Robotics and Autonomous Systems 66 (2015) 159–174

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Modular robot systems towards the execution of cooperative tasks in large facilities ☆

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HIGHLIGHTS

- We present the results of cooperative task execution using heterogeneous modular robotic system (MRS).
- It is performed using tight and loosely coupled inter and intra robot configurations.
- The approach is based on the use of an inventory of three types of basic modules of the modular robot system.
- The heterogeneity in MRS is an advantageous property for the diverse tasks in large facilities.

ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form
1 October 2014
Accepted 13 October 2014
Available online 2 January 2015

Keywords:
Heterogeneous
Modular robots
Cooperative task
Synchronising

ABSTRACT

Large facilities present with wide range of tasks and modular robots present as a flexible robot solution. Some of the tasks to be performed in large facilities can vary from, achieving locomotion with different modular robot (M-Robot) configurations or the execution of cooperative tasks such as moving objects or manipulating objects with multiple modular robot configurations (M-Robot colony) and existing robot deployments. The coordination mechanisms enable the M-Robots to perform cooperative tasks as efficiently as specialised or standard robots. The approach is based on the combination of two communication types i.e., Inter Robot and Intra Robot communications. Through this communication architecture, tight and loose cooperation strategies are implemented to synchronise modules within an M-Robot configuration and to coordinate M-Robots belonging to the colony. These cooperation strategies are based on a closed-loop discrete time method, a remote clock reading method and a negotiation protocol. The coordination mechanisms and cooperation strategies are implemented into a real modular robotic system, SMART. The need for using such a mechanism in hazardous section of large scientific facilities is presented along with constraints and tasks. Locomotion execution of the mobile M-Robots colony in a bar-pushing task is used as an example for cooperative task execution of the coordination mechanisms and results are presented.

1. Introduction

Various robotic solutions have been developed and deployed in hazardous environments to execute tasks and perform missions [1,2]. Hazardous environments being clean up of nuclear plant decommissioning, search and rescue missions and others. The various approaches developed use specialised robot systems or multi robot systems. The single robot system needs to be designed to meet all the requirements and tasks, while a multi robot system provides flexibility in performing the tasks and missions. Multi robot system could be made of homogeneous or heterogeneous robots and ensuring the robots ability to cooperate with each other to successfully complete tasks is important. Using a modular approach would further increase the flexibility of the robot system. As modular robots have advanced from proof-of-concept systems to elaborate physical implementations and simulations, versatility, low-cost and robustness have been the key motivations [3]. Over time size, robustness and performance of modular robot systems have been continuously improving. The introduction of reconfigurable robotic system with the biologically-inspired cellular robot (CEBOT) by Fukuda [4] leads to a wide variety of homogeneous and heterogeneous modular robot systems [5,6]. The work progressed in various directions for modular robots like distributed programming aspects [7], self-recognition and kinematic planning of the motions for rearrangement between configurations, flexible form

☆ Parts of the work has been published in the Journal for Robotics and Autonomous Systems (Baca et al., 2012) [22] and IEEE International Conference on Robotics and Automation (ICRA), 2011 (Baca et al., 2011) [23].

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http://dx.doi.org/10.1016/j.robot.2014.10.008
0921-8890/

factor, utilising many degrees of freedom, high torque-to-weight ratio, ease of docking/undocking, and power management. Despite these important contributions in the field of modular robotics, the multi-robot research community has focused primarily on implementing cooperative control strategies in conventional robots that were designed for a specific task. The implementation of collaborative strategies in multi-robot teams formed by modular robots and the evaluation of this type of system during the execution of cooperative tasks have been less explored [8,9].

The execution of robotic cooperative tasks such as moving an object towards a desired destination by pushing or manipulating an object, requires movement coordination between the robots belonging to the colony at the beginning of the mission and continuous coordination during the task. A variety of techniques have been proposed in order to approach the problem of motion coordination in multi-robot systems [10]. For instance, tight cooperation strategies such as behaviour-based [11] and schemas-based [12], and loose cooperation strategies such as market-based [13] and auction-based [14] to name a few.

Modular robot systems are capable of forming different robot configurations made up of *n*-modules, which have to work in a coordinated/synchronised fashion. Their ability to rearrange their modules and to adapt to different circumstances, allows them to cope with multiple tasks such as different types of locomotion and manipulation. The complexity in the execution of a cooperative task with a colony based on modular robotic systems is high due to the fact that each robot (modular robot configuration) is composed of modules which have to be coordinated in a proper way to successfully work. Therefore, it is critical to implement collaborative strategies that enable complete coordination of the modules belonging to each robot configuration [15,16], and also overall coordination of the colony formed by modular robots [17,18].

