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Predictive control and stabilization of nonholonomic formations with integrated spline-path planning

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HIGHLIGHTS

- Spline path planning integrated in model predictive control of formations is proposed.
- Autonomous change of shape of formations enforced by environment is enabled.
- Inter-vehicle coordination and collision avoidance after a failure of a team member.
- Decomposition of the control system into two planning loops with different rates.
- Convergence and stability of the method shown on the basis of Lyapunov theorems.

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ABSTRACT

A path planning in the space of multinominals integrated into a model predictive control mechanism for driving formations of autonomous mobile robots is presented in this paper. The proposed approach is designed to stabilize the formations in desired shapes, and to navigate the group into a final position in a partly known environment with dynamic obstacles. In addition, the system provides inter-vehicle coordination and collision avoidance in the event of failure of a team member. The method is aimed at reaching the final position of the formation in the desired shape, but it enables to change temporarily this shape if it is enforced by the environment (in narrow corridors, on response to an impending collision with obstacles and faulty team members, etc.). This autonomous emergent behaviour increases the robustness of the system and its usability. It enables a proper compromise to be found between the formation driving requirement and the effort to fulfil the mission objective, i.e., to move the group from the current state into the required position. In this paper, the convergence of the method and the requirements for stability are shown on the basis of the results of the Lyapunov theorems of stability. These theoretical achievements imply constraints on the applicability of the system, which are verified in numerical simulations and in various tests with real autonomous robots. The performances of the entire system and of independent sub-systems in various formation driving scenarios are also shown in these tests.

1. Introduction

The deployment of large, closely cooperating multi-robot systems in complex environments increases the number of possible applications of mobile robots, and often significantly improves the performance of the robotic systems that are employed nowadays. To fully exploit all benefits of multi-robot systems, new advanced techniques for autonomous coordination and control of particular team members are required, with a particular focus on robustness. In fact, multi-robot systems should achieve the same performance in terms of speed and smoothness of their movement in dynamic real-world environments as single robots deployed in the same application, but with increased reliability due to possible redundancy of the vehicles. Especially appealing and effective tools for solving these issues are techniques designed for stabilization of robots in a formation (formation driving methods), which significantly simplify inter-vehicle coordination and reduce possibility of collisions within closely cooperating teams.

The aim of this paper is to take advantage of the explicitly determined linkages in the leader–follower technique of the formation driving approach, and to develop a complex system that enables fast and smooth movement of robotic teams stabilized in a compact shape. The proposed system should enable navigation and stabilization of formations of predefined shapes, together with abilities to change the formation structure temporarily if

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it is enforced by the work-space of robots (e.g. in a constrained environment, in narrow corridors, by dynamic obstacles) or by a faulty robot within the team (i.e. inter-vehicle collision avoidance).

The idea presented here is based on the unique integration of a spline-path planning mechanism with a Model Predictive Control (MPC) technique, both suited for requirements of nonholonomic mobile robots. This approach enables to achieve motion performance of the multi-robot system that touches the limits of motion capabilities of individual robots that are moving independently, even if the multi-robot system is constrained by the desired relative positions between the team members. Fast and fluent movement of the group of robots is enabled due to the spline-path planning mechanism, which is integrated into the formation stabilization and control, and which respects the current motion constraints of the formation. The obtained plan is feasible for the entire group, and for all robots following their desired positions within the formation of a given shape. Then the MPC control and stabilization method responds only to disturbances caused by imprecise sensors and actuators, and to the dynamics of the environment (e.g. dynamic and later detected obstacles).

Another advantage of the proposed method is the possibility to make an explicit analysis of the stability of the system and to define required properties of the system performance (mainly limits on uncertainties of sensors and actuators) that guarantee convergence of the system into the final equilibrium (the desired position of the formation). The requirements on the abilities of the deployed robots can be specified prior to the mission on the basis of this theoretical work. These requirements are necessary for the deployment of the system in emergent applications, where the reliability and the predictability of its behaviour are crucial. In this paper, we present a proof of convergence inspired by Lyapunov stability theory, which enables explicit specifications of limits on the disturbances allowed for the robotic system in the given task.

