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Optimal formation and control of cooperative wheeled mobile robots

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A B S T R A C T

In this paper, the optimal formation of a team of wheeled robot is dealt with for manipulating a common object. The robotic team has been commanded to transport the object from an initial pose along a specified path to a terminal pose. To this end, a proper cost function encompassing various aspects will be established and the grasping points of the object will be then determined employing various numerical optimization techniques such as Simulated Annealing, Genetic Algorithm and Particle Swarm Optimization. Finally, the team is controlled using a virtual structure-based approach and multiple-impedance-control strategy so as the obtained optimal formation can be realized.

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1. Introduction

Cooperative multi-robot systems, ranging from multiple mobile robots [1,2], multiple manipulators [3–6], multi-fingered hands [7,8] and multi-legged vehicles [9] have been extensively studied in a variety of contexts. We restrict our attention to cooperative mobile robots that have pivot grasped a common payload. Most publications in formation control of cooperative robots, see, e.g., [2,10–12], classify formation control approaches into three basic strategies, i.e., behavior based, virtual structure, and leader following. Behavior-based approaches start by designing simple behaviors or motion primitives for each individual robot, then more complex motion patterns can be generated by using a weighted sum of the relative importance of these primitives and the interaction of several robots [12]. The main problem of this approach is that the mathematical analysis of this approach is difficult and consequently the convergence