A Human-Robot Collaborative System for Unknown Area Exploration

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Abstract— **Recently, there has been an increasing realization that multi-robot systems can play a crucial role in providing solutions that will replace single robot systems due to efficiency/cost/scalability considerations. However, the state-of-the-art robots lack human intelligence, decision making capabilities, proactive and reactive mechanisms especially in executing complex missions such as, unknown/unstructured area exploration. To this end, we propose a multi-agent system that tries to bridge this gap by including human as a part of the system. In this paper, a model for a human-robot collaborative multi-agent system is presented. Further, simulation results for a sample unknown area exploration application with the proposed system are presented demonstrating 1.5X performance improvement.**

I. Introduction

The concept of distributed, autonomous robotic system has gained increased attention and has brought tremendous changes in various socio-economic aspects of human society [1]. Mobile autonomous robots have wide range of applications due to their ability to work in challenging unknown and unstructured environments [2-4]. Also, robots can perform a variety of tasks by minimizing human involvement. Such mobile robots don't typically make mistakes (unlike humans), saving a lot of important output and production time. Further, robots have many advantages that contribute to various factors such as improvement in execution time, better quality, safety, etc. They provide optimum output with regards to quality as well as quantity. The collective (team) behavior emerges from the interaction between the robots and the interaction of the robots with the environment. There is a body of work that describes different algorithms and software capabilities to enable such teams of robots [5-6]. However, the practical deployment and application of these teams are hindered due to the limitations of the robots in taking timely and intelligent decisions especially in an unknown and unstructured environment.

On the other hand, humans have irreplaceable cognitive abilities, such as, intuition, creativity, analytical skills, and in general, much superior intelligence and decision making capability compared to robots [7-12]. However, humans lack the ability to execute the tasks with speed and precision compared to robots, especially when the tasks are arduous/laborious and demanding extended hours of operation (such as, large area exploration). To this end, we propose a collaborative system of humans and robots to take complete advantage from both the worlds. In this approach, robots and humans work together to accomplish a complex task such as unknown/unstructured area exploration. The overall idea is to bridge the robots speed and precision with humans' intelligence and decision-making qualities to realize a practical multi-agent system. The overall concept is depicted in Fig. 1. The human-robot collaborative system is presented considering the key communications requirements.

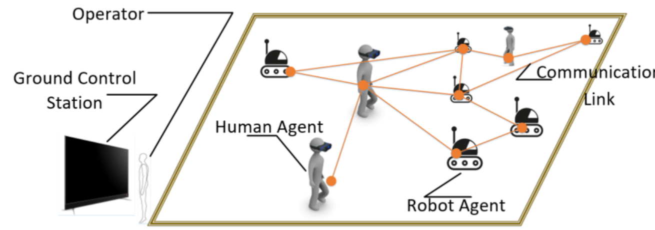

Fig. 1. Depiction of the proposed approach

The remainder of the paper is organized as below. The system framework details are provided in Section II. Simulation details and results are presented in Section III. The paper is summarized in Section IV.

II. System Framework

The system framework for human-agent collaboration in an unknown environment towards accomplishing the area exploration mission is presented in this section. 2D (terrestrial) robots are considered in this work. Note that, all the robots/humans in the system need not necessarily interact directly. Depending on the mission, size of the team, location of the agents in the team, and the optimization targeted, only a subset of agents will interact to accomplish the mission. The overall system diagram for the proposed approach is presented in Fig. 2.

For the unknown/unstructured area exploration mission, multiple teams of robots will be deployed as shown in Fig. 2. At the highest layer (Operator level), human operators are present. The operators are connected through long-range, high-speed communication network. This layer is responsible for distributing the higher level mission to the teams. Further, robot intelligence takes care of breaking down the mission in to smaller tasks and getting it done.

The team shown in Fig. 2 is a bio-mechanical hybrid system with robot and humans working together to get a particular task done. The robot and human agents are very different from each other and have capabilities which are mutually exclusive. The humans have advanced sensing, manipulation, communication, decision making capabilities, however, are limited by certain capabilities such as, execution of repetitive, dull, boring and mundane tasks, fast locomotion speed, etc. The combination of these agents will help in accomplishing the mission in the most efficient way. The number of agents and the human to robot ratio in a group can vary from system to system. All the agents of the group need not be connected one to one (e.g. a mesh network). The neighboring groups can be connected through a virtual link which can be established through the operator.

Each agent in the system incorporates the following entities:

(i) *Task list:* These are the tasks allocated to the particular agent by the operator or the team itself.

