COTORRA: COntext-aware Testbed foR Robotic Applications
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Abstract—Edge & Fog computing have received considerable attention as promising candidates for the evolution of robotic systems. In this letter, we propose COTORRA, an Edge & Fog driven robotic testbed that combines context information with robot sensor data to validate innovative concepts for robotic systems prior to being applied in a production environment. In lab/university, we established COTORRA as an easy applicable and modular testbed on top of heterogeneous network infrastructure. COTORRA is open for pluggable robotic applications. To verify its feasibility and assess its performance, we ran set of experiments that show how autonomous navigation applications can achieve target latencies below 15ms or perform an inter-domain (DLT) federation within 19 seconds.

Index Terms—Edge, Fog, robotic applications, testbed, orchestration, DLT, multi-domain.

I. INTRODUCTION

Networked robotics combines robotics with communication networks to enhance capabilities of robots. A clear example is Cloud robotics [1], which aims to integrate Cloud computing resources in robotics systems to increase re-configurability as well as to decrease the complexity and cost of robots. Thanks to Edge [2] & Fog [3] computing, real-time applications as autonomous navigation will run closer to the robots, and the robot-to-cloud communication will be enhanced thanks to improved latency and reliability. Since the robot-to-cloud communication will traverse fewer network links, higher bandwidth rates, and bounded jitter are achievable. Moreover, real-time context information about the robots is expected to be available in the Edge, allowing dynamic adaptation of application’s logic to the actual status of the communication (e.g., radio channel) [4]. Therefore, executing robotics applications in the Edge of the network is considered as a potential evolution of robotics system.

Most of the existing work focuses on Cloud robotics testbeds or platforms [5]–[10]. In [5], the authors indicate the feasibility and challenges of a real world Cloud robotics implementation over Cloud testbed infrastructure. Besides, [6] suggests a Cloud robotics testbed that can be effective for developing not only robot-related experiments but also network applications. By providing a Cloud robotics testbed for mobile robots, VC-bots [7] tries to address some important factors such as mobility, traffic scenario, protocol, cloud resources and localization awareness. Furthermore, due to the set of constrains (e.g., cost, time, safety) when performing physical testing of Unmanned Areal Vehicles, [8] develops an Cloud-enabled, open-source simulation testbed for UAVs, thus reducing the entry barrier of UAV development and research. Finally, [9] and [10] propose Cloud robotics platforms that address number of implementation-related issues.

However, it is relevant to note that all the existing robotics testbeds or platforms depend on the use of Cloud computing. Unfortunately, no Edge & Fog robotics testbeds are explicitly mentioned in the existing literature, despite the need for an analysis on implementation issues, standards and validation for Edge robotics applications. There is a lack of practical experience on context-aware real-time environments in robotics systems. That leads to limited applicability in production systems and final products.

In this work we propose COTORRA, a real-time context-aware testbed architecture that we implement and validate. This testbed is particularly suitable for time-sensitive robotic applications and mobile robots in Edge & Fog environment. Additionally, to consider the time-sensitivity in computational offloading decisions, the COTORRA testbed offers network emulation capabilities. To validate COTORRA, we implemented two applications on top of it: an orchestration and a federation solution for robotic systems. The experiments and results illustrate how COTORRA can be used to enhance robotic applications.

The remainder of this letter is organized as follows: we propose our real-time context-aware testbed for robotic applications in Sec. [II] and its possible implementation in Sec. [III]. Finally, we evaluate the testbed in Sec. [IV] and we conclude this letter in Sec. [V].

II. COTORRA SYSTEM DESIGN

COTORRA system model follows a modular design as shown in Fig. 1. The hardware layer (bottom) is a weighted graph $G$ with graph embedding$^1$ that capture the state of robots $r_i \in V(G)$ and hardware components present in a domain infrastructure, i.e., Radio Units (RUs) $R_i \in V(G)$, switching entities $w_i \in V(G)$, and servers $s_i \in V(G)$. The plug-in layer is a set of user-defined algorithms to control and manage both the robots and the infrastructure. The COTORRA core layer (middle) is a set of building blocks enhancing the interaction between the plug-in (top) layer and hardware (bottom) layer.

$^1$COTORRA uses node $f(n), n \in V(G)$ and edge embeddings $f(n_1, n_2), (n_1, n_2) \in E(G)$ of the hardware graph $G$. 
Network formation among layers and COTORRA core layer building block, and explains the exchange of in-

A. COTORRA core layer building blocks

This section presents the functionality of each COTORRA core layer building block, and explains the exchange of information among layers and COTORRA core layer building blocks.

