State of the Art in Control Systems for Cooperative Distributed Mobile Robots in a Healthcare Environment

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Abstract

In this article we are presenting the state of the art in robotic control systems for healthcare environments. First, we identify the motivation and needs for healthcare robots in the state of the art, then we present an analysis of the challenges for their implementation, the existing solutions presented in literature and their limitations, and finally, our motivation and proposed future contribution in the field. The future work will involve the design of a robust robotic control system architecture for cooperative distributed systems of mobile manipulators used in hospital environments, as well as the validation of the control strategies in a simulated environment. The most promising solutions will be deployed on prototype mobile manipulators and validated in testing environments and, if possible, in real environments.

Keywords: healthcare robots, robot control, robotic cooperation, robotic mission planning

1 Introduction

Due to the constraints generated by infectious diseases in medical environments such as hospitals, the need for multi-robotic assistance has exponentially increased. In certain situations, such as when dealing with infectious diseases and immunocompromised patients, physical contact of healthcare personnel with patients must be minimized, without compromising the attention and care that every patient deserves. This became especially obvious during the COVID-19 pandemic, when over exposure to the virus triggered the need of using personnel protective equipment (PPE) at all times with every patient, following a very strict protocol to put it on and remove it. The fact that this procedure must be followed for nursing or medical staff in between visits to every inpatient makes it extremely time consuming, while incurring very high costs. By using robots for simple tasks, for example food tray or medicine distribution, these costs can be lowered significantly [13].

Robots sharing spaces with humans must operate safely at all times, be very robust and include the possibility of self-recovery. When there is a pool of robots working in a certain environment, coordination between their work becomes an essential requirement. Other factors to take into account are the autonomy of the robot, the scalability and flexibility of the robotic pool, the availability and reliability strategies of the multi-robot system, human safety and possible recovery scenarios.

At the moment, there is no standard in the field of robotics that would cover the needs of a safe and robust multi-robotic system. Such a system requires a full-stack multi-OS framework, covering everything from software running on embedded platforms on the individual robots, to cloud-level applications for coordination. Monitoring and control would need to be performed from different devices such as computers, tablets or smartphones on different operating systems. Internet of Things (IoT) solutions usually provide that level of vertical portability but do not adapt well to complex robotic systems. Robotic dedicated solutions, such as ROS, instead, lack that level of vertical portability. A full-stack system would facilitate the implementation of multi-robot systems for a wide range of applications, from hospital service robots to assist the nursing staff to urban search and rescue, combining heterogeneous platforms such as aerial, ground or underwater robots into a unique control system. In the field of healthcare, robots performing diverse types of tasks are needed, such as room disinfection, food and medicine distribution to patients, patient monitoring and hospital logistics. In this paper we research hospital robotic systems in literature, we present the most important requirements for implementation of robots in healthcare environments, and finally we propose a future work on a flexible and modular common control system for a heterogeneous, cooperative distributed hospital robot fleet.

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2 Healthcare Robots

2.1 Motivation

Modern healthcare is quickly transitioning into the digital era, introducing different novel technologies in hospitals, which are key in leading the technological adaptation and development. Some examples are interactive displays to support coordination and communication at surgery wards, radio-frequency identification for trauma care, mobile technology for transmitting, storing, modifying and retrieving data, transitions from paper to digital systems at emergency departments, automatized dispensation of medicines and introductions of electronic health records. At a larger system level, technological implementation in hospitals is also transforming the healthcare sector, and studies show that healthcare personnel is keen to collaborate and support the design of novel technological advancements that can be beneficial for their work [11].

The COVID-19 pandemic has shown the need of reducing unnecessary human contact in order to reduce the virus' spread. In healthcare environments, such as hospitals, contact between patients and medical or nursing personnel happens at all times. Both personnel and patients must be protected from potential infection without compromising their work and patient care. Shortages in nursing staff due to an increased number of inpatients and additional time consuming tasks they must perform, such as the wearing and removal of PPE, make the introduction of service robots crucial in order to alleviate the work load from tasks that do not provide much value, and allow healthcare personnel to focus on more important tasks.

