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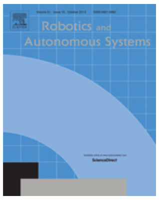

Towards the creation of tactile maps for robots and their use in robot contact motion control

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HIGHLIGHTS

- We introduce the notion of artificial somatosensory maps for robots.
- We propose an architecture that addresses all the various phases necessary to implement tactile-based representation and control.
- We show that artificial somatosensory maps are a good representation for controlling robot contact tasks.

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ABSTRACT

The recent availability of large-scale tactile systems for robots implies the design and development of tactile representation frameworks able to inform tactile-based robot control strategies. As a matter of fact, this is a non-trivial problem in knowledge representation. Starting from the previous work, we introduce the notion of *tactile maps* for robots, and we propose an architecture that addresses all the various phases which allow us to implement tactile-based representation and robot control. The proposed architecture is validated using simulations, which are aimed at assessing the robustness and the performance of the chosen control strategy with respect to the accuracy of the robot skin representation as well as to the force feedback needed to implement tactile-based contact tasks.

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1. Introduction

In the past few years, a new trend in the design of robots has emerged. Robots are no longer considered just the workforce of assemblage industrial plants. Instead, the goal has become to create highly skilled and versatile robots able to interact and cooperate with humans in the first place. Among the many strands that contribute to the so-called Human–Robot Interaction (HRI) field, physical HRI plays a major role [1,2]. Robots are expected to interact with humans and objects in their environment. Specifically, when humanoid robots are considered, it is expected that advanced skills in the physical interaction are available. For example, let us consider joint assemblage work involving both humans and robots in a plant cell setting, or the task of folding clothes in a home service scenario. In both cases, robots must be able to infer the amount of force the environment is exerting on precise locations of their body surface, associate it with a (possibly context-dependent) meaning, and react accordingly.

In physical interaction tasks, there is no shortage of reasons to believe that robot control plays a fundamental role. To date, a number of approaches (each one characterized by advantages and flaws) have been presented in the literature, with the aim of implementing motion algorithms able to react appropriately to exerted forces, which are typically detected using force/torque sensors. Examples include impedance control [3], hybrid force–position control [4] and parallel force–position control [5], just to name but few. Needless to say, the use of a force/torque sensor (usually located at the level of the robot *shoulder* if the force exerted on the overall arm is to be detected) limits considerably such motion control algorithms, because it detects the force distribution as it was all concentrated in the sensor location. This lumped information cannot provide control algorithms with enough information to implement advanced capabilities as far as a complex reaction to distributed forces is concerned.

In order to overcome these limitations, significant research activities have been carried out to provide robots with a sense of touch distributed throughout all the robot body surface [6–11]. As pointed out in [12,13], large-scale, whole-body tactile sensing is considered a key technology for implementing robot tasks where physical contact must be properly *controlled* (and not only reacted to). A distributed sense of touch can indeed provide the robot with

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local information about the distribution of the exerted forces [14], which is indeed the major flaw associated with the sole use of force/torque sensors.

Two are the problems emerging with the introduction of large-scale *robot skin*. The first problem is *representation*. On the one hand, differently from other sensing modes (e.g., vision), the notion of a *tactile image* is not straightforward to define. Since all the tactile elements (henceforth referred to as *taxels*) are located on the robot body, the *shape* of the actual sensing surface depends on the specific configuration in 3D space assumed by the robot itself. The actual tactile feedback may depend on the mutual configuration of robot parts. This happens, for example, when a robot mechanical configuration (henceforth referred to as a *posture*) occurs in which two robot body parts are in mutual contact. On the other hand, tactile data processing algorithms (which are at the basis of tactile-based intelligent behaviours and eventually control algorithms) need standard, robot morphology independent *data structures* to operate upon. As a matter fact, available algorithms to contact shape reconstruction assume an infinite elastic half-space as well as small deformations, i.e., a *flat* surface interested in the contact event. The second problem is related to how such a representation *can be useful for robot control during contact events*. Inferences about occurring contacts are not useful unless they can be back-projected on the robot external surface and used for robot control. Under this perspective, a principle integration between interaction-oriented robot control frameworks and representation structures for large-scale skin-like systems is currently an important challenge to face. On the one hand, it is necessary to devise suitable control laws able to keep the robot in contact with humans or objects in the workspace under well-defined conditions related to stability and safety. On the other hand, it is necessary to be able to design, implement and control precise interaction patterns at the contact to enforce purposive interaction capabilities.

