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Virtual fields and behaviour blending for the coordinated navigation of robot teams: Some experimental results

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ABSTRACT

This paper proposes an approach to manage the collective movement of robot groups, based on virtual fields, situation awareness and basic behaviour blending. Being of reactive nature, the method is intended for local navigation. The robots are anonymous, the navigation system is fully decentralized and there in not need of leader or specific coordination protocol. Robots can simply navigate holding the cohesion of the group or they can also navigate building up some kind of formation. The method can be implemented providing a set of simple suitable rules to the robots. It has been consistently tested both in simulations and experiments carried out on robot formations, proving to be reliable. The main results achieved are presented in this paper.

1. Introduction

This paper presents some of the results achieved both from simulated and real experiments, for the navigation guidance and control of a team of autonomous mobile robots. The experiments explore the application of a novel method of cooperative control for multi-agent systems.

A detailed description of the method was published in previous papers, Cifuentes, Giron-Sierra, and Jimenez (2012a, 2012b) and also in a Ph.D. Thesis, Cifuentes (2013). It combines the use of potential fields and a behaviour-based approach to guide the robots and maintain the structure of a prescribed formation, whilst avoiding collisions among robots or with other obstacles.

Usually, behaviour based approaches employ a blending process to merge the different behaviours that guide the robots. The method proposed in these previous papers was intended to systematise such blending process.

Potential fields provide a way to gather and synthesise the information a robot captures by its sensors. Each potential field is associated with the description of a specific situation the robot can be involved in. For example, proximity sensors detect the distance from the robot to different obstacles. This information is gathered in a single *obstacle* potential, the positions of other robot-mates are merged in a single *other robots* potential, etc. Thus, each potential reflects a particular situation in which a robot can be. It is interesting to notice that several situations can coexist for the same robot as far as they are not contradictory. For example, a robot could be near an obstacle and near also to another robot.

The situations generated by the different potentials are further evaluated to establish proper actions. This evaluation is based on the so-called behaviour-based approach (Matarić, 1999). Each possible behaviour, the robot is provided with, establishes a hight level rule the robot will try to seek. For example: *reach the goal* or *avoid collision*. Besides, each behaviour leads to a set of specific actions which determine how such high level rules are implemented.

The behaviour-based approach has to decide how to take the most suitable action when several behaviours coincide and, in particular, to cope with the problem of incompatible actions. This rises whenever the actions prescribed by simultaneous behaviours clash. For example, when an action, intended to avoid a collision with an obstacle, makes a robot move opposite to the goal direction or leave the formation the robot belongs to.

Usually, these problems are solved by some external arbitration function which helps to *blend* behaviours. The two classical approaches are: (a) To establish a hierarchical relationship among behaviours, such is the case of the Subsumption Architecture, (Brooks, 1986). (b) To seek a consensual solution, where all behaviours are simultaneously considered but with different relevance. This last is the case of the Motor Schemas (Arkin, 1998). Eventually, some mixed methods, which combine both approaches, have also been developed; for instance, the Null Space method (Antonelli, Arrichiello, & Chiaverini, 2008).

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In our approach, the problem is tackled in a slightly different way. There are no specific actions belonging to each behaviour. Instead, all possible robot actions are evaluated to ascertain how well they suit a specific behaviour. These evaluations stablish a *degree of suitability* for each action.

In a second step, The behaviour blending process works with this information on the *suitability* of the actions and the relevance of the behaviours to obtain a final single action. The arbitration or blending function acts as a cost function which analyses the complete action space.

Simulated and real experiments have been successfully carried out for single robot navigation in scenarios with static and moving obstacles, and also for robot groups and robot formations (for details, please, see Cifuentes et al. (2012a, 2012b) and Cifuentes (2013)). This paper focuses on the results achieved in formation setting up, because such process illustrates well the fine features of our approach. A clear advantage of it is that as far as the action suitability is represented in the same way, the same blending function can work with different behaviours, different actuations or even with different kinds of robots.

Although the pertinent background has been partially introduced in the articles Cifuentes et al. (2012a, 2012b), it is convenient to mention landmarks, important reviews and current works concerning the main aspects of our research.

One specific contribution in our proposal is to take decisions based on the discrimination of several potential fields. The use of virtual fields was proposed in Khatib (1986). This seminal paper awakened an intensive research, as it was an intuitive method for mobile robot obstacle avoidance. Some inherent limitations were discovered (Koren & Borenstein, 1991), like for instance local traps. Ways of alleviating these problems have been introduced in a number of papers, like the vector field histogram (Borenstein & Koren, 1989, 1991) or more recently the nearness diagram, (Minguez & Montano, 2004). Another question is the optimised design of the potential field, like it is done in Palm and Bouguerra (2013) using particle swarm optimisation. Even though many papers consider several potential fields, they are usually added to form a resultant and so important information that can be obtained from discrimination- is lost.

