Collaborative Control of Mobile Robots Using Analog Twin Framework

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***Abstract*—Resource-constrained mobile robots that lack the capability to be completely autonomous can rely on a human or AI supervisor acting at a remote site (e.g., control station or cloud) for its control. Such a supervised autonomy or collaborative control of a robot poses high networking and computing capabilities requirements at both sites, which are not easy to achieve. This paper introduces and analyzes a new analog twin framework by synchronizing mobility between two mobile robots, where one robot acts as an analog twin to the other robot. We devise a novel collaborative priority-based bilateral teleoperation strategy for supervised goal navigation tasks to validate the proposed framework. The practical implementation of a supervised control strategy on this framework entails a mobile robot system divided into a master-client scheme over a communication channel where the Client robot resides on the site of operation guided by the Master robot through an agent (human or AI) from a remote location. The master robot controls the client robot with its autonomous navigation algorithm, which reacts to the predictive force received from the Client robot. We analyze the proposed strategy in terms of network performance (throughput), task performance (goal reach accuracy), task efficiency, and computing efficiency (CPU utilization). Real-world experiments demonstrate the method's novelty and versatility in realizing more practical reactive and collaborative planning and control applications.**

***Index Terms*—Analog Twin, Collaborative Control, Teleoperation, Mobile robots, Networked Systems.**

I. Introduction

CYBER-PHYSICAL Systems (CPS) encompass robots, autonomous vehicles, smart grids, and other such complex systems [1]. Recent developments in Industry 4.0 Technology and the future Industry 5.0 innovations are driven through the advancements in CPS and robotic systems, with the concept of Digital Twin (DT) playing a pivotal role in it [2]. Besides being used as a prototype in digital space representing a physical entity in the real world, DT also allows for commanding control and remote supervision of tasks. Although demanding high fidelity, DT offers an opportunity to visualize the active states of the robots and test the models before deploying them on real robots. However, DT is currently only used for design, simulations, modeling, or verification before deploying the models onto real robots. Currently, DT is limited in evaluating algorithms and models in synchronization with the actual robot operations [3].

We address this gap by proposing an analog twin (AT) framework focusing on mobile robot system. In addition to verifying robotic algorithms and creating a computation collaboration between real (or simulated) robot twins, it also provides the benefit of synchronization in mobility and actions between the twins (both simulated or real).

When a robot's processor falls short of capability to process incoming sensor data for real time applications which involves processing, training and modeling of constant stream of real time data like object detection, artificial vision involving neural network etc., then such a system can significantly benefit from collaboration with other robots to take advantage of the collective computing power of the group [4], [5], [6], [7]. This paper applies an analog twin framework to a mobile robot system, focusing on a supervised teleoperation and navigation task. Our objective is to enhance robot resource efficiency, connectivity, and usage by collaborating with other robots/servers to execute computationally heavy operations. We aim to improve computing workload, network throughput, without affecting the control task performance and efficiency by the use of collaborative robots. The main contributions of this work are the following:

- We propose a new framework termed Analog Twin, exploring the novel idea of synchronized (supervised) control of mobile robots through a networked system. The framework leverages the capabilities of a fully autonomous robot to operate another robot for algorithmic collaboration and verification remotely.
- We construct a collaborative control scenario in which the less computational field robot offloads/shares its intensive computational tasks to a remote (or cloud) server, reducing resources cost.
- We demonstrate the proposed system through real-world robot experiments, where we look at each instance's navigation, communication and computation performances.

II. Proposed Methodology

We introduce a supervised bilateral teleoperation through a Master robot situated on the remote server, which provides map-based path planning to the Client coupled with the Master, thus collaboratively implementing the navigation task. The Client, in turn, provides a reactive feedback for corrective navigation over a wireless network. Contrary to conventional approaches, this predictive feedback force is provided to an autonomous Master robot rather than an impact force traditionally applied to a haptic device operated by a human. The master robot assures rerouting the Client around obstructions by leveraging feedback and acts as a physical surrogate of the remote agent on the control site. The predictive force also serves for improved awareness for the human operator.

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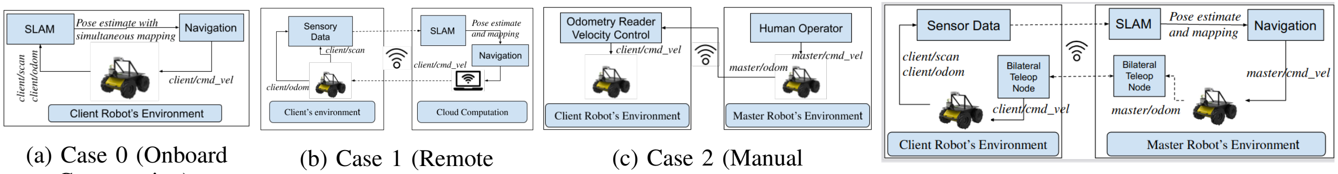


