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First-Order Synergies for Motion Planning of Anthropomorphic Dual-Arm Robots[⋆]

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Abstract: This paper addresses the problem of designing a planning algorithm for anthropomorphic dual-arm robotic systems to find paths that mimics the movements of real human beings by using first-order synergies (correlations between joint velocities). The key idea of the proposal is to convert captured human movements into a vector field of velocities, defined in the configuration space of the robot, and use it to guide the search of a solution path. The motion planning is solved using the proposed algorithm, called FOS-BKPIECE, that is a bidirectional version of the KPIECE planner working with an improved version of the extension procedure of the VF-RRT planner. The obtained robot movements follow the directions of the defined vector field and hence allow the robot to solve the task in a human-like fashion. The paper presents a description of the proposed approach as well as results from conceptual and application examples, the latter using a real anthropomorphic dual-arm robotic system. A thorough comparison with other previous planning algorithms shows that the proposed approach obtains better results.

Keywords: Robotics, Path Planning, Dual-Arm Robots, Synergies, Human-Like Motions.

1. INTRODUCTION

Motion planning is nowadays a quite researched issue in robotics, even more since the robots became a vital part of many application fields (e.g. the electronic and medical industries, or the computational biology and computer animation). The importance of this problem is manifested when the motion planning of mechanical hands or anthropomorphic dual-arm systems is attempted, i.e. systems involving a high number of degrees of freedom (DOF). In addition to this, sometimes not only a valid path is required but also the one that optimizes some path quality metric (e.g. minimizing the path length or the execution time). This is a typical problem in the humanoid robotics, where the motion planning should not only focus on the efficient search of a valid solution, but also on the search of robot movements that mimic the movements of the human beings. Pursuing this goal, the human-robot collaboration is facilitated because the humans can adjust their motions to avoid possible injuries or enhance the collaboration since they are familiar with the robot motions (Fukuda et al., 2001).

The motion planning of complex systems has been addressed with different planning algorithms, being the sampling-based planners the most commonly used (Elbanhawi and Simic, 2014). Among them, the Probabilistic Roadmap planners, PRM (Kavraki et al., 1996), or the Rapidly-exploring Random Trees, RRT (Kuffner and LaValle, 2000), are the most outstanding. Nevertheless, these planning algorithms are non-optimal. To really find an optimal solution, some variants like the PRM* and the RRT* algorithms have been proposed (Karaman and Frazzoli, 2011).

In order to obtain human-like movements, the right coordination between the robot joints is crucial and therefore the real movements of a human being are commonly used as a reference (Argall et al., 2009). Some relevant pioneering works dealt with the grasping problem analyzing the correlations of the finger joints when the human hand was grasping objects (Santello et al., 2002). These correlations were called *hand postural synergies* and mapped into a mechanical hand (Ciocarlie and Allen, 2009). The synergies existing in the human hand were also used for other objectives such as the analysis and design of robotic hands in order to mimic human grasps (Ficuciello et al., 2014), the design of specific hand control systems (Wimböck et al., 2011), or the identification of the hand pose using low-cost gloves (Bianchi et al., 2013). Nevertheless, there exist other approaches that, instead of studying the hand synergies while grasping an object, compute the synergies from hand movements when the human tries to cover the whole hand configuration space in an unconstrained way (Sun et al., 2010). These synergies can be used then to simplify the motion-planning problem by reducing the dimension of the search space as well as to mimic human postures (Rosell et al., 2011). More recently, a compliant model, called *soft synergies*, was also introduced and used in the selection of grasping forces, in their control, and in the control of the motion of the grasped object (Gabiccini et al., 2011; Prattichizzo et al., 2013). In addition, the synergies were used in a dual-arm anthropomorphic system while performing manipulation tasks (Suárez et al., 2015).

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Fig. 1. Human operator performing a task with both hands while wearing the measurement equipment.

