

A. Applications of Hybrid Cloud Robotics

Recent advances in deep learning enable automated analysis of robots' sensor data in particular cameras to query objects of interest, either for obstacle avoidance or for purpose specific tasks. Such state-of-the-art deep learning OR algorithms are computationally expensive, especially for a robots on-board capacity. By performing frame sampling of the frame on the robot, partial data processing for ROI (region of interest) tracking on the edge node, and the recognition of the object in the cloud, the overall latency of the task process is dramatically reduced.

To show the application of the proposed model in robotics, we implemented an OR algorithm using RGB data. In our demonstration, a robotic platform is equipped with a single-board computer (SBC) which is approximately credit-card sized (Raspberry Pi 3) with 2450 MIPS and a Xtion PRO as an RGBD sensor. If such a task is performed only on the SBC, the performance of the process is $\sim$0.07fps, the user sees new images with detected objects every $\sim$13 seconds. While, using our proposed *hybrid cloud robotics* model, the entire process improves to $\sim$30fps, which translates to the user into a real-time visualization of the detection process[1].

As a second use case, a SLAM algorithm was implemented using the previous robotics platform setup with an RGBD sensor. In this setup, the generated map was stored on the C2RO cloud-based dashboard [2] and can later be shared with other robots introduced to the environment as a shared available map. This way, the burden of exploration and map building are omitted for the new robots and the need for additional sensors are minimized. Our results show if the map is built locally on the SBC the SLAM algorithm update rate is $\sim$5Hz, while by using our *hybrid cloud robotics* model, the map update rate was enhanced to 30Hz[3].

III. CONCLUSIONS

Although cloud robotics has been significantly pushed the barriers of robotics applications, it is not still a proper model for latency sensitive robotics applications. To this aim, we proposed *hybrid cloud robotics* model where the computation is dynamically distributed among three layers including the computation on the robot, edge and cloud. The application of this model for an object recognition and a SLAM algorithm showed that the performance is significantly improved.

[1] C2RO OR demo video: `https://youtu.be/tg1h6bvLfvU`

[2] For academic usage: `http://lnked.in/c2ro-cloud-rob`

[3] C2RO SLAM demo video: `https://youtu.be/RdLwU0uKD08`

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