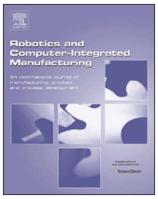
Robotics and Computer-Integrated Manufacturing 42 (2016) 73–85

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

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



Coordination of several robots based on temporal synchronization

Andrés Montaño, Raúl Suárez*

Institut d'Organització i Control de Sistemes Industrials (IOC), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain

ARTICLE INFO

Article history:
Received 26 December 2014
Received in revised form
4 March 2016
Accepted 3 May 2016
Available online 25 May 2016

Keywords:
Multi-robot systems
Motion planning
Temporal coordination
Motion synchronization

ABSTRACT

This paper proposes an approach to deal with the problem of coordinating multi-robot systems, in which each robot executes individually planned tasks in a shared workspace. The approach is a decoupled method that can coordinate the participating robots in on-line mode. The coordination is achieved through the adjustment of the time evolution of each robot along its original planned geometric path according to the movements of the other robots to assure a collision-free execution of their respective tasks. To assess the proposed approach different tests were performed in graphical simulations and real experiments.

1. Introduction

The efficient coordination of several robot arms in order to avoid collisions while they carry out some independent given tasks in a common workspace is a frequent problem of relevance in several robotic fields, both in industrial and service applications. This work proposes a practical approach to solve this problem modifying the temporal evolution of the robots along their precomputed geometrical paths, as it was initially presented in [1].

The problem of coordinating the movements of several robots working in a common workspace is an important issue in robotics and manufacturing as described in several recent works [2–4]. This problem can be solved following two different strategies, which lead to the centralized and decoupled approaches [5]. In the centralized approaches multiple robots operating in a shared workspace are considered as a single multi-body robot operating in a composite configuration space including the Degrees Of Freedom (*DOF*) of each robot, and then classical planning algorithms are applied to simultaneously find coordinated collision-free paths for all the robots. In the decoupled approaches each robot is treated as a single independent system and the motion planning process is divided into two phases; in the first phase an independent search for each robot path is performed considering only static obstacles and ignoring the presence of other robots in the environment, whereas the second phase (either off-line or on-line) applies coordination methods to avoid potential collisions when the robots are executing the movements simultaneously in the shared workspace.

The advantages and drawbacks of the centralized and decoupled approaches are presented in [5] and a comparative study of both approaches using a PRM planner is presented in [6]. The conclusion was that in applications that require critical coordinations (small clearances) the use of a centralized planner is more desirable. The centralized approach is complete but it involves a higher number of *DOF* and therefore it is computationally much more expensive than the decoupled approach, which could then be a valid option from the practical point of view.

Many approaches have been proposed to solve the trajectory coordination problem for manipulator robots using the decoupled strategy. The use of priorities was one of the first tools used to search for the robot coordination, by assigning priorities to the robots and sequentially searching for collision-free paths for the robots in order of priority in the configuration-time space [7]. Another approach proposed the use of a prioritization scheme to determine the robots that must adapt their movements in order to avoid collisions with the other robots using attractive elastic forces and repulsive potential field forces to modify the robot paths [8]. Prioritization has also been used with control techniques to coordinate industrial robots [4], in this case task-priorities and sliding control theories are combined to achieve the robot coordination. The main idea of this approach is to define constraints for the multirobot system in order to satisfy them using sliding control and a coordination supervisor, which generates the commanded joint accelerations for the robots. Priority schemes used in industrial applications are usually static, but service applications imply scenarios where priorities may change while the tasks are being executed. The approach proposed here can also use priorities to select the rules of motion in order to avoid collisions. The coordination is achieved modifying only the time evolution along the robot paths, while the geometric trajectory defined by the each robot path is not modified at all. Besides, in service applications the planned motions are likely executed only once because, in

---

* Corresponding author.

http://dx.doi.org/10.1016/j.rcim.2016.05.008
0736-5845/

general, service tasks are always different and if they have to be repeated it is under different conditions, and the motion planning has to be done on-line; therefore, if there are several robots in the workspace, in order to avoid collisions their motion coordination has to be done also on-line. Broadly speaking, in off-line approaches the objective is to plan time or energy optimal motion trajectories because the computation time is not an important factor, but, in on-line approaches, this optimization cannot be satisfactorily achieved because the complete robot plan may be unknown and the computational time of the motion optimization is usually too large.