When developing robotic solutions for healthcare environments, it is crucial to research the needs, opinions and concerns of healthcare workers who are presented with robotic aids. A study was done on the needs and perceptions of healthcare workers as end-users of service robots in their field of work [8]. Results show that healthcare personnel have concerns regarding the integration of robotic systems into existing hospital IT infrastructure, the potential problems that existing building structures can cause for robot movements and the complexity of integrating robotic controls to their tasks. Most healthcare personnel agrees that by introducing robots in hospitals, these will become dependent on the technology provider's support. All these points must be taken into account when designing service robots and their complete control system for hospitals.

2.2 Robot Control Design Requirements

Robotic system integration and deployment in indoor environments presents several challenges for its design and control. If, in addition, the system needs to be designed for hospital or healthcare environment use, there are some additional challenges that must be overcome.

- **Area of operation:** It is important to verify the conditions of the area where the robot will operate. This factor will be key in deciding the robot's locomotion (wheeled, legged, etc), its size or its structure. Furthermore, it can be very beneficial for the robotic system to adapt the area in a way that would make a more reliable robot operation.

- **Localization:** The localization of a robot is a well known challenge in indoor mobile robotics. It is essential to know where the robot is and whether the absolute map of the environment is available or not. An indoor environment of operation that is known in advance, as is the case in a hospital plant, can prove advantageous for the robot. The possibility of equipping a robot with a set of different sensors and adapting the environment with some positioning aids, supposes a big improvement in the reliability of the robot's navigation.

- **Navigation:** For a successful robot navigation approach within an environment, a robot must simultaneously perform localization and keep track of its surroundings. This is known as simultaneous localization and mapping (SLAM). Navigation presents four major concerns, which are environmental modelling or mapping, localization, path planning and obstacle avoidance [9].

- **Safety:** Robotic systems deployed in hospitals must coexist with a set of static and moving objects (furniture, wheeled beds or chairs, etc) and with humans. A robot must never be a reason of concern for the safety of the people interacting or sharing the environment with it, so it must be ensured that the operation of the robot and its autonomous tasks guarantee a high level of safety. Safety mechanisms must be an integral part of the robot mechanics and control system, including a set of sensors for detecting obstacles or humans, and anti-collision algorithms as part of the robot's navigation features.

- **Dexterity:** A healthcare robot must be dexterous enough to guarantee the performance of its tasks without putting personnel or patients in risk.

- **Energy management:** Mobile robots in non-adapted environments are required to be powered by batteries. An energy management strategy must be part of the robot's control system in order to optimize its availability and the completion of its tasks. A charging station must be designed and introduced in the environment, taking into account the robot's missions and featuring recovery possibilities.
- **Cost:** Healthcare robots must be cost effective, since they are intended to be needed at a large scale. If costs are too high, the introduction of hospital robots will not be possible in most parts of the world [2]. Choosing the robot components becomes a big challenge when limiting the costs without sacrificing the performance and safety of the system.
- **Autonomy:** Healthcare staff must be able to control the robots through a simple and intuitive user interface, allowing them to configure robot tasks that the robots will perform autonomously.

2.3 Robots in Healthcare

The use of robotic systems in healthcare has been expanded in recent years. Novel applications have surged from the COVID-19 pandemic, such as disinfection robots. The work in [14] presents a robot prototype built with an Arduino UNO Development Board. Equipped with UV-C LEDs, it is intended for UV sterilization of hospital floors. The prototype robotic platform has also been tested to deliver medicines to patients and blood samples to testing laboratories, but does not yet present any autonomous features.

A Danish company, UVD Robots [1], developed a commercial autonomous disinfection robot, featuring a mobile platform, Lidar sensors and a UV lamp array. The robot requires a first manual run in order to generate a map of the environment and detect the surfaces to disinfect, and afterwards it runs autonomously using SLAM. For safety, the robots run only when humans are not present in the environment.

