A methodology for design and analysis of cooperative behaviors with mobile robots

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Abstract New methodologies are needed for modeling of physically cooperating mobile robots to be able to systematically design and analyze such systems. In this context, we present a method called the ‘P-robot Method’ under which we introduce entities called the p-robots at the environmental contact points and treat the linked mobile robots as a multiple degree-of-freedom object, comprising an articulated open kinematic chain, which is manipulated by the p-robots. The method is suitable to address three critical aspects of physical cooperation: a) analysis of environmental contacts, b) utilization of redundancy, and c) exploitation of system dynamics. Dynamics of the open chain are computed independent of the constraints, thus allowing the same set of equations to be used as the constraint conditions change, and simplifying the addition of multiple robots to the chain. The decoupling achieved through constraining the p-robots facilitates the analysis of kinematic as well as force constraints. We introduce the idea of a ‘tipping cone’, similar to a standard friction cone, to test whether forces on the robots cause undesired tipping. We have employed the P-robot Method for the static as well as dynamic analysis for a cooperative behavior involving two robots. The method is generalizable to analyze cooperative behaviors with any number of robots. We demonstrate that redundant actuation achieved by an adding a third robot to cooperation can help in satisfying the contact constraints. The P-robot Method can be useful to analyze other interesting multi-body robotic systems as well.

Keywords Physical cooperation · Mobile robots · Dynamics · Design

1 Introduction

Development of autonomous team of mobile robots to explore unknown, hazardous terrain continues to be an important area of robotics research. Recently, a number of mobile robot teams have been designed for exploration. For many search and rescue applications a large team of small robots is preferred over a few expensive robots, due to the need for access to tight spaces, redundancy, and expendability. However, limited mobility of individual small robots can inhibit overall accessibility of the team. Mobility of teams involving small robots can be greatly enhanced by physical cooperation among the team members. Mobility improvement by physical cooperation among mobile robots is an emerging area of research. Teams proposed in the earlier work including SwarmBots, Millibots etc. are some of the examples of this research (Fukushima et al. 1998; Brown et al. 2002; Mondada et al. 2003; Deshpande and Luntz 2007b). However, additional research is required to develop a team of robots that can autonomously cooperate to cover and search on an unknown terrain.

Current research is focused either on robot hardware and sensor system design, for example (Brown et al. 2002; Mondada et al. 2003), or on designing physical cooperation to overcome specific type of obstacles, for example, gap crossing in Fukushima et al. (1998). To be able to generalize these ideas of physical cooperation there is a need for a systematic approach to design, analysis and testing of the
robots and ways in which cooperation is carried out. Mobility can be greatly improved if we can systematically address the following questions: Under what limiting environmental conditions certain cooperation can be accomplished? If cooperation fails, what type of design changes are necessary? Will recruitment of more robots help cooperation?

In our earlier work we have presented a hierarchical approach for mobility improvement for a team of mobile robots (Deshpande and Luntz 2006b, 2007b). In this approach simple fundamental cooperative behaviors lead to cooperative maneuvers to overcome discrete obstacles, and a set of cooperative maneuvers leads to improved mobility. For example, ‘cooperative lift’, as shown in Fig. 2, is a fundamental behavior to many cooperative maneuvers as demonstrated in the previous work (Brown et al. 2002; Mondada et al. 2003; Deshpande and Luntz 2007b). For example a gap crossing maneuver can be composed by successive cooperative lift behaviors.

Our focus is on the design and analysis of fundamental cooperative behaviors. To design the building block cooperative behaviors it is necessary to derive and analyze the mathematical motion models describing the physical interactions among robots. We have identified three aspects of motions models that are critical for achieving physical cooperation, namely: a) environmental contacts, b) redundancy, and c) system dynamics. Firstly, cooperative behaviors involving mobile robots are dependent on interactions with the environment. For example, ground interaction forces can help as one robot pushes or pulls another as demonstrated in the case of SwarmBots (Mondada et al. 2003). In our earlier work we have shown that actuation for cooperation can be achieved solely by pushing against the ground (Deshpande and Luntz 2006b, 2007b). So, determination and satisfaction of the contact constraints is critical for achieving cooperative behaviors. Secondly, redundancy in the number of robots is available in a large number of small robots in a team, so difficult obstacles can be overcome by recruiting many robots in physical cooperation. For example, to climb steps a robot can be lifted up by a chain of assisting robots pulling and pushing it. In such a scenario, characterization and utilization of redundancy in number of robots is important to design the cooperative behaviors. Finally, the ability of physically cooperating robots to overcome obstacles can also be improved by utilizing the body dynamics of the robots during cooperation. For example, we have demonstrated that cooperative lifting of robots is assisted by acceleration of robots (Deshpande and Luntz 2006b, 2007b). Thus characterization of dynamic forces can improve cooperative behaviors.

A systematic method to generate the motion models is necessary to design a variety of cooperative behaviors leading to a larger class of maneuvers involving multiple robots. In this paper we present a method, called the ‘P-robot Method’, to derive models of motions resulting from physical interactions among robots. Our method simplifies the derivation of models of physically connected robots that need to satisfy contact constraints to achieve cooperative behaviors. The method is suitable for the design of behaviors by taking advantage of redundancy and body dynamics. Figure 1 is a schematic showing the P-robot Method in the context of hierarchical approach to cooperative mobility improvement. In this approach the P-robot Method will be used to design fundamental cooperative behaviors in the presence of contact constraints, redundancy and dynamics. The fundamental cooperative behaviors lead to cooperative maneuvers to overcome discrete obstacles, and a set of cooperative maneuvers will lead to improved mobility. Based on the performance of the team ideas for new behaviors and robot design changes can be analyzed with the P-robot Method.

2 Related work

Researchers have proposed and developed teams of robots in which team members physically cooperate to improve mobility. Fukushima et al. (1998), Hirose and Morishima (1990) have developed a team of mobile robots that connect in a chain and move in a snake-like motion to inspect hazardous areas of a nuclear plant. A team of small robots called ‘Millibots’ (Brown et al. 2002), each around 6 cm long, is another example of physically cooperating