- The Robot Middleware (a) collects, (b) stores and (c) exposes real-time \( \{r_i\} \subset V(G) \) robots’ data; and (d) sends instructions to the robots, e.g., robots’ movements. The Robot Middleware periodically collects the robots’ Radio Unit (RU) attachment \( \phi(r_i, R_i) \in \{0, 1\} \), and a vector of sensor data \( \sigma(r_i) \in \mathbb{R}^n \) holding values such as the robot position \( \sigma_p(r_i) \), \( 2 \leq p \leq d \), with \( d \) being the space dimension. Using the aforementioned information, the Robot Middleware creates a contextual embedding \( \kappa(r_i) \)

\[
\kappa: \{r_i\} \rightarrow \mathbb{R}^n
\]

\[
r_i \rightarrow (\phi(r_i, R_1), \ldots, \phi(r_i, R_N), \sigma(r_i))
\]

that is stored (via the Measurements API) in the Measurements building block, and exposed (via its own API) to the plug-in layer (see Fig. 1). Latter, a plug-in uses the contextual embedding to elaborate real-time navigation \( \sigma_p(r_i) \) (e.g., robot movement) and RU attachment instructions \( \phi(r_i, R_i) \), and forwards them to the Robot Middleware API. Finally, Robot Middleware sends the plug-in instructions to the robots.

- The Network Control (a) collects, (b) exposes, and (c) stores network and RU context information. One of its main functionalities is to (d) emulate network conditions. As well, it (e) maps Virtual Network Functions (VNF) and Virtual Links (VL) in the hardware graph, (f) stores, and (g) exposes the VNF/VL mappings. The Network Control collects a vector with RUs’ context information \( \nu(R_i) \in \mathbb{R}^m \), \( R_i \in V(G) \), so as the links’ throughput \( \lambda(n_1, n_2) \), \( (n_1, n_2) \in E(G) \), and delay \( d(n_1, n_2) \).

B. COTORRA applicability: an example use case

COTORRA is designed following the principles and definitions of some of the most known implementations of Edge and Fog computing such as Multi-access Edge Computing (MEC) [12] and OpenFog working group in Industrial Internet Consortium (IIC) [13]. COTORRA building blocks, namely, Robot Control, Network Control, Measurements and Plug-ins can be represented as autonomous applications and context-aware services running on top of a virtualization infrastructure. This implies that by using COTORRA we are contributing to the experimental evaluation of MEC and IIC compliant applications.

Let consider an Edge robotic autonomous navigation scenario where the robot driver VNF \( v_j \) runs on the robot \( r_i \), and an autonomous navigation VNF \( v_g \) runs on an Edge server \( s_j \). A plug-in can use the Network Control and Measurements APIs to obtain RUs’ context information \( \nu(R_i) \) (e.g., RSSI, throughput, etc.) and Robot Middleware to obtain robot sensor data \( \sigma(r_i) \) (e.g., odometry, LIDAR, and camera data). Based on this information plug-ins can be designed, developed and tested with autonomous navigation algorithms that through the
Robot Middleware APIs can adapt the robot speed (present inside $\sigma(r_i)$) based on the radio link status $l(R_i)$. Additionally, packet drop $\delta(n_1,n_2)$ and queuing delay $\phi(n_1,n_2)$ can be emulated using the Network Control to simulate congested network environments.

III. COTORRA IMPLEMENTATION

Fig. 2 shows an implementation of COTORRA tested on a mobile robot. This implementation is used to verify the effectiveness of COTORRA in testing innovative mobility features. The COTORRA testbed consists of: (i) x5 ASUS WL500G Premium v1 Access Points (APs) running OpenWrt 18.06.2; (ii) x5 MiniPC, with x4 vCPUs and 8GB of RAM each. Two MiniPCs are used as APs and the rest as servers. Two of the server MiniPCs simulate Edge and Cloud nodes by introducing an artificial queuing delay of 5 and 10 seconds, respectively. The third MiniPC server acts as a local Fog node. All APs and MiniPCs are deployed along a corridor of the Universidad Carlos III de Madrid, interconnected with 10Gbps Ethernet connectivity. For the mobile robot, we used a ROS-compatible Kobuki Turtlebot S2 robot equipped with a laptop with 8-GB RAM and 2 CPUs, and a RPLIDAR A2 lidar for 360-degree omnidirectional laser range scanning.