Typically, virtual fields are used for reactive control, while higher level navigation functions such path planning- are solved with other methods.

In our proposed approach, robot navigation decisions are taken with a geometrical basis similar to some aspects of fuzzy logic. Actually, there are many papers that apply fuzzy logic for mobile robot control (see the chapter Hong, Karasfi, & Nakhaeinia (2012) for an overview). Like other methodologies based on rules, a main practical problem is to write and specify those rules. In fact, when one considers non-trivial control of mobile robots, the number of fuzzy control rules increases, as it can be noticed in Mucientes, Alcalá-Fdez, Alcalá, and Casillas (2010) or in Rodríguez-Fdez, Mucientes, and Bugarín (2015). Another problem is that the result can easily become too specific for a particular robot, so a new robot may require significant changes in the rules. One of the main targets of our proposal is to provide a structured decision framework easy to generalise.

Another way of looking at the questions involved in mobile robot navigation, is that it requires a multi-objective behaviour control. This is the perspective adopted in Pirjanian and Matarić (2001), which sees contradiction difficulties in case of using fuzzy logic, and so it recommends behaviour blending.

Situated robotics is described in Matarić (2006) with examples of mobile robots that move in complex and challenging environments, like city streets, a museum, teams of interacting robots, etc. This was in contrast with robots living in fixed, highly structured environments. The motion of a situated robot implies spatial reasoning, which is more complicated in case of robot groups (Bandini, Manzoni, & Simone, 2002). Spatial reasoning involves many possible cases, as reflected by the many rules that arise when using fuzzy logic. A recent article, Wang, Liu, Liu, Dickson, and Wang (2014) proposes a multi-granularity approach. Another alternative is mereology (Polkowski & Ośmiałowski, 2008), which can be combined with potential fields (Omiaowski, 2009).

As shown in Cifuentes et al. (2012a), the proposed methodology can be homogeneously extended for situated multi-robot systems, with a moderate increase of reasoning effort.

Multi-robot systems have attracted a lot of research activity. They can be regarded as examples of multi-agent systems (Ferber, 1999; Wooldridge, 2009). The evolution of multiple mobile robot systems can be followed by a series of reviews that have been published along the years (Arai, Pagello, & Parker, 2002; Kernbach, 2013; Parker, 2000, 2008a, 2008b). Aspects concerning cooperation and coordination were considered in Cao, Fukunaga, and Kahng (1997) and Pirjanian (1999).

Social potential fields were proposed in Reif and Wang (1999) and Balch and Hybinette (2000) for the control of several mobile robots. Virtual leaders and potentials were combined, for the same purpose, in Leonard and Fiorelli (2001). A recent interesting application can be found in Bennet and McInnes (2012). There, authors propose a virtual field method for spacecraft formation flying. They use a classical virtual field approach and introduce bifurcation theory to shift the virtual field and, subsequently, the shape of the spacecraft formation. Such scenario fits very well with the method proposed in the present paper.

Robot groups can be spatially disordered, or be in a certain formation. This aspect, formation control, has been considered by many papers, as reviewed in Chen and Wang (2005). A number of papers have employed potential fields in different contexts, like Barisic, Vukic, and Miskovic (2009) for ships formation or, in the case of aerial robots, (Chen, Yu, Su, & Luo, 2015) using a virtual target point, and Dang and Horn (2015) based on leader following. Repulsion forces are used for swarms in Goswami, Saha, Pal, and Das (2014), which includes an interesting review. Indeed, target tracking is a clear objective in the case of robot soccer, as in the case of Conceicao, Scolari, Nascimento, and Moreira (2014) that combines predictive control and potentials. Other recent contributions that use potential fields are Hernandez-Martinez and Aranda-Bricaire (2013) and Seng, Barca, and Sekercioglu (2013). Of special interest is the approach of Ge and Fua (2005), which imposes the formation geometry via potential trenches with suitable shapes; in our work a similar concept is applied for the considered potentials.

There are recent works that include extensive reviews of multi-robot systems, and that devote sections to the use of virtual fields, like Hoy (2014), and the dissertations Cai (2013) and Schneider (2013).

An alternative for formation control is the use of virtual structures. In the case of Urcola, Riazuelo, Lazaro, and Montano (2008) this is combined with a leader, for evacuation application in complex urban environments. A virtual structure is also experimentally used by Wagdy and Khamis (2013). Commonly, virtual structures are associated to rigid formations, perhaps with some tolerances if a spring-damper analogy is chosen. Instead of it, our approach considers non-rigid formations in the sense that it is enough for our robots to fit inside the desired formation shape, so mutual distances between robots may vary.

In his famous book on turtles, termites and traffic jams, Resnick (1994), the following crucial observation was done: bird formations work in silence, no communication of messages is needed. In line with this remark, Fredslund and Mataric (2002) proposed a robot formation algorithm requiring minimal communication. Recently, a non-communicating multi-robot system was introduced by