Analysis and Classification of Multiple Robot Coordination Methods[1]

Eduardo Todt[2], Gustavo Raush, Raúl Suárez

Instituto de Organización y Control de Sistemas Industriales

Universidad Politécnica de Cataluña – Av. Diagonal 647, planta 11 - 08028 Barcelona – Spain

todt@ieee.org, raush@ioc.upc.es, suarez@ioc.upc.es

Abstract

The use of multiple robots sharing a workspace can increase the productivity and the versatility of complex applications, making the existence of cells with several robots more common. On the other hand, when the robots are used to perform independent tasks in a shared workspace each one becomes a mobile obstacle for the other. Several methods have been proposed to deal with the problem of robot coordination in order to avoid collisions in these situations. This paper analyzes these methods identifying the basic tools used in each one and trying to unify the nomenclature. Illustrative works are listed and classified. The classification of the different approaches can be useful for future developments in the field.

Keywords: coordination, multiple robots, workspace

1 Introduction

The coordination of two or more robots consists in making compatible the execution of their respective movements, so that they execute their tasks without collisions among them. This is achieved by means of the adjustment of the geometric paths so that they never cross, or by fixing the velocity profiles so that the robots do not cross the same place at the same time. Several approaches have been presented to coordinate robots in different contexts. In this paper the basic concepts used in published works are analyzed and a classification is done. Illustrative works in each category are included.

The scope of this work includes the coordination of robots as open cinematic chains, thus, for instance, cooperation of robots that are grasping the same object is not considered.

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[2] Professor at Pontifícia Universidade Católica do Rio Grande do Sul, Brazil Currently PhD student at Universidad Politécnica de Cataluña

2 Aspects involved in robot coordination

Nomenclature:

Geometric path (GP): sequence of configurations that the robot follows to execute the task from an initial configuration to a final one.

Trajectory (T): geometric path plus a velocity associated to each configuration.

Velocity profile (VP): description of the module of the robot velocity as a function of the configuration.

2.1 Relationship between the generation and coordination of robot movements

The coordination methods can be classified as coupled if the generation of the geometric path and the velocity profiles are determined considering the coordination of the robots, and decoupled otherwise. Since the velocity profile is independent of the geometric path, a modification of the velocity profile implies a space-temporal modification of the movement, but maintaining the defined geometric path.

The coupled methods plan the geometric paths and the velocity profiles of all the robots in one phase, and the generation of the trajectories and their coordination are inseparable processes (figure 1). On the other hand, the decoupled methods present a coordination phase separated from the path-planning phase. The decoupled methods can adjust the geometric paths, introduce pure delays in the execution of the movements or modify the velocity profiles (figures 2 and 3). It should be observed that the pure delay is a particular modification of the velocity profile, consisting in the introduction of wait times at the instants where the velocity of the robot that suffers the delay is zero. Figure 4 shows the classification according to this criterion.

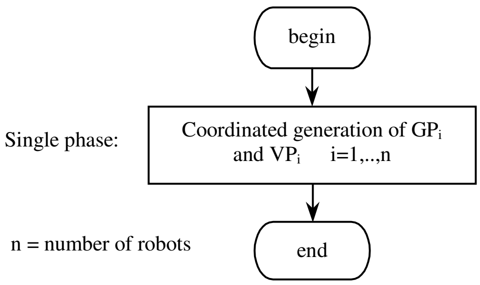

Figure 1: Coupled coordination of trajectories.

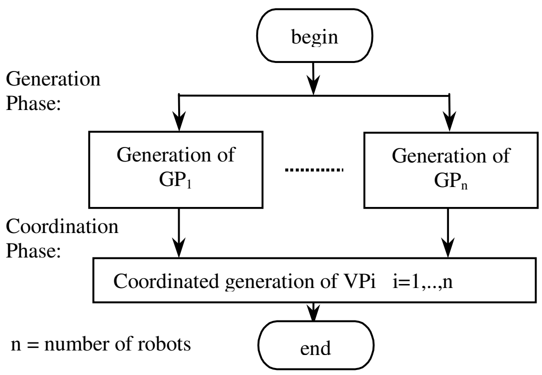

Figure 2: Decoupled coordination of trajectories: independent generation of GP and coordinated generation of VP.

