Centralized Multi-agent Mobile Robots SLAM and Navigation for COVID-19 Field Hospitals

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***Abstract*—In this paper we focus on the proof of concept prototype of fully autonomous centralized Multi-Robot System (MRS) consisting of a Hexapod walking robot and a six wheeled mobile robot. Recently, there has been an increasing demand for such systems as they can be involved in several tasks such as collaborative search and rescue, surveillance, monitoring, and disinfecting Field hospitals. To name a few, COVID-19 pandemic showed the weak points in the medical sector around the world, including those in the most advanced nations that had to go through hard decisions due to the lack of medical supplies and personal protective equipment. The developed system was rapidly adjusted due to COVID-19 pandemic to perform additional tasks like disinfection and remote body temperature detection. The developed system abide by ISO 13482 safety requirements for personal care robots, meaning it will be used and deployed in Field hospitals. We implemented the proposed approach in a game setting of a field hospital where the Hexapod is used to scan and draw a map of the Field hospital environment and to draw a path then the six wheeled mobile robot acts as a medical cargo delivery that enters based on the predefined map and path.**

Keywords: Service Robotics; Robot operating system (ROS); COVID-19; Pandemic; Field hospitals; Hexapod; Multi-robot system (MRS).

I. Introduction

During COVID-19 pandemic robots have been gaining much attention outside factories and entering unstructured environments such as homes, schools and field hospitals. These robots ranges from small social robots such as Pepper developed by SoftBank robotics [1] and Lynx developed by UBTECH [2] which were developed for interaction and entertainment purposes to large physical robots that are capable of autonomous navigation in both indoor and outdoor environments. As the COVID-19 contagion has demonstrated pandemics lead to shortage of medical and nursing staff in many countries, which leads to attempts to use robotics and intelligent systems to address this problem [3]. Moreover, the medical staff are experiencing harsh working environment due to stress, long working hours and an increased number of cases daily. It is estimated that by the year of 2030 there will be a possible staff shortage of about 500,000 medical staff in Germany [4].

Multi-agent systems have gained great attention in the last decades due to its capabilities in solving many problems in many domains. These systems are still under study, investigation and development, because of the several constraints and challenges that exist in software and hardware of its construction on different levels and layers [5]. Some of the software challenges are control, decision making, localization and mapping, path planning and state estimation. Some of the hardware challenges are the controllers of such systems, power source, sensors, etc. There are various application that practically make use of multi-agents and much more are still under study and development in the research labs and institutes. These applications are covering a wide spectrum of interests in both civilian and military purposes. Some of these practical applications are search and rescue, surveillance, ocean floor mapping, inspection, mineral exploration, etc. Some prospective applications like medical cargo delivery to disaster areas, as it will not depend on the normal road maps if they still exist. Usually, previous information about the environment is assumed to be given in the form of a rough map for the area required to be delivered to.

One of the conventional ways of generating optimal control decisions in multi-agent systems control is to design a centralized controller. The centralized controller receives full information about the environment and the agents and generates decisions that are communicated with each individual agent to execute [6]. However, centralized controllers are able to generate decisions but they suffer from scalability in the number of agents and single point of failure [7]. Moreover, centralized controllers assumes full knowledge about the environment and the agents status all the time which is a kind of impractical due to the previously mentioned limitations [8].

Another more advanced way to generate decisions in multi-agent systems is to design a decentralized controller. This controller proved to be more practical in many systems, such as formation control [9], collaborative object transportation [10], distributed parameters estimation [11], [12], and wireless sensor networks [13], [14]. Moreover, each agent generates its own control decisions based on its very limited knowledge of the world and the other surrounding agents. So, with such a controller the decision making approaches can be scalable and the single point failure phenomenon is eliminated. But, most of the currently available decentralized controller method rarely address the real time implementation and validation on actual systems. Fig. 1 shows two simple models for centralized and decentralized control architectures.