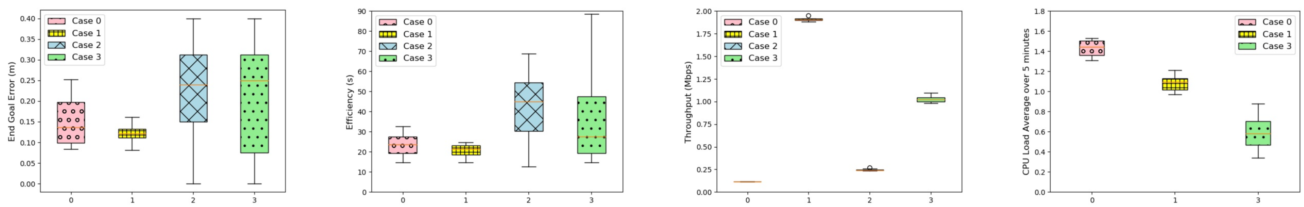
(a) Case 0 (Onboard Computation).

(b) Case 1 (Remote Computation).

(c) Case 2 (Manual Teleopration).

(d) Case 3 (Proposed Collaborative Strategy).

Fig. 1: Thematic representation of the experiment cases analyzed in this experimental study. Here, 'odom', 'scan', and 'cmd_vel' are the ROS topics for odometry, LIDAR scan, and command velocity (control) information.



(a) End Goal Error

(b) Task Efficiency

(c) Network Throughput

(d) CPU Utilization

Fig. 2: Task (Goal accuracy and efficiency), network (throughput), and computing (CPU utilization) performances.

Collaborative Priority-based Control Strategy: Here, similar robots are considered at Master and Client side to avoid kinematics mismatch. The Master acts as an enabler for the resource-constrained Client by allowing it to share computational and storage-intensive activities like mapping, localization, and navigation to the Master. The proposed priority-based master-client analog twinning performs concurrent bidirectional teleoperation on a low-priority queue through a velocity multiplexer (MUX) on both sides. A MUX arbitrates incoming commands velocity messages from several topics, allowing only one channel (topic) at a time to publish, based on priorities. Both agents subscribe to the reactive feedback force on a high-priority channel. Contrary to the traditional closed loop bilateral teleoperation, here the Client subscribes to the Master's velocity in an open-loop manner where no feedback is provided until an obstacle is encountered and then corrective action on the master is applied, thereby exhibiting a switching based control. The method guarantees stability through the open-loop architecture achieved through the multiplexing mechanism.

The proposed Analog Twin framework possess the following advantages: 1) it can be added to an already established digital twin through the proposed priority-based synchronization; AT provides reliable and stable synchronization between the physical and remote environments; 2) it provides additional storage and computational power through remote offloading for the physical system with reduced network-induced latency; 3) it provides an avenue in closing the simulation-to-real gap in the design and verification of robot algorithms.

For performance comparison, the following experimental cases were implemented: Case 0 (standalone client robot with SLAM running onboard), Case 1 (client robot with conventional remote computation for autonomous navigation), Case 2 (master-client coupled with conventional manual teleoperation) and Case 3 (the proposed analog twin framework with master-client coupled with the proposed AT-based prioritized force feedback). Fig. 1 depicts an overview for each of these four cases on how two robots collaborate for teleoperation.

III. Real-world Robot Hardware Experiments and Results

To evaluate the real-time expediency of the proposed scheme, we verified the proposed strategy using the above four experimental cases on two identical collaborative robots, Turtlebot 2e's, in our laboratory environment connected via a Wi-Fi network and are placed in two separate rooms, mimicking Master and Client sides. Each room is marked with a 3x3m sub-square with rectangular obstacles with eight trials conducted for each case, with goals in range $(\pm 1.5, \pm 1.5)$. The Client environment has some obstacles placed in its environment. The Master room has no obstacles for all cases, except case 2.

Results from our experiments indicate our proposed approach performing at par with Case 2 (manual teleoperation) as shown in Fig. 2a showing a minimal disturbance in *goal accuracy* due to the force feedback. We observed through the data collected in Fig. 2b that it takes more time on average to arrive at the goal position when using a bilateral teleoperation system with predictive force, as expected, since the feedback triggers rerouting the path frequently to avoid obstacles. Nevertheless, the proposed system *efficiency* is comparable to the remote offloading scenario without transmitting all sensor data. We also see around a 2x reduction in *network throughput* requirement (Fig. 2c) comparing the proposed framework (Case 3) to conventional offloading (Case 1), allowing higher scalability of operations using the proposed strategy. Compared to the baseline (Case 0), The *CPU utilization* drops by around 57% for our strategy (Case 3), as shown in Fig. 2d.

These results insinuate a promising potential for creating collaboratively an alternative bilateral teleoperation system with a stable open-loop control system within a collaborative control system. The data shows that our proposed system can synchronize two robots creating an analog twin to achieve a collaborative planning and autonomy. Experimentation in larger real-world scenarios could shed more light on the benefits and limitations of the proposed analog twin-aided collaborative control and teleoperation framework. This is an avenue for our future work.

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