Another UVD robot, AIDBOT [3], shown in Figure 1, equipped with RGB-D cameras, laser sensors and UV-C lights, aims to disinfect 99.9% of virus and bacteria from surfaces and objects at quarantine sites.

AIDBOT features a visual SLAM approach using multiple RGB-D cameras that obtain a map of the surrounding area and simultaneously estimate the robot's location, a path planning module and an object detection module to identify the object to disinfect, all running in real-time on the robot's embedded system.

Figure 1: AIDBOT disinfection robot [3]

Apart from direct disinfection, and in order to avoid hospital acquired infections, robots can also be used in hospitals to transport and handle contaminated items and bring equipment to sterilization departments, such as the robot prototype presented in [2]. This robot, based on a Lego robotic kit, can perform the tasks autonomously and is equipped with an arm and gripper, ultra-sonic sensors for avoiding collisions, sound and touch sensors for identifying the object to grab.

Transport robots have been used in hospital logistics for a while, especially for technical hospital areas that are not shared with patients or healthcare personnel. OPPENT robotic platforms EvoCart [7], shown in Figure 2, are commercial mobile robots used for handling supplies and transporting them around hospitals. They move autonomously and use natural structures in the environment, such as furniture, as positioning references, avoiding expensive infrastructure changes for aiding navigation. Their anti-collision feature using laser scanners makes them safe to share spaces with humans.

Figure 2: Oppent robotic platforms EvoCart [7]

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Nursing assistant robot prototypes have been developed and tested as well in the past few years. TRINA [6], depicted in Figure 3, was designed to minimize nurse exposure to infectious diseases. It consists of a humanoid mobile manipulator in shape of a torso with two arms, including an integrated console for tele-presence, mounted on an omni-directional platform. Powered through a cable, the robot can only move inside the patient's room.

Figure 3: TRINA nursing robot [6], reprinted from blog.spacemed.com

2.4 Robot Fleets in Healthcare

Multi-robot systems can perform tasks more efficiently than a single robot. By increasing the availability of the system they can accomplish tasks that are not executable by a single one. In addition, multi-robot systems have advantages like increasing tolerance to possible robot fault, providing flexibility to the execution of tasks and taking advantages of distributed sensing and actuation.

Individual control of each robot in a fleet is always possible, but the real challenge comes when the control is merged for fleet coordination features.

The work in [10] presents an implementation of a Fleet Management System (FMS) that plans and controls the execution of logistic tasks by a set of mobile robots in a hospital.

The FMS consists of a routing engine for route calculation and a task scheduler to solve the task allocation problem. Figure 4 shows the FMS architecture. Running on a cloud service, the routing engine calculates the robot's route by computing the cost of moving between points, the task scheduler assigns tasks to robots based on shortest paths, and a controller module supervises and verifies that the tasks are executed. Before execution, the user validates the plan through a web user interface. Robots report their status periodically and the controller calculates a new plan if necessary, re-scheduling the tasks. Obstacle avoidance

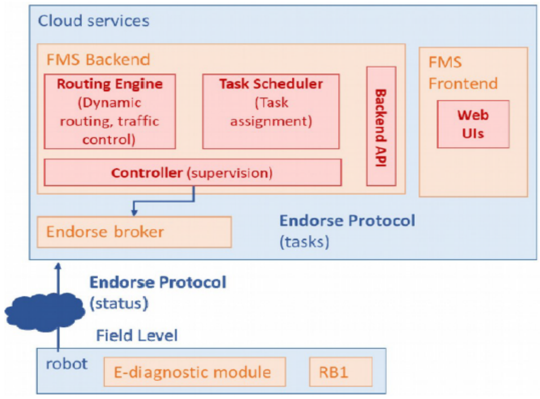

Figure 4: Fleet Management System Architecture, reprinted from [10]

features are implemented on-board each robot. At the moment of publication, the environment map must be edited manually using a CAD tool, but a navigation system is mentioned as part of future work, along with proposing algorithms for path planning of multiple robots in dynamic environments.