An analysis and classification of multiple robot coordination methods was presented in [9], showing that the motion coordination algorithms can be applied on different representations of the workspace (e.g. physical space, composite configuration space, composite configuration-time space, path-time space or coordination space). In all cases, the main goal is to find a coordination curve in the corresponding space that avoids collisions between the robots [10]. There are different approaches to find this curve, like for instance adding a precomputed time delay at the beginning of the movement executions guaranteeing the collision avoidance between the robots [11–13]. On-line approaches has been also proposed. An event-based approach for on-line and off-line collision-free trajectory planning for dual-arm assembly systems was proposed in [14], the approach is based on a fast geometric collision detection algorithm, but the robot paths are fully known a priori and the obstacles in the coordination space are discovered by checking the collision between all the robot configurations. Another real-time approach has been proposed for a dual-arm system using a heuristic searching method in the configuration space of the robot [3]. All these methods require a priori knowledge of the robot paths in order to build an entire representation of the coordination space, this is a time expensive procedure, and it is valid only if the robot paths do not change. The approach proposed here does not require a priori analysis of the coordination space, instead of this, the coordination space is explored while the robots execute their tasks, this allows to work with partially known paths.

Dynamic programming has been also used to find a coordination curve [15,16], in this case, the main goal is the minimization of the execution time of the tasks, considering the dynamics of the robots and the torque restrictions in the robot joints. The obtained coordination curve is used to design the velocity profile for each robot so that collisions are avoided. The robot coordination can be also achieved introducing an adjustment in the geometric paths identifying the regions of the physical space swept by the robots and then modifying the paths planned a priori so that the robots do not occupy these regions simultaneously, if it is not possible to modify the robot paths then their execution time is modified so that the conflictive regions are occupied by only one robot at a time [17]. The problem of multirobot coordination in pick-and-place tasks on a conveyor band has been addressed in [18], presenting an approach based on noncooperative game theory where each robot uses local observations of the conveyor band and their neighbor robots to decide its actions. Each robot chooses the actions that are optimal for it, minimizing a cost function that depends on the relative positions of the robots and the products on the conveyor band. These approaches are valid for applications where the task is repetitive and can be optimized off-line. The approach proposed here intends to be useful for service applications, which are not repetitive and, besides, the paths to accomplish the tasks may be not completely known a priori, which does not allow the use of off-line optimization methods.

A method that solves the robot conflicts based on a path modification sequence was introduced in [2]. The coordination is achieved by re-planning of the paths of the robots in collision. The paths are ordered in a dynamically computed path modification sequence, which selects the path that must be re-planned. On the contrary, in our proposed approach the robot paths are not modified at all, and the coordination is achieved modifying the time evolution along the robot paths, which requires less computation.

The differences between the approach proposed in this paper and other coordination approaches can be summarized as follows. Most of the coordination methods require a priori knowledge of the robot paths to build the coordination space (off-line). The proposed approach just needs knowledge of a limited set of intended movements of the robots since the coordination space is explored at the same time as the robots execute their paths (on-line). The coordination is achieved by the modification of the time evolution along the robot paths, thus, the geometric robot paths are not changed at all. The proposed approach can use priorities to select the proper set of rules used to decide the time evolution along each robot path.

The paper is organized as follows. Section 2 presents an overview of the proposed approach, describing the main features and, specially, the advantages and drawbacks. Section 3 formally describes the proposed approach, it includes a subsection dealing with the problem modeling and another one describing the coordination procedure itself. Section 4 describes the application of the proposed approach to the case of two robots, including simulated and real experimentation, in such a way that different aspects can be illustrated in detail. Section 5.1 discusses the extension to the case of more than two robots, using simulated examples with three robots to illustrate the concepts. Finally, Section 6 presents a summary of the proposed approach, a brief discussion regarding its application, and expected future work.

2. Overview of the proposed approach

According to the categories described in previous section, the robot coordination approach proposed in this paper is a decoupled one that can be applied on-line. Basically, it is assumed that several robots have to work in a shared workspace and that their paths have been determined independently of each other (either off-line or on-line), so each robot path does not have collisions with the objects in the workspace but nothing can be guaranteed with respect to collisions with the other robots. Then, the coordination is performed by controlling the evolution of the robots along the planned geometrical paths, without producing any change on their geometry. Since the robot paths are described as a discretized sequence of robot configurations, it is assumed that if there are no collisions at two consecutive robot configurations in the sequence then there are no collisions at any intermediate ones (i.e. the path discretization is fine enough).

To illustrate the addressed problem consider the two robots shown in Fig. 1, one of them has to remove the red cans from the table and the other has to remove the white cans (partially occluded by the red ones in the picture). The motion planning is independently done for each robot (either because they are real independent systems or just in order to reduce the complexity and running time of the planning process), so none of the robots will collide with the table or the cans if it is moved alone, but, if the two robots work at the same time collisions between them may actually occur. In order to avoid these potential collisions the proposed approach adjusts the time evolution of each robot along its path according to the movements of the other robot to assure a collision-free execution of their tasks, and this is done while the robots are already executing their movements. Then, the approach requires that each robot knows the sequence of the expected future configurations of the other robots. This information can be exchanged when the robots have already planned it, which is the