The COTORRA core layer is implemented using VNFs (shown as red rounded boxes on Fig. 2). The Robot Middleware is implemented using Robotic Operating System (ROS) to (i) collect and expose the lidar and odometry sensor data $\sigma(r_i)$ to the plug-ins layer, and (ii) send to the robots the navigation instructions $\sigma_p(r_i)$ received from the plug-ins. In addition, as part of the Robot Middleware, we use a Localization service to provide probabilistic robot localization $P(\sigma_p(r_i))$ based on the lidar data. The Network Control is implemented using a WLAN Access Information Service (WAIS) to provide real-time context information (e.g., signal level $l(R_i)$, transmission and reception bit rates $\lambda(r_i,R_i)$, etc.) through a REST API. In addition, Network Control emulation is implemented with NetEm, so as to introduce artificial latency and packet loss. And for the Network Control VIM functionalities, we have used Fog05\(^3\) which implements the mapping functionality mentioned in Sec. II-A. The Measurements embeddings history $\mathcal{E}$ is stored and exposed with a MySQL database. Finally, our COTORRA implementation used a ROS brain as a plug-in to provide autonomous navigation for the mobile robot through the Robot Middleware.

IV. EXPERIMENTAL VALIDATION

In this section we validate COTORRA tested by an evaluation of (an orchestration and a federation) applications on top of the COTORRA implementation described in Section III.

A. Service orchestration that meets key performance indicators

OKpi\(^4\) is a service orchestration heuristic that meets latency, and mobility requirements. OKpi was implemented as a plug-in interacting with COTORRA to orchestrate an autonomous navigation service as described in Section II-B. In the experiment, OKpi used the Localization service to obtain the real-time robot $r$ position $\sigma_p(r)$, and MySQL for network links delays’ $d(n_1,n_2)$. Based on that, it sent (i) to fog05 the autonomous navigation VNF mapping $a(s_i) = \{v_d\}, s_i \in \{\text{Fog, Edge, Cloud}\}$, and (ii) 802.11r handovers $\phi(r,R_i)$ to the robot $r$ as it traveled along a corridor (see Fig. 2 dashed trajectory).

The experiment goal was to compare a State Of the Art (SoA) autonomous driving with periodic probing for RU attachment, against the theoretical OKpi-t and empirical OKpi-e performance of OKpi; and if the latter achieved a service time below 15 ms. Fig. 3 illustrates (at the top) that the service time remained most of the time over 15 ms when using the SoA autonomous driving, and $a(\text{Cloud}) = \{v_d\}$; whilst at the bottom, both the theoretical, and empirical performance of OKpi remained below 15 ms except for the handover peaks. Additionally, Fig. 3 shows the RUs attachments over time.

B. DLT federation

In\(^5\), we designed a federation of a robotic service using a Distributed Ledger Technology (e.g., Blockchain). Service federation is a set of procedures that enable orchestration of services across multiple administrative domains. We used COTORRA tested to deploy the DLT solution and perform experimental evaluation of the multi-domain federation. The experiment consisted of a moving robot towards out-of-coverage area of Domain 1 (on Fig. 2) and extending the connectivity range, on-the-fly, in Domain 2. An orchestrator

\(^3\)Fog05 project: https://fog05.io/ [Accessed: 26 November 2020]

\(^4\)Elapsed time between the emission of robot position packets, and the reception of robot navigation packets.
In this letter, we introduce COTORRA, a modular tested built to enable and validate innovative mechanisms or applications in robotic system. Additionally, we showed that COTORRA can be easily implemented over commodity hardware that offers support for a rapid prototyping and validation. The network emulation feature in COTORRA can simulate unpredictable network conditions that enables near production robotic environment where new pluggable applications can be tested. We validated this by running experiments for orchestration algorithms that interact with both the network infrastructure, and mobile robots. Finally, the flexibly and scalability of COTORRA enabled us to showcase an application of DLT for federation in an Edge robotic service, guaranteeing service footprint extension.

V. Conclusion

In this letter, we introduce COTORRA, a modular tested built to enable and validate innovative mechanisms or applications in robotic system. Additionally, we showed that COTORRA can be easily implemented over commodity hardware that offers support for a rapid prototyping and validation. The network emulation feature in COTORRA can simulate unpredictable network conditions that enables near production robotic environment where new pluggable applications can be tested. We validated this by running experiments for orchestration algorithms that interact with both the network infrastructure, and mobile robots. Finally, the flexibly and scalability of COTORRA enabled us to showcase an application of DLT for federation in an Edge robotic service, guaranteeing service footprint extension.

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