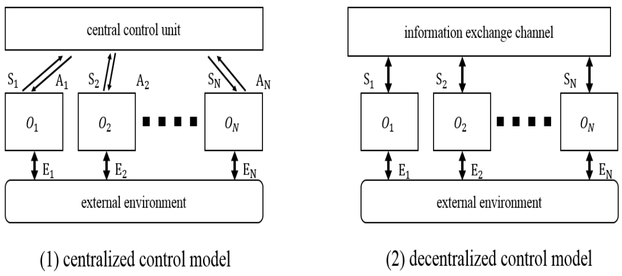

Fig. 1. Centralized vs. Decentralized control architecture

Simultaneous Localization and Mapping (SLAM) techniques are usually addressed in order to build a map of the environment while in the mean time localizing the robot inside this map. In action, these two issues can't be separated and solved independently from each other. As before the robot can sense what is the nature that is surrounding it that looks like a previously given set of perceptions, it needs to know how these perceptions have been made. In the current time, it is very tricky to measure the current position of a robot without a map. Later research has concentrated on making these algorithms more productive, and incremental so they can develop sequentially. Multi-level relaxation (MLR) enhanced the basic Gauss-Seidel unwinding problem by unraveling the system at many levels of determination [15]. The Tree-map algorithm perform reproductive designs with a tree-based subdivision of the map into weakly related parts [16]. The Smoothing and Mapping algorithm (SAM) depends on a QR factorization of the framework data to permit a productive estimation of the situations of the system nodes with a proficient back-substitution [17].

II. System Description

A. Mechanical Design

1) Hexapod Walking Robot: Legged walking robots became the main goal of many studies and researches as the main role of legged robots is to simulate the characteristics of some biological inspired organisms [18]. The Hexapod multi-legged robot have powerful potentials compared to tracked or wheeled robots. Legged robots have the ability to adapt to complex external environments and deal with dangerous or unreachable tasks, whereas tracked and wheeled vehicles are only effective with obstacles that are smaller than half the wheel diameter. Moreover, legged robots have the ability to find the local horizontal footholds in regional steep terrain, as they can climb extreme angles [19]. The available types of legged robots ranges between single-legged hoppers, bipedals, tripods, quadrupeds, hexapods, octopods and other types having more limb legs [20]–[22]. Hexapod robots demonstrated distinctive advantages, such as walking on unstable or irregular terrain, and having more mobility, flexibility and stability than tracked and wheeled robots [23]–[25]. The applications include but are not limited to exploration, mining, search and rescue and industrial environments on earth and below [26]. There are also many studies about hexapod robot models, especially in gait planning and control, as in [27] that describes a central pattern generator to generate the gait or in [28] that implements a free based gait on posture control.

2) Six Wheeled Robot: Wheeled locomotion is the most common and advantageous locomotion, as it can perform smoothly and fast on hard and muddy terrains. It can carry high payload and it is efficient in energy consumption. The control and implementation of wheeled locomotion is simple compared to other types from a technical point of view. These systems are characterized by its simplicity, making it the most common attractive locomotion system. However, when it comes to unstable payload, very smooth surfaces, obstacle or holes bigger than the radius of the wheels, this type of locomotion can not perform well.

B. Robot Simulation

There are a variety of robotics simulations in the field nowadays, such as AirSim, Gazebo, V-REP, etc. A comparison between these frameworks can be found in [29].

*1) **Unified Robot Description Format (URDF)**:* To visualize the two robots in Rviz, we need to to convert them into URDF format by using SolidWorks to URDF exporter. The exported models are shown in Figs. 2 and 3.

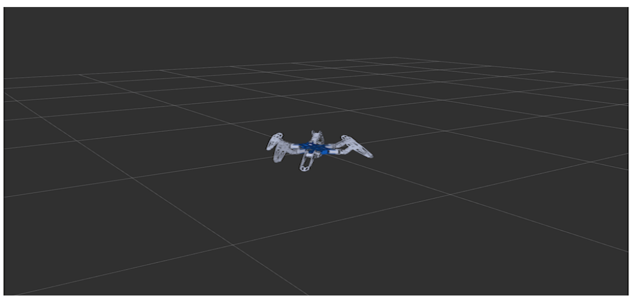

Fig. 2. Hexapod robot visualization in RViz

The URDF file describe all the elements in the robot and their relation with the predecessor and successor elements for our two robot models.