The work presented in [4] also addresses the routing problem for multiple robots in hospital logistics, aiming to increase the efficiency of a robot fleet by assigning multiple delivery tasks to a single robot, instead of one task at a time. As shown in Figure 5, hospital staff can enter a delivery request via user interface. After that, the request data are sent to the server, which verifies the status of all robots and selects an appropriate one to send the command to.

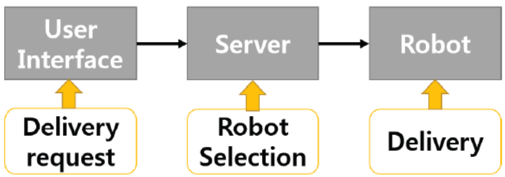

Figure 5: Multi-robot delivery framework, reprinted from [4]

Considering all robots connected to the hospital's wireless network, when a robot is moving to deliver an already assigned task, a new delivery task can be allocated to it by the server if no other robot is available in standby state. If instead, robots are not connected at all times, new tasks are added to a queue until a robot has finished executing its tasks and becomes available again. For these two types of behaviour they use two different algorithms, called single (STA) and multi (MTA) task allocation. MTA algorithm is based on calculating the cost of each robot for performing the given task, and selecting the robot consuming the minimum cost, and it has shown a 32% increased efficiency compared to STA.

3 Proposed Contribution

The literature review on healthcare robots has shown that, although many prototypes have been designed and developed, and some systems are already in use in hospitals, there is still room for improvement in terms of robot control features and robot design, in order to overcome the aforementioned challenges.

Table 1 contains a comparison of works found in the available literature according to features they present.

Table 1: Hospital robotic systems comparison

Work	Multi-robot	Mission	SLAM
UVD [1]	-	-	✓
AIDBOT [3]	-	-	✓
Robot [14]	-	-	-
EvoCart [7]	-	-	✓
Robot [2]	-	-	-
TRINA [6]	-	-	-
FMS [10]	✓	✓	✓
MTA [4]	✓	✓	✓
Work	**Modular**	**Recovery**	**GUI**
UVD [1]	-	-	✓
AIDBOT [3]	-	-	-
Robot [14]	✓	-	-
EvoCart [7]	-	-	✓
Robot [2]	-	-	-
TRINA [6]	-	-	-
FMS [10]	✓	-	✓
MTA [4]	-	-	✓

A few robotic systems for hospitals or healthcare have already been developed and tested in real environments, and some of them, shown on the table, are even deployed and working nowadays. But from the literature review and comparison, it is observed that the existing systems do not include a multi-robot control architecture and are mainly operated individually. When reviewing hospital robot fleet controls, some research has been conducted in path planning, mission planning and multi-task allocation, obtaining promising results, but not optimized nor deployed in real hospital robots yet.

Furthermore, no work has been found so far in literature on a complete control architecture for a hospital multi-robot system, that would include: a novel and intuitive multi-platform graphical user interface, a high level mission planner and task scheduler, optimized navigation, collision avoidance and safe movement in a dynamic environment, modularity for adapting to a heterogeneous robot fleet, energy management and recovery scenarios in case of failure.

3.1 Proposed Architecture

Taking into account the analysis performed in previous sections, a proposed control system architecture for a multi-robot system for hospital use is presented. It is composed of the following modules, as depicted in Figure 6:

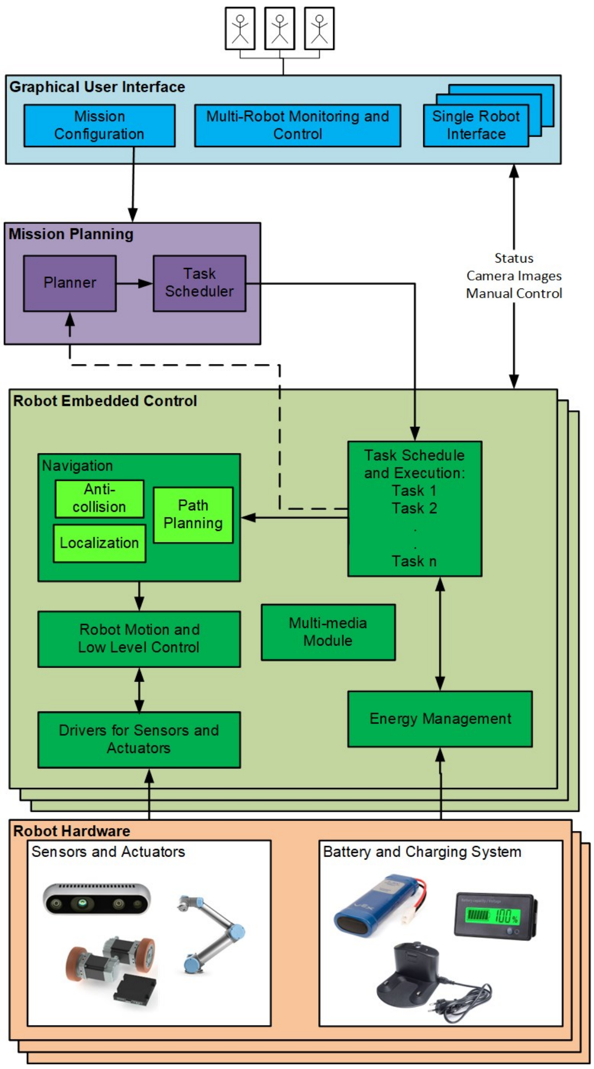

Figure 6: Proposed Multi-Robot Control System Architecture

- **Graphical User Interface**: with the possibility to be displayed from a web server or a phone application, users will be able to easily verify the location and status of each robot, as well as configure and start a mission. Through the single robot interface, users will have the possibility to interact directly with

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a single robot if necessary, without the need to configure a mission.

- **Mission Planning**: running on a server or cloud service, the mission planner will take the input from the user through the graphical interface, plan the mission according to the location and availability of the robots, generate the task schedule and load it on each robot. During the execution of a mission, the mission planning service will monitor the status of each robot.
- **Robot Embedded Control**: running on an on-board computer, the robot control will consist of the drivers for all sensors and actuators (including all communication services), an energy management application that will verify the battery status and the charging procedure, a navigation module consisting of anti-collision, localization and path planning features, and a task schedule and execution module, that will receive the task schedule from the Mission Planning and execute the tasks in order when a mission is initiated. The robot control will allow tele-operation of the robot from the user interface if requested by a user.
- **Multi-media Module**: the robot will allow video-calls between patients and medical staff or family members through the multi-media module, connected to the single robot user interface.
- **Robot Hardware**: it will consist of a set of sensors and actuators for the basic motion and navigation of the robot, a battery and charging system, an embedded computer and communication module, and the needed sensors and actuators for the specific missions the robot will perform.

3.2 Proposed Control Features

After reviewing hospital robot fleet control in literature, it is concluded that mission planning and task scheduling algorithms must run on a server or cloud service, and communicate with each robot when needed. Further research will be conducted on path planning and task allocation algorithms in order to find the most suitable and optimal solution, both in terms of robot fleet performance and computational availability.

Recovery scenarios present an important control feature that has not been identified in literature for hospital robots so far. When a robot cannot complete a task or mission, for whatever reason, the situation must be assessed and, if possible, the robot must move to a standby position where it does not disturb the patients and hospital personnel.

The graphical user interface design and implementation is of great importance for the successful operation of a hospital robot fleet. Healthcare personnel must feel comfortable using it for robot or mission control, and it must ensure that robot operation does not take much of their time.

The design proposal of the most significant control features is presented in this section.