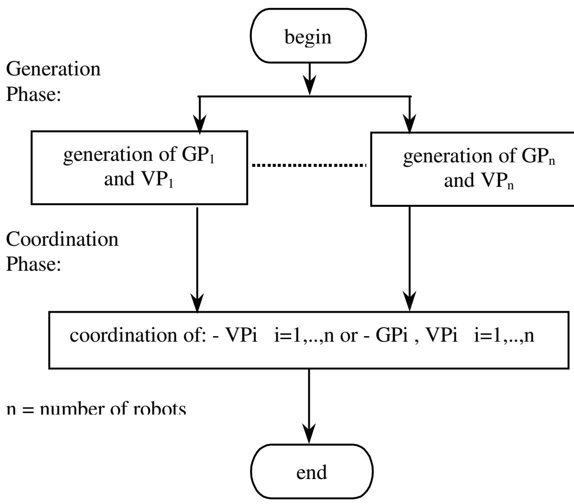

Figure 3: Decoupled coordination of trajectories: independent generation of GP and VP and coordinated adjustment of them.

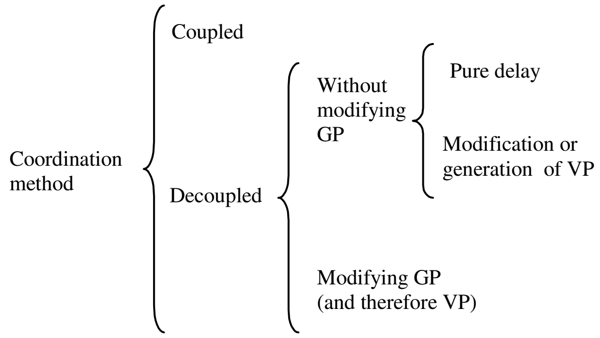

Figure 4: Classification of the coordination methods according to the generation and coordination.

2.2 Coordination time

The coordination can be carried out off-line, i.e. before the task execution, or on-line, i.e. once the robots are already being moved (figure 5).

There are two types of off-line coordination. In one type, called fixed off-line coordination, the coordination is determined a priori and it is not altered during the execution of the coordinated tasks. In the other type, called variable off-line coordination, an a-priori coordination of the robots is determined off-line, but there exists the possibility of choosing alternatives at certain points during the execution of the movements, for example, as a function of run-time acquired information. This is equivalent to a piecewise fixed off-line coordination.

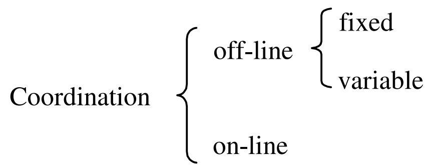

Figure 5: Classification according to the instant of execution of the coordination

2.3 Existence of coordination priorities

The coordination methods can be classified as:

With Priorities: one of the robots has higher priority in the execution of its movements and the others have to adapt their movements in order to avoid collisions. Different priorities can be used to define an order of priority relationship among all the robots of the system.

Without Priorities: none of the robots has higher priority than others when a conflict has to be solved to avoid a collision.

2.4 Coordination cost evaluation

The coordination can be done according to the following criteria:

Delay minimization: trajectory modifications are done so that they produce a minimum delay in the conclusion of all the movements, for one selected robot or for all the robots.

Velocity smoothing: trajectory modifications are made trying to minimize abrupt changes in the velocities.

Energy minimization: trajectory modifications are made trying to minimize the energy required for the execution of the movements.

Path length minimization: trajectory modifications are made trying to minimize the length of the robot paths, which is an indirect way of looking for minimum time delay or minimum energy.

2.5 Workspace representation

The coordination algorithms can be applied on different representations of the workspace, such as the geometric space, the configuration space or the coordination space.

Physical space (P-space)

The physical space is the one directly represented in terms of the coordinate system that describes the world where the robot is inserted.

Configuration space (C-space)

To specify the position of the points of a rigid object it is necessary to define *n* independent parameters that uniquely determine the position and orientation of the object. The n-dimensional space generated by these parameters is called configuration space (C-space) [16] and each point of this space is called a configuration.

The composite configuration space (CC-space) is the space obtained by the combination of the C-spaces of different robots. Therefore, the configurations of several robots are represented jointly in a single space of higher dimension.

The configuration-time space (CT-space) is the configuration space plus the temporal dimension. The composite configuration-time space (CCT-space) is the space composed of the combination of the CT-spaces of different robots. It allows the representation of the configurations of more than one robot with the temporal dimension in a single space.

Parameterized path space

A path parameter that uniquely identifies the robot configuration along the path is defined for each robot. In general this parameter is normalized, varying between 0 and 1 from the initial configuration to the final one, that can be coincident in case of a repetitive task.