All these works dealt with synergies involving correlations between joint positions. However, it seems natural to complement the information embedded in these traditional synergies with new synergies computed from samples captured in the velocity space of the system, generalizing thereby the concept of postural synergies. These synergies obtained in the space of the first derivative of the configuration trajectories were called *first-order synergies* (García et al., 2015). In that work, the position synergies were used, on the one hand, to detect the relevant region of the configuration space, i.e. the area where the synergies have been computed. On the other hand, they were used to classify the first-order synergies by dividing this region into several *synergy cells* where the first-order synergies are significantly different. Moreover, studies made by Grinyagin et al. (2005) and Vinjamuri et al. (2007) expressed the angular velocities of finger joints as linear combinations of a small number of *kinematic synergies*, which were also angular velocities of finger joints. The kinematic synergies were also used in tracking arm movements (d'Avella et al., 2006). However, the velocity synergies have not been investigated in dual-arm movements neither used in the motion planning of bimanual tasks. Hence, this opens a completely new field of research that is addressed in this work.

After this introduction, Section 2 presents the problem statement and gives an overview of the proposed approach, Section 3 details the proposal, the approach is validated in Section 4 and finally Section 5 presents the conclusions and future work.

2. PROBLEM STATEMENT AND APPROACH OVERVIEW

The goal of this work is to solve the motion planning of an anthropomorphic dual-arm robot trying to mimic the movements that a human does to solve a given task. To this end, a sampling-based planning algorithm is designed and the movements of human operators are used to guide the motion planning. The main features of the proposed approach are the following:

1. Human movements are captured, and then mapped to the anthropomorphic dual-arm robotic system, in order to obtain the synergies that exist in the dual-arm movements when humans solve a task.
2. The computed synergies are used to generate a vector field over the configuration space of the robot, $\mathcal{C}$. This vector field guides the motion planning by assigning a desired velocity to each configuration in $\mathcal{C}$.
3. The synergies are also used to select the subspace ${}^0B_r$, a lower-dimensional subspace in $\mathcal{C}$, that contains a predefined high portion of the sample variance of the captured movements. During the motion planning, the projection of the tree samples into ${}^0B_r$ gives an idea of the coverage of $\mathcal{C}$.
4. A bidirectional sampling-based planner is designed to bias the tree growth towards the directions of the synergy-based vector field. Hence, human-like movements are obtained. The proposed planning algorithm is based on the planner Vector-Field RRT, VF-RRT (Ko et al., 2014), and on the planner Kinodynamic Planning by Interior-Exterior Cell Exploration, KPIECE (Şucan and Kavraki, 2010), and it is called First-Order Synergies Bidirectional KPIECE, FOS-BKPIECE.

3. PLANNING PROCEDURE

3.1 Generating vector fields from synergies

This subsection presents a procedure to capture synergies from human operators and model them as a vector field of desired velocities. As stated in the previous section, the movements of human beings are used here to plan human-like motions for anthropomorphic dual-arm robots.

First, with magnetic trackers and sensorized gloves, the position and orientation of the human wrists are captured during the execution of a given task (see Fig. 1). The wrists of the dual-arm robot are placed at the captured poses, by solving the inverse kinematics of the arms, in order to map the human movements to the robotic system (Suárez et al., 2015). Thereby, for the given task execution, a sequence of configuration samples is obtained in the robot configuration space $\mathcal{C}$. Then, the synergies are computed in $\mathcal{C}$. The concept of first-order synergies (correlations between DOF velocities) was introduced by García et al. (2015), and in turn the couplings of DOF positions were called zero-order synergies. The Principal Component Analysis (PCA) of the captured configuration samples in the joint space, returns a new basis of $\mathcal{C}$ (eigenvectors) with the axes ordered in decreasing order of the corresponding sample dispersion along each axis (eigenvalues). Each axis of this basis represents a zero-order synergy and the movement along it, equivalent to a single DOF, implies the coordinated movement of several (or all) the actual DOF of the system. The first-order synergies are obtained similarly, but in this case using velocity samples. In practice, since only measured positions are obtained from the task execution, the velocities can be approximated with the central finite difference method of second-order accuracy (Fornberg, 1988). A PCA is run on this set of velocity samples, giving as a result a new basis of the velocity space. Each axis of this new basis represents a first-order synergy.

The zero-order synergies are used here to detect the relevant region of $\mathcal{C}$, called box ${}^0B$, where the captured motions take place (see Fig. 2). Notice that the directions