3.2.1 Mission Planning

The Mission Planner and Scheduler will be running on a server/cloud service, as previously seen in literature [5], [10]. The cloud service will perform the following steps as part of its control sequence:

1. Verify availability of the robot fleet
2. Divide tasks given by GUI operator between available robots according to energy level and current position
3. Load task schedule on each robot
4. Monitor mission performance on each robot and display on GUI

The robot will receive a task schedule and a command to start a mission, then it will perform the following steps as part of its control sequence:

1. Verify its energy levels. They must be enough to complete the mission and return to charging station
2. If energy levels prove to be sufficient, start executing first task
3. Continue tasks in order while updating status to server
4. When tasks are completed, return to idle position. If a new mission is loaded, continue with the next mission

Tasks can be interrupted for several reasons. When this is the case, the Mission Planner and Scheduler will reschedule and load the failed tasks on the available robots.

3.2.2 Recovery Scenarios

Recovery scenarios will be added to all control modules and will depend on the situation the robot must recover from.

When a robot is performing a mission and, unexpectedly, its energy levels are too low to continue, the robot must stop the task safely and move to a charging station. The decision will be taken by the robot on-board control, informing the Mission Planner on the cloud. Then, the Planner will reschedule the missed tasks and load them on the available robots. The algorithm should try not to interfere with a big number of robots, optimizing the task reschedule.

If a sensor or actuator on board of a robot encounters an error or failure it cannot be recovered from, the robot must stop its current task and, if movement is possible, move to the closest standby position. The users will be notified through the user interface if human intervention is required. As with low energy levels, the tasks will be rescheduled.

Further failure and recovery scenarios are expected to be identified by hospital personnel. Then, they will be taken into account and added to the robot and cloud-based control. For this reason, the software design will be modular, adaptable to allow the implementation of new scenarios without involving big changes in the control.

3.2.3 Hospital Robot Interface

The graphical user interface will be composed of two main parts: the multi-robot mission planning interface and the single robot interface. The latter is currently under development [12], following a fast prototype technique, and depicted in 7. In future work, the interface will feature a robot mission planning module, from which healthcare personnel will be able to select the tasks to perform and follow up on the scheduled mission at all times.

4 Conclusions and future work

This article presented a state of the art in robotic systems for healthcare environments. Existing hospital robots, as well as some multi-robot systems, were reviewed in literature, and then compared between each other with respect to the challenges that such systems must be designed to overcome. Limitations were identified in the existing solutions, such as the implementation of a complete multi-robot control system, and a proposed control system architecture was introduced.

The control system will be tested and validated on a simulation environment that is already in place. Using a hospital plant 3D Unity model as a basis, a wheeled mobile robotic platform is implemented into the model, including basic control features and web user interface. In future work, a navigation module will be implemented on the robot model and tested in the hospital plant. Once this has been validated, several robotic platforms will be added and the mission planning module will be integrated. Further research on the most optimal planning and task schedule allocation algorithms will be carried out. Final validation will be done in a real hospital robotic platform prototype, when available.

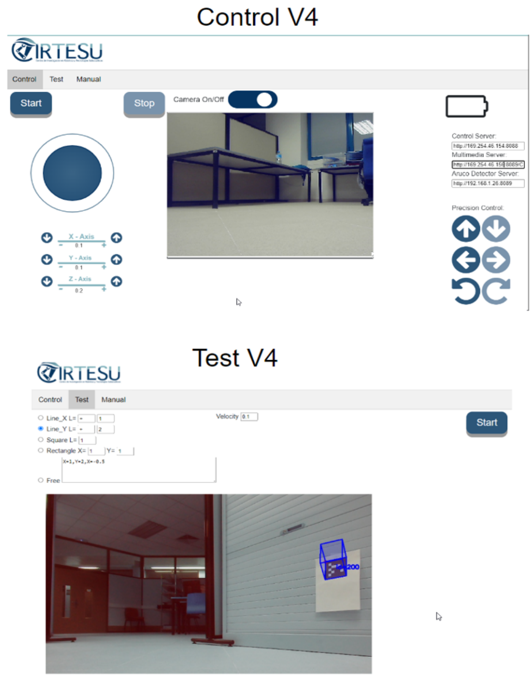

Figure 7: Graphical User Interface Prototype for Hospital Robot [12]

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