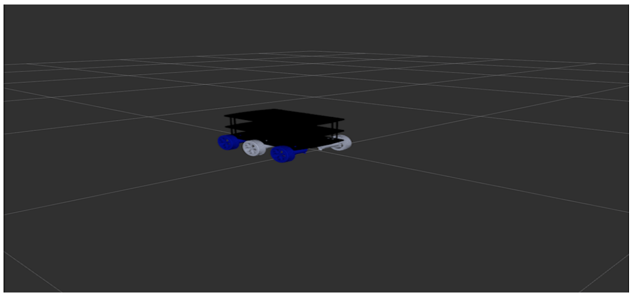

Fig. 3. Medical cargo delivery robot visualization in RViz

*2) **RViz:*** To implement autonomous navigation, RViz is used. Rviz is a 3D visualization tool for displaying sensor data and state information. By using Rviz, visualization of the robot's current configuration on a URDF model of the robot. Also, a live representation of the sensors values coming from other topics including camera data, infrared distance measurement, and lidar data can be displayed as shown in Fig. 4 .

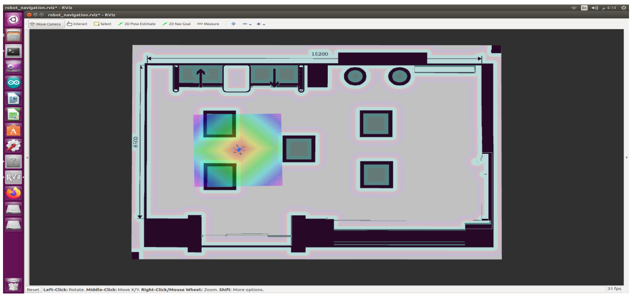

Fig. 4. Hexapod robot sensor data visualization in RViz

First of all we have to perform SLAM using the hexapod robot to build a map for the field hospital environment and after that we run AMCL nodes for localizing the two robots on the generated map. To map the field hospital environment, we controlled the hexapod robot manually using a joystick. After completing the complete mapping for the field hospital environment we can command the six wheeled medical cargo delivery robot to go to a specific place to deliver the material and come back to the home position to be reloaded with medical cargo once again.

Moreover, in order to simulate the detailed movement of the hexapod in RViz a connection between it and MATLAB was established in order to update the hexapod inverse kinematic position as shown in Fig. 5 with the new position of the robot.

III. Hardware Implementations

System integration and testing are key aspects of Robotics in general. As mentioned before, the main focus of this work, besides the simulation, is to provide a complete physical system to validate the proposed real-time centralized algorithm. In mobile robots, power consumption and weight are major constrains that can limit their endurance. Therefore, it is

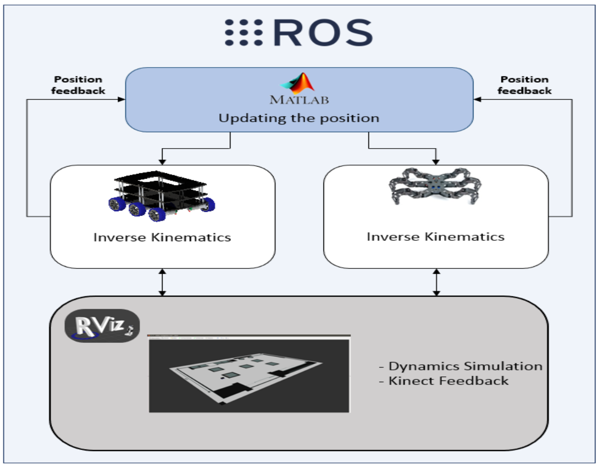

Fig. 5. Simulation setup architecture

always preferred to reduce pay- load and power consumption as much as possible. In that regard, we used low- power and low-weight affordable components that allow us to achieve the computational needs and real-time execution for the proposed approach. We present a complete indoor experimental setup that shows the validity of the proposed framework.