The contribution of this article is two-fold.

1. Define a suitable representation framework for large-scale tactile systems that guarantees a well-defined *mapping* between tactile elements on the robot surface and their representation, and that can be easily accessed by tactile-based intelligent behaviours implementing interaction models.
2. Demonstrate that such a representation framework can be integrated with classical robot control architectures in order to accurately *plan* robot motions during contact events.

The article is organized as follows. Section 2 describes how this problem has been dealt with in Robotics research. Section 3 provides the reader with a general overview of the proposed framework. Section 4 introduces the concept of *tactile maps* for robots, which is at the basis of our proposal. This concept is used in Section 5, where an account is given about how to implement tactile-based robot behaviours. Simulations in Section 6 help in discussing the main properties of the proposed framework. Conclusions follow.

2. Related work

In order to design a comprehensive architecture for large-scale tactile data representation, it is necessary to determine the location of tactile elements on the robot surface, as well as the mapping between tactile elements and their representation [13].

In humans, a direct link can be established between mechanoreceptors in the skin and well-defined areas in the brain. The *location* of a stimulus corresponds to the set of *active* neural pathways leading to specific brain areas (i.e., brain *maps*), which encode neural information originating from mechanical transduction of exerted pressure in the corresponding portion of body surface. As a consequence, the location of a stimulus strictly corresponds to the set of neural areas that are innervated by active neural pathways. Different mechanoreceptors exist, which are specialized at detecting different properties of contact phenomena [15,16]. The activation of specific populations of neurons in the brain as a consequence of the mechanical stimulation of corresponding areas on the body surface entails the presence of a topographic arrangement characterizing such maps [17]. Recent evidence suggests an active role of the somatosensory area also in motor control [18], which opens up interesting possibilities for sensory–motor processes.

Accordingly, robot frameworks aiming at processing and using large-scale tactile feedback for motion control must be able to address the following questions.

1. How can a useful representation of the robot skin be *automatically* generated starting from the location of tactile elements distributed throughout the robot surface?
2. Is it possible to obtain a representation that allows us to design tactile data processing algorithms which are *independent* from the actual robot-specific body surface (i.e., equivalent of brain maps)?
3. How to *correlate* the 3D position of tactile elements on the robot surface with a well-defined location in the robot skin representation? In more general terms, how can a *topographic representation* be obtained, which preserves pairwise spatial relationships between tactile elements?
4. How to *exploit* such a robot skin representation for tactile-based robot motion control during contact events?

During the past few years, a number of approaches discussed in the literature addressed these key issues only to a partial extent. In particular, the work discussed in [19–23] exploits logic or information theoretic principles.

A computational model aimed at translating contact events into language-like discrete symbols with a well-defined semantics has been presented in [19]. The focus is how to render tactile features as logic symbols. Although the aim is to obtain a high-level, cognitive representation out of tactile information, the approach does not really address the previously posed questions. In particular, there is neither evidence of any topographic representation (the problem is completely avoided), nor any use of such *tactile symbols* for control purposes.

The work presented in [20] faces the problem of learning topographic body maps through sensory–motor interaction processes. A simulated baby-like agent capable of full-body movements is able to interact both with its own body and the surrounding environment. During the interaction process, the agent builds a tactile map of its body by temporally correlating signals from tactile sensors distributed on its surface. However, what is obtained is a topographic representation of temporally and spatially correlated locations: on the one hand, if two distant body locations were always stimulated together, they would be represented close in the topographic map; on the other hand, the approach works well for local body areas, because it is likely that close tactile elements are stimulated together as the effect of the same contact event. Approaches following the same principles have been pursued in [21–23]. Based on insights borrowed from the field of *Information Theory*, the work presented in [21] is aimed at building *sensoritopic maps* of groups of (visual) sensors using self-organizing processes. Feedback from groups of tactile sensors has been used in [22] to determine somatotopic connections between correlated tactile elements. In particular, the topographic map is bootstrapped in a human–robot interaction process: a mostly manual learning process is used to activate groups of nearby tactile elements, which are then considered topographically close to each other in the robot skin representation. Finally, the work described in [23] further extends the techniques developed in [21] to take into account the tactile domain.

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