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Bio-inspired construction with mobile robots and compliant pockets

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HIGHLIGHTS

- Study of an autonomous construction system that uses compliant pockets.
- Development of a bio-inspired, stochastic control algorithm.
- Extension of the control algorithm to swarm construction.

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ABSTRACT

In this paper, we develop an autonomous construction system in which self-contained ground robots build a protective barrier by means of compliant pockets. We present a stochastic control algorithm based on two biological mechanisms – stigmergy and templates – that takes advantage of compliant pockets for autonomous construction with single and multiple robots. The control algorithm guides the robot(s) to build the protective barrier without relying on a central planner, an external computer, or a motion capture system. We propose a statistical model to represent the structures built with the compliant pockets, and we provide a set of criteria for assessing the performance of the proposed system. To demonstrate the feasibility of the proposed system, real-robot and simulation experiments were carried out. The results show the viability of the proposed autonomous construction system.

1. Introduction

Robots could be the only viable alternative for construction and manipulation tasks in environments that are hazardous or inaccessible for humans [1], e.g., disaster areas, extraterrestrial surfaces, underground mines, or undersea. However, the employment of autonomous robots in these environments is still very challenging, and demands more research. Nature is one of the sources of inspiration that can help us in this regard. We can see, by observing nature, how simple agents employ adaptive and robust solutions to construct in dynamic and unstructured environments. Examples of such constructions include beaver dams, termite mounds, caddisfly cases, bee hives, social weaver nests, spider webs, and anthill structures. The construction of these structures is based on carefully evolved and well adapted rules. In particular, the usage of compliant materials along with special stochastic deposition rules can help coping with the uncertainties and the unpredictability of the environment. Our goal in this paper is to develop an autonomous construction system by taking inspiration from these biological examples.

We define *autonomous construction* a robotic activity in which one or many autonomous robots repeatedly *grasp, transport*, and *deposit* material in order to build a structure. In an autonomous construction system, we need to specify the task objective, which defines the form or function of the structure to be built; the building material of which the structure will be made; the autonomous robots that build the structure, in terms of their sensing, processing, and actuation capabilities; and the control algorithms that are implemented on the robots.

In this paper, we study an autonomous construction system whose task is to build a barrier exploiting filled bags as compliant material. Each robot in the system is a ground robot controlled by

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a reactive stochastic algorithm that exploits information already available in the environment. We describe the motivations for this study in terms of the above-mentioned aspects in the following.

1.1. Task objective

The task objective in this study is to build a protective barrier surrounding a generic dangerous area. The real-world applications that motivate our task objective – and therefore this study – include building radiation shields after nuclear disasters, lunar and Martian infrastructures like the one proposed in NASA's In-Situ Resource Utilization project [2], emergency shelters after earthquakes [3], and levees against tsunamis. The functional and performance requirements that are imposed by these applications include fast and simple realization, low cost, radiation exposure reduction, structure integrity, and impact resistance.

1.2. Building material

The building material must be chosen according to the task objective. In this work, we employ filled bags for building the protective barrier. The usage of this type of material, particularly in an autonomous construction system, is novel, and is coherent with some recent research. For example, Cal-Earth [3] proposes the use of sandbags for emergency shelters, and NASA [2,4,5] proposes the use of regolith bags for building lunar habitats.

Filled bags are built by enclosing some amorphous material into fabric pockets, so that they maintain a certain degree of deformability. As a consequence, filled bags (henceforth compliant pockets) have some of the properties of both rigid and amorphous materials, making them very appropriate for the autonomous construction of the aforementioned structures. In particular, they have the following features:

(i) They can conform to the shape of the environment in which they are placed. This property allows to construct on rough and uneven surfaces, and achieve packed structures. In addition, it makes quick deposition possible, because compliant pockets do not require edge alignment. Quick deposition can decrease the construction time.
(ii) They can fill voids in a structure. This property allows the robots to start building the structure simultaneously from different seeds as the different pieces of the structure can seamlessly join one another. In contrast, building structures with rigid parts requires to start from one seed [6]. Compliant pockets can remarkably improve the efficiency in parallel deposition.
(iii) They can be fabricated by exploiting in situ materials. Materials such as soil and sand on earth and regolith on the Moon, Mars, etc. are generally amorphous and cannot stay on their own. Compliant pockets are recognized as a simple, inexpensive, time-saving, and flexible approach for shaping these amorphous materials [2,3].

1.3. Autonomous robot

The robots must be equipped with the necessary sensors, processors, and actuators in order to be able to interact with the environment and manipulate the building material. In this study, each robot is completely self-contained, i.e., sensing, processing, and actuation are onboard. The robot is able to move and search for the building material in the environment. In addition, a manipulator with few degrees of freedom is sufficient for handling compliant pockets, thanks to the low precision required in their positioning and alignment.

1.4. Control algorithm

The control algorithm for autonomous construction should guide the robots to grasp the building material, transport it, and deposit it at the right place. Our control system uses two biological mechanisms – stigmergy and templates [7,8] – to achieve this goal:

(i) Stigmergy is the coordination of actions through modification of the environment by the agents. In stigmergy, the current state of the environment is the result of the previous building activity of the agents and it is used by the agents to guide their subsequent actions.
(ii) Templates are heterogeneities of the environment (e.g., a temperature gradient) that can be recognized by the agents and that can influence their behaviors. The final shape of the structure can be specified by the use of a template.

Adopting a control algorithm based on stigmergy and templates and exploiting the properties of the compliant pockets, the robots can compensate the uncertainties of the environment and organize the construction activities without the need of a blueprint or of any explicit representation of the structure to be built. Additionally, stigmergy and templates naturally lend themselves to cooperative construction in multi-robot systems, as discussed next.

1.5. Swarm construction

A swarm robotics system is an autonomous system in which multiple robots locally cooperate to accomplish a common task in a distributed fashion [9,10]. Swarm robotics systems can possess different functional properties. They can be *robust* against individual failures, *adaptive* against environment changes, *scalable* with respect to the swarm size, and *parallel* in work accomplishment. These properties make swarm robotics systems very appealing for applications such as autonomous construction.

The main challenge in swarm construction is how to design a distributed controller for the robots that allows them to cooperatively build a structure. Since interactions and communication between robots are local, coordination of activities between different robots to achieve the desired global structure is not trivial. In addition, interference between robots can degrade the performance of the system.

1.6. Contributions and outline

The contributions of our study are[1]: (i) the experimental investigation of the feasibility, merits, and performance of an autonomous construction system that uses compliant pockets as building material; (ii) the development of a bio-inspired, stochastic control algorithm that exploits the properties of compliant pockets for autonomous construction; (iii) the extension of the control algorithm to swarm construction and the analysis of the performance of such a system. The results presented in this paper are based on both simulation and real-world experiments.

The remainder of the paper is organized as follows. Related work is discussed in Section 2. The scenario definition, the specification of the building material and of the robots, and the architecture of the controller are provided in Section 3. The metrics used to evaluate the construction performance are presented in Section 4. Results of single-robot and multi-robot experiments are discussed in Sections 5 and 6, respectively. Finally, concluding remarks are made in Section 7.

[1] A preliminary version of the research presented in this paper was published in [11].