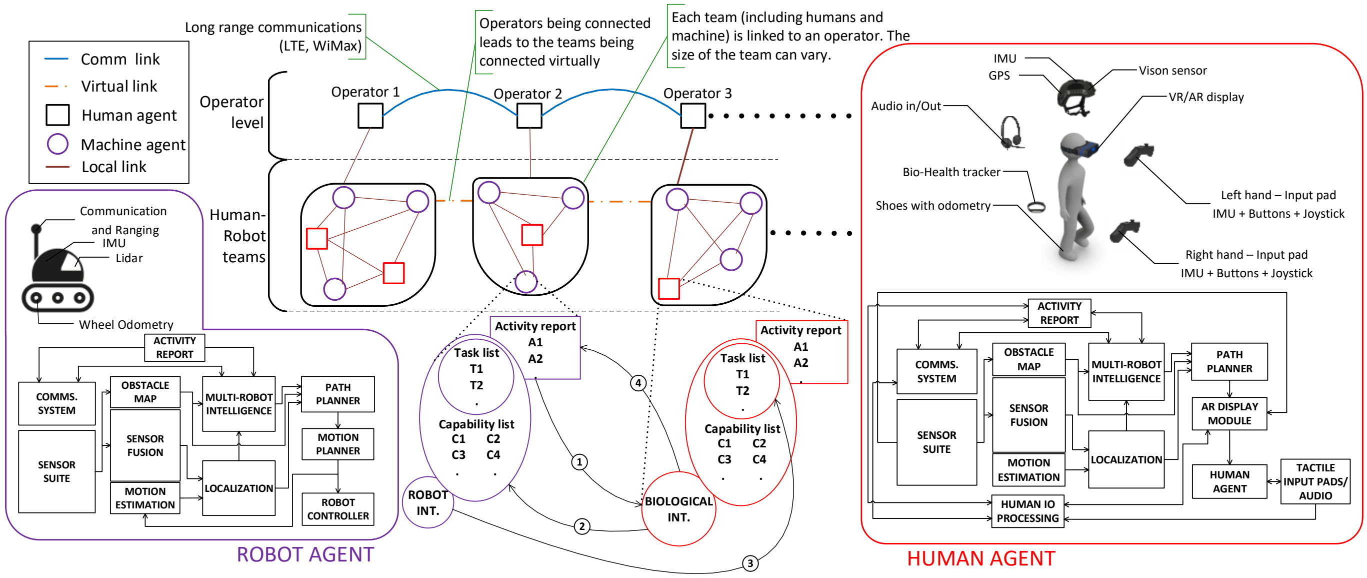

Fig. 2. Human-robot collaborative multi-agent system

(ii) *Capability list*: These are the agent's capabilities such as path planning, perception, object detection, collision avoidance, guidance, navigation, decision making, etc.
(iii) *Activity report:* Activity report contains (a) agent's plan for the execution of the tasks and priority (b) current status of tasks (c) authority level for the robot etc.
(iv) *Intelligence:* The intelligence can be either be a set of algorithms, artificial intelligence (AI) or a combination of both. When the agent is a human, it is a combination of biological and logical intelligence mentioned above.

The agents have to communicate to operate in a team. These are low level communications over the mesh network. Along with this, other critical high level communication is required to enable collaboration as below (shown in Fig. 2):
(i) *Monitoring:* Communication link 1, where the human is checking the status and the intentions of the robot agent.
(ii) *Intervention:* Communication link 2, where the human is taking direct control of the robot capabilities (e.g. tele-op). Communication link 3 and Communication link 4 are to enable robots suggesting tasks to humans and humans suggesting tasks to robots, respectively.

III. SIMULATION/CASE STUDY

For simulation, we choose three representative scenarios which map to a mission being carried out by (a) only humans (b) only robots and (c) finally as a combination of both. The scenarios were selected in such a way that the task itself is simple, while constraining the actions of the human and robot to relative terms i.e. both groups are restricted by the rules of the scenarios. The activity acts as a case study detailing the efficiency of balanced interactions between humans and robots in a combined workforce over only human and only robots workforces in the present day. In this setup, a test environment is enabled with a region of interest, where a target is spawned at random. The agents in the region are restricted by the rules set by the test environment (e.g. velocity and perception are limited to realize a real world scenario). Using this test environment, above mentioned three scenarios are simulated.

Simulation results are presented in Fig. 3. In general, humans are efficient in smaller area exploration, while the advantage quickly diminishes as the area size increases. Humans often slow down over a period of time. In case of the robots, the capability remains the same. In cases where both robot and humans are involved, the capabilities are augmented and the better parts of both are taken and hence it performs better in both of the cases. From the experiments performed, we see ~1.5X average improvement in the performance. As the exploration area increases, the performance further improves.

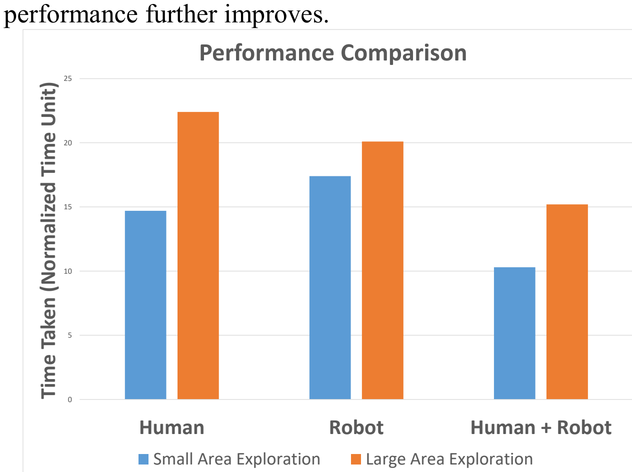

Fig. 3. Performance comparison for different scenarios

IV. SUMMARY

It is extremely challenging to realize robust and reliable human-robot collaborative systems with safe interfaces, which will allow mutual communication and adaptation between humans and robots in natural and smart ways. Such systems must operate for extended periods of time in complex domains to accomplish a given mission. To address this, a detailed system level framework is presented in this paper for enabling human-robot teams for accomplishing a complex unknown/unstructured area exploration mission in a collaborative manner. Further, simulation results are presented to validate the performance of these collaborative multi-agent systems.

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