A. *System Architecture*

We used a master PC to act as a publisher and two Raspberry Pi on-board computers mounted on the hexapod and the six wheeled medical cargo delivery robots to act as a subscriber to the master instructions. The on-board computers acts as a data acquisition device which senses the position of the robot from the IMU and kinect sensors then sends these information to the master PC to receive instructions that are sent to the Arduino to control the motors speed as shown in Fig. 6.

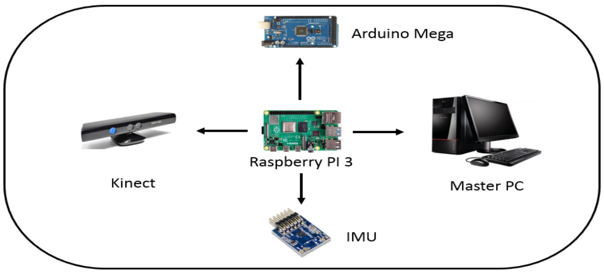

Fig. 6. Overall System architecture

B. *Centralized Framework*

We chose to implement a centralized framework as its computationally feasible to implement it in computationally constrained hardware. The used PC runs Ubuntu 16.04 with ROS Kinetic and the Raspberry Pi runs Ubuntu mate with ROS kinetic as well. The Raspberry Pi is connected via a USB cable to the Arduino and the Arduino sketches are executed from the Raspberry Pi via rosserial Arduino package. The Arduino is used to interface the motors via a mounted motor sensor shield and it updates their positions from the perceived commands from the master as shown in Fig. 7.

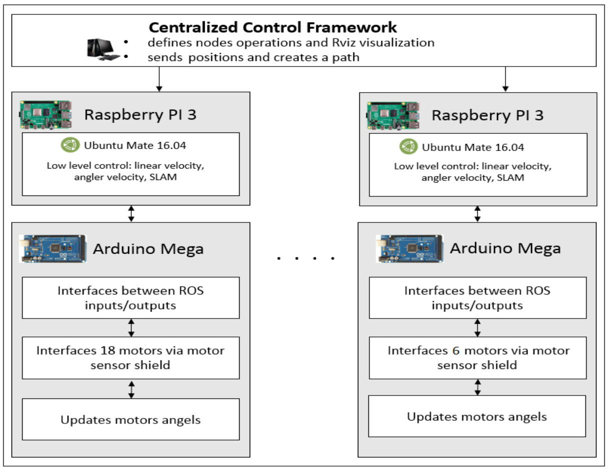

Fig. 7. Architecture of the Hardware setup

C. Centralized System State and Actions

The state in this model represents the level of occupancy of each sector in the field hospital. The state of each sector s_i is $x_{si}, \in Z_+$, which is the number of its occupants, where Z_+ is the set of non-negative integers. The state of the field hospital grid with respect to an agent i in $r \in \{d, a\}$ is

$$x_i^r = \left[x_{s_1,i}^r \dots x_{s_{n_s},i}^r \right]^T \in \mathcal{B}^{n_s} \tag{1}$$

where $\mathcal{B} \triangleq \{0, 1\}$ and

$$x_{s_j,i} = \begin{cases} 1 & i \text{ occupies } s_j \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

The state is restricted to be in $\{0, 1\}$ in order to have one agent per grid at any time, for collision avoidance purposes. The state of the grid with respect to all the agents in $r \in \{d, a\}$ is

$$\mathbf{x}^r = \sum x_i^r \tag{3}$$

Actions or controls describe the transfer of agents or quantity of occupancy between sectors in S. For an agent i, we define an input vector that describes all transfers from sector s_j to sector s_k as follows

$$u_{s_j \to s_k,i} = \begin{cases} 1 & x_{s_i,i} = 1 \text{ and } i \text{ transfers to } s_k \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