Large facilities focused on scientific research like nuclear fusion reactor (JET—Joint European Torus) and particle accelerator (CERN—European Organization for Nuclear Research, Geneva) are shutdown to perform maintenance and modifications depending on the experiments to be conducted. There is a need for robot deployment to reduce personal exposure to the ionising radiation. In this scenario it would be beneficial to have the deployed robot system cooperate with other robots to overcome the given task or situation. This paper is towards the execution of cooperative tasks by modular robots and leverage the use of a modular robot system for all the requirements of task execution inside such an environment. Hence, the communication architecture and the coordination strategies must be selected properly to ensure an appropriate balance between performance and accuracy in the execution of cooperative tasks with modular robot systems. The approach presented is based on the combination of two communication types *i.e.*, Inter robot and Intra robot communications. Through this communication architecture, tight and loose cooperation strategies are implemented to synchronise modules belonging to an M-Robot (modular robot) configuration and to coordinate M-Robots belonging to the colony. The coordination mechanisms and cooperation strategies are implemented in the SMART system and by means of real experiments their performances are analysed.

Details of the requirements are presented in the Section 2. Section 3 briefly describes the heterogeneous modular robot system SMART. The coordinating mechanism inside a single robot configuration and between different modular robots is shown in Sections 4 and 5 respectively. Task planning executions and results are presented in Sections 6 and 7.

2. Constraints and tasks

The requirements and constraints are taken from the ISOLDE facility at CERN. ISOLDE is an isotope separator on-line (ISOL) radioactive ion beam facility. Different radioactive species are produced at the target by the bombardment of high-energy proton beam. Fig. 1 shows the 3D layout of the facility. The section highlighted in red is the location where two industrial manipulators are employed to exchange and store targets [19]. The need to find a larger and longer storage of the radiation emitting used targets is present. As the industrial robots are limited to moving along the rail on which they are mounted new robot solutions are being explored to transport the used targets to a different storage cell for longer storage. Like, mobile robots collaborating with the industrial manipulators. To solve the same problem we present modular robots as an option.

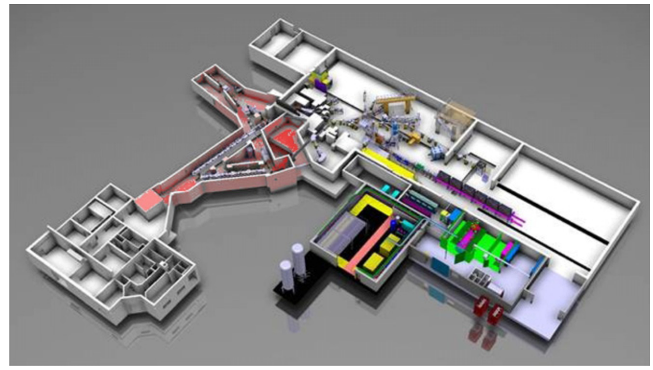

Fig. 1. Layout of the ISOLDE facility [20]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Generalising the requirement, the new robot deployment employed should be flexible to collaborate with the existing remote handling strategies and industrial robots deployed in the facility by augmenting to their capabilities. Also, the new robot deployment should be capable of dynamically adjusting to the task needs and have short development time which over time saves cost. As, during the course of operation unforeseen situations can be encountered and special tools and remote handling strategy may be needed. Lastly increased use of the new robot platform leads to reduced human exposure to the hazardous environment. Hence, the new robot platform should be capable of performing basic preventive, corrective maintenance and measurements.

The previously mentioned requirements also have physical constraints which are as follows. *Hazardous* environment due to the ionising radiation which is fatal on prolonged exposure and causes single event upsets [21]. Therefore special need to protect the electronics needs to be taken. The other hard constraints being the *Facility* itself and *Equipment* in it. As the facility cannot have, major changes to accommodate robot deployment and also the safety of the equipment present inside the facility are critical.

Hence, it would be beneficial for the facility if it is a modular robot system. As modular robots are more flexible than conventional robots and cut the development time of creating new conventional robots as new tasks arise. The ionising radiation present in the environment affects the electronics [21] and therefore the electronics need to be isolated and shielded. Hence a heterogeneous modular robot system is suited more than homogeneous modular robot. Also the different types of actuation are required depending on the tasks and having interchangeable actuation module is necessary. The advantages of such a deployment being, reduced sown time of the facility, effective execution of the tasks and collaboration with existing robot solutions in the facility.

Simplifying the problem of the different tasks, the modular robot system should be able to transport specialised new tools for the existing system as well as move the material (used beam targets and others) to various locations of the facility. To achieve this the cooperation problem and bar-pushing experiment are