2. State-of-the-art methods and progress beyond current formation driving approaches

2.1. Stabilization and control of formations of mobile robots

Algorithms for formation stabilization and for formation control along a predefined path or into a desired location can be divided into three main categories: virtual structures [1,2], behavioural techniques [3,4], and leader–follower methods [5–9]. We apply the leader–follower approach, which is frequently used in applications for car-like robots. A virtual leader is used in our method, and all robots in the formation act as followers. This approach increases the robustness of the system, since in case of a failure of any robot, the remaining team members can continue with their task without the need to select an alternative leader.

Two main tasks are investigated in the literature dealing with formations of mobile robots. In formation stabilization [6,1], a group of independently moving robots is aimed at merging into a formation of a given shape (with pre-defined relative positions). The second task investigated in the literature is formation driving into a predefined location, which is also the main problem addressed in this paper. This task usually starts if the formation is already stabilized in its fixed shape. Then the formation is controlled along a pre-defined or pre-planned path [5,10] (as is proposed in the leader–follower scheme in this paper) or trajectory planning is integrated into the motion control [11,12].

The most relevant and the most up-to-date works that can be considered as state-of-the-art methods for leader–follower based path planning and trajectory tracking are presented in [10,8]. The work in [10] is focused mainly on formation stabilization and on following a simple desired path only in plane environments without obstacles. This work does not consider any possibility of temporarily changing the desired shape of the formation as is proposed here. The problem of motion planning in excessively narrow corridors for a formation of ideal holonomic robots that keeps its desired shape is investigated in [8]. The authors introduce a leader–follower concept with priorities defined for each of the followers. The formation is then able of adapting its shape based on the environment constraints. Our work goes beyond this paper in several aspects. The proposed method is designed for use in dynamic environments with the possibility of fast MPC replanning when minor changes are detected in the proximity of the robots, and complex path replanning, which is employed if the structure of the environment is changed significantly. The decomposition of the planning into two control loops with different rates also enables to efficiently deal with failures of robots and uncertainties of their sensors and actuators as it is shown in the experimental part of the paper. In addition, the contribution of the paper is the possibility of specification of the requirements for convergence into the desired equilibrium prior to the mission on the basis only of the initial plan. This is crucial mainly in safety critical applications, in which the task of the formation cannot be interrupted during its motion.

2.2. Path planning techniques designed for formation driving

Various path planning techniques, including potential field, vector field histogram, visibility graph, occupancy grid, Voronoi diagram, rapidly-exploring random trees, road maps, and many others, can be found in the literature (see [13,14] for an overview). Algorithms for path planning in the space of splines are often designed for unmanned aerial vehicles, since they enable demanding requirements on smooth movement to be satisfied, which is crucial for fast aeroplanes [15]. Unfortunately, existing spline path planning methods are rarely applicable for car-like robots or even for formations with the possibility of changing their shape if necessary due to environment constraints. The contribution of our paper is the method that enables to find a proper path even in situations where a feasible solution for a formation with a fixed shape does not exist or is too expensive (the feasible path is for example too long). This provides a possibility to achieve a compromise between two mission objectives: stay in the desired formation as long as possible, and reach the desired state in a shortest time. Besides, as is shown in [16], continuous second derivative, which is held in a string of cubic splines in the proposed approach, is necessary for designing smooth manoeuvres of formations of car-like robots defined in curvilinear coordinates. It provides the possibility of smooth alternation between different shapes of the formation, which may be required by constraints imposed by the neighbouring environment.

2.3. MPC based methods in formation control

Receding Horizon Control (RHC), also known as Model Predictive Control (MPC), is especially appealing for involving physical (mobility) constraints, environment constraints (obstacles) and constraints of inter-vehicle relations (changing shape of the formation) into the formation stabilization method. In addition, MPC provides a proper level of cognition, which is given by frequent replanning, and adaptation to a changing environment. A detailed survey of MPC methods can be found in [17] and in references reported therein. Various MPC techniques have been presented in the formation driving literature, mainly for solving the task of stabilization of robots into a desired shape of the formation [18–24], and some of them also for tracking a given path by an already stabilized formation [25–27].

The most relevant and recent work using an MPC-based method for formation path tracking along a predefined path is presented

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