An augmented input vector for agent i is

$$\mathbf{u}_{s_j,i} = \begin{bmatrix} u_{s_j} \to s_1, i & \cdots & u_{s_j \to s_{j-1},i} u_{s_j \to s_{j+1},i} \cdots \\ & & u_{s_j \to s_{n_s},i} \end{bmatrix}^T \tag{5}$$

If agent i occupies sector s_j, then $\mathbf{u}_{s_j,i} \in \mathcal{B}^{(n_s-1)}$ represents its transfer to some other sector in the grid. The complete input vector of agent i in team $r \in \{d, a\}$ with respect to all the sectors in the grid is

$$\mathbf{u}_i^r = \left[\left(\mathbf{u}_{s_1,i}^r\right)^T \left(\mathbf{u}_{s_2,i}^r\right)^T \dots \left(\mathbf{u}_{s_{n_s},i}^r\right)^T \right]^T \in \mathcal{B}^{n_u} \tag{6}$$

where $n_u = n_s (n_s - 1)$ similar to the states, the input vectors for the two robots are

$$\mathbf{u}^d = \sum \mathbf{u}_i^d \quad \mathbf{u}^a = \sum \mathbf{u}_i^a \tag{7}$$

D. MRS Communications

In this work, we used WiFi to establish peer-to-peer communication linking between the master publisher PC and the two subscriber Raspberry Pi's as shown in Fig. 8. We decided to use a single master instead of independent master in each robot, as in the standard ROS network there is a single master node that establishes the communication links between all nodes in the ROS network and to distribute the computational power as the Raspberry Pi is not computationally wise. Also, communication is needed to arrange the working sequence of the robots as only one robot is allowed to enter the field hospital at the first time.

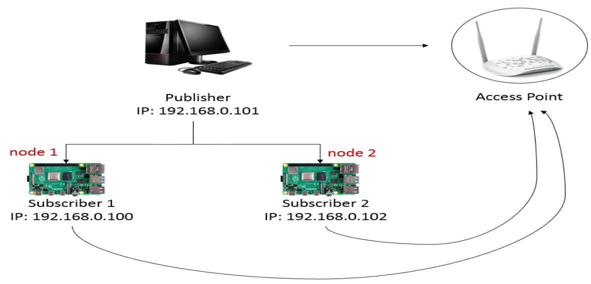

Fig. 8. Communication Architecture

IV. Mapping Technique

To get a detailed map, we used the kinect sensor as an external sensor mounted on top of the hexapod. The kinect sensor is a depth camera that was developed by Microsoft and Primesense for the Xbox360. It differs from other cameras as it has the ability for recording a separation set of objects and this is achieved through the expansion of the IR transmitter and receiver [30], microphone array, and a tilt motor as shown in Fig. 9. Moreover, the Kinect sensor has a 57°. horizontal field of view and a 43° . vertical field of view. The reason behind it is use in many platforms is its cheap price compared to a Hokuyo Laser sensor and a LIDAR sensor [31].

Fig. 9. Internal components of Microsoft Xbox 360 Kinect

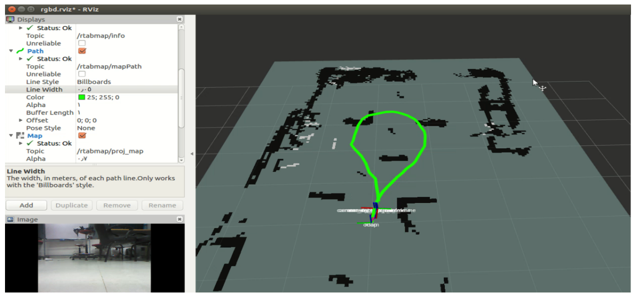

Fig. 12. Path to be used by the medical cargo delivery robot

In order for the robot to navigate through the maze, the hexapod robot will be manually controlled with a joystick to draw a predefined map of a room in the field hospital as shown in Fig. 10 where the red boxes resembles patients beds. The dimensions of the room is 15.2×8.5 m^2, and each obstacle is of 50×50cm.

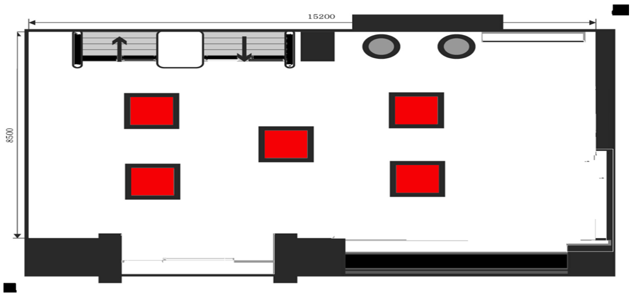

Fig. 10. The pre-defined Field hospital room map with Patients

Then after that the hexapod robot will map the entire room in order to detect the obstacles inside the patients room, and to draw a path which will be used by the other medical cargo delivery robot to navigate through the maze without any collision as shown in Figs. 11 and 12.

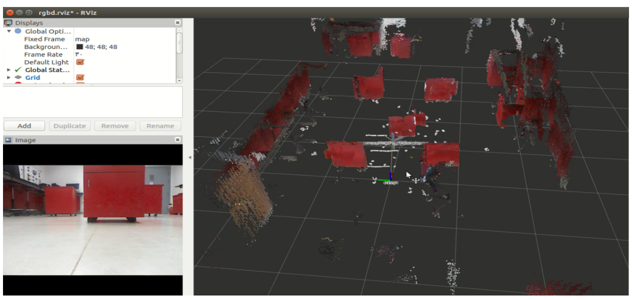

Fig. 11. 3D map of patients room in the Field hospital

V. Modifications for COVID-19 Pandemic

To face the COVID-19 pandemic, additional modifications were introduced to assist the medical staff in these uncertain circumstances. In contrast to other COVID-19 specifically designed robots, our system carries out these additional functionalites beside its regular functionality inside Field hospitals. Remotely controlled item delivery to the medical staff and infected patients has proved to be beneficial as it is carried out in a contact-less way.

A common indicator of doubtful infected patients is High Body Temperature (HBT). In governmental institutions were visitors are allowed, a common precaution measure that emerged during COVID-19 pandemic is to measure the body temperature of the people who are entering this building by using a remote measurement device where a human operator points it towards each individual visitor forehead. Our system uses a kinect sensor which acts as a thermal camera placed on the back of the robot. Visitors detected by the Kinect sensor in colored images are then mapped to the thermal Heat Map (HM) images. HBT is carried out by comparing the relative body temperature differences of normal healthy people, whom are recorded through the calibration process of the passer-by visitors as shown in Fig. 13. If a visitor with HBT is detected an alert will be instantiated and the human operator will be notified to carry out another manual temperature measurement of the doubtful visitor.

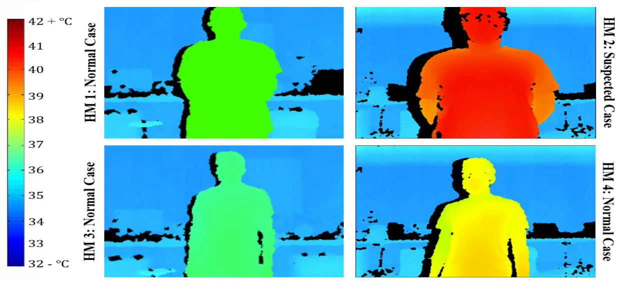

Fig. 13. Heat Maps of normal and suspected cases

VI. Conclusion

Autonomous mobile systems is used to disinfect facilities in the more common applications of robotics. In this article, the two different mobile robots platforms have been used and the ROS navigation stacks algorithm have been applied to the mobile robots navigation. SLAM based hexa-bod robot using kinect and machine vision has been applied to produce the unknown 3D map to be used by the six wheels mobile robot as navigation map. The proposed algorithms are successfully verified through simulations and real-time experiments in the different environments. Simulation and experimental results demonstrate the importance of the proposed compination between the multi robots and provide better performance with ROS .

VII. Supplementary Material

Video link: https://vimeo.com/453659151

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