The path-time space (ST-space) represents the temporal evolution of the path parameter.

The coordination space (SS-space) is the n-dimensional space determined by the *n* path parameters of *n* robots.

3 Existent approaches and representative works

In this section the main existent approaches for the solution of the problem of robot coordination as well as some representative works are presented.

3.1 Solution of the problem in the physical space

One of the most direct coordination approaches is based on the identification of the regions in physical space swept by each robot during the task execution. The intersection of these regions represents the part of the space where the robots can collide. Using this concept different methods are applied to avoid the collisions (Cheng [06], Faverjon and Tournassoud [08], Tournassoud [22], Alison [01], Shih, Sadler and Gruver [19]).

Cheng [06] identifies the regions of the space swept by the manipulators and then he tries to modify the a priori planned paths so that the robots do not occupy these regions simultaneously. If this is not possible, then semaphore techniques are used with the purpose of organizing the sequence of the tasks so that the conflict regions are occupied only by one robot at the same time.

A different proposal is based on the continuous evaluation of the distance among the robots, modifying the physical paths, when it is necessary, with the goal of preventing that the distance gets under a predefined threshold (Tournassoud [22] and Faverjon and Tournassoud [08]).

Shih, Sadler and Gruver [19] transform the physical space with the purpose of facilitate the representation of the collision region. The robot links are represented by line segments (only one dimension) and only collisions between the end links of each robot are considered. Given the robot trajectories, the intersection points of each end segment are represented by a parameter that varies between 0 and 1. The collision region is then represented by a unitary square in the space defined by the two parameters, that is used to search for a collision free path. From this solution the inverse the inverse transformation is used in order to obtain the path of each robot in the original physical space.

3.2 Solution of the problem in the configuration space

The main disadvantage of the configuration space is the high dimension that it may have, making the search for collision free paths very hard in computational terms. Barraquand, Langlois and Latombe [03] propose several methods for the exploration of composite configuration spaces in order to coordinate multiple robots. To avoid the regions defined by the fixed and mobile obstacles they use artificial potential fields that move the coordination paths away from the collision regions.

Despite the problem of the high dimension of the configuration space, Li and Latombe [15] present a real time coordination method for a cell composed of two robots. To obtain fast results, they make simplifications in the workspace of the robots, limiting the number of obstacles that the robots can find during the execution of their movements. They also use a decentralized approach, decomposing the problem into several small dimension configuration spaces. Then, potential field methods are applied to find a reliable path.

3.3 Solution of the problem in a parameterized space

Solution in ST-space

With the path parameterization an upper level of abstraction of the coordination problem is achieved, compared with the representation in the physical space. Kant and Zucker [09], Lee and Lee [10], and Chang, Chung and Lee [05] use the ST-space considering an independent planning of the movements of each robot.

The work of Kant and Zucker [09] is one of the first works that unfolds the planning of the trajectory into the planning of the geometric path and the planning of the velocity profiles. This procedure results in a significant reduction in the complexity of the coordination problem.

Lee and Lee [10] uses the ST-space to explicitly represent the collision regions. In the ST-space, the temporal evolution of the path is a monotonic crescent function since it is not accepted that a robot goes back on the geometric path. Again, if the curve that represents the temporal evolution of a robot intersects the collision region it is necessary to apply some method of trajectory re-planning. They modify the velocity profile of one of the robots by means of a succession of cycles of acceleration and deceleration, until the temporal evolution curve does not intersect the collision region (note that the collision region in the ST-space of one robot changes when the velocity profile of another robot is modified).

In another approach, Chang, Chung and Lee [05], and Shin and Zheng [20] calculate the value of the pure delay that should be applied at the beginning of the execution of the movements of one robot so that it does not collide with the other robots. This is equivalent to displace the curve of the temporal path evolution of one robot in ST-space until it does not intersect the collision region.

Solution in the SS-space

In the coordination space, SS-space, both the combined evolution of the robot movements and the collision region are represented. Representing in the same space and in the same way all the robots, using only one variable for each one, facilitates the process of finding solutions for the coordination problem. A crescent monotonic curve in this space is called coordination curve, and it represents a time coordination solution while keeping the same geometric path for each robot. O'Donnel and Lozano-Pérez [18] look for a suitable coordination curve in the SS-space to solve the robot coordination problem.

SS-space is also used by other authors to find coordination curve that optimizes the time of task execution.For instance, Lee, Moradi and Yi [13] and Lee and Kardaras [14] solve the problem starting designing the desired coordination curve by means of adjusting a piecewise lineal function, and moving it away from the region of collision using a function of artificial potentials. The obtained coordination curve seems an elastic string adapted to a complex surface.

Lee, Nam and Lyou [11] and Mohri, Yamamoto and Marushima [17] find an optimized coordination curve using dynamic programming. Their main goal is the minimization of the execution time of the tasks, considering the dynamics of the robots and the torque restrictions. The obtained coordination curve is used to design the velocity profile for each robot so that collisions are avoided.

Bien and Lee [04] make a combined use of the SS-space and the ST-space to obtain the robot coordination. Using the independent planned trajectories of two robots, the collisions region is obtained in the SS-space. This collision region is projected from SS-space onto the ST-space of the robot to be delayed, and it is used to compute the pure delay that should be applied at the beginning of the movement of the delayed robot. The same procedure is applied delaying the other robot and, as final step, the coordination curve that produces the smaller delay is chosen.

3.4 List of representative works

A list of representative works of the main coordination approaches is presented in the table 1, together with their classification according to the criteria introduced above.

4 Conclusions

The following conclusions can be obtained from the analysis carried out in the paper:

- There is an evolution in the degree of abstraction of the coordination problem along the time. The first works deal with the problem in the physical space, and then the formulation of the coordination problem moves to a more appropriate form. It is observed a simplification in the complexity of the methods.
- Only two robots are considered in the majority of the analyzed works.
- Only the temporal cost criterion is considered for the evaluations of the solutions. Other possible criteria, like the minimum energy or minimum length of the path, are not considered.
- The analyzed works do not refer to the complexity of obtaining the collision regions in any space.
- Current works are centered mostly on the decoupled methods. These methods do not always guarantee to find a solution, although it may exist. Nevertheless, they are preferred methods due to the reduction in the computational complexity.
- The coupled methods are associated, in general, with problem analyses in the physical space.

Table 1: Representative works of the main coordination approaches

Nomenclature used in the table:

C : Coupled
CC : Composite configuration space
CCT : Composite configuration-time space
DGP : Decoupled with changes on geometric path
DPD : Decoupled with pure delay
DVP : Decoupled with changes on velocity profile
MDR : Minimum delay for an elected robot
MPL : Minimum path length
MTD : Minimum total delay
N : No
NA : Not applicable
OFF : Off-line
ON : On-line
P : Physical space
SS : Coordination space
ST : Path-time space
VS : Velocity smoothing
Y : Yes

References	Coord. Method	On/Off Line	With Priority	Cost Criteria	Work-space
Erdmann and Lozano-Pérez 1986 [07]	C	OFF	Y	NA	CCT
Tournassoud 1986 [22]	C	ON	Y	VS	P
Kant and Zucker 1986 [09]	DVP	OFF	Y	MTD	ST
Lee and Lee 1987 [10]	DVP	OFF	Y	MDR	ST
Faverjon and Tournassoud 1987 [08]	C	OFF	Y	NA	P
O´donnel and Lozano-Pérez 1989 [18]	DPD	OFF	Y	MDR	SS
Shih, Sadler and Gruver 1991 [19]	C	OFF	N	MPL	P
Barraquand and Latombe 1991 [02]	C	OFF	N	MPL	CC
Barraquand, Langlois and Latombe 1992 [03]	C	OFF	N	MPL	CC
Bien and Lee 1992 [04]	DPD	OFF	N	MTD	SS y ST
Shin and Zheng 1992 [20]	DPD	OFF	N	MTD	ST
Morhi, Yamamoto and Marushima 1993 [17]	DVP	OFF	N	MTD	SS
Alison 1994 [01]	DGP	ON	Y	MPL	P
Chang, Chung and Lee 1994 [05]	DPD	OFF	Y	MDR	ST
Lee, Nam and Lyou 1995a [12]	DPD	OFF	N	MTD	SS y ST
Cheng 1995 [06]	DGP	OFF	N	MPL	P
Lee, Nam and Lyou 1995b [11]	DVP	OFF	N	MTD	SS
TenBrink and Popovik 1996 [21]	C	OFF	N	MPL	CCT
Lee, Moradi and Yi 1997 [13]	DPD	OFF	N	MTD	SS
Lee and Kardaras 1997 [14]	DPD	OFF	N	MTD + VS	SS
Li and Latombe 1997 [15]	C	ON	Y	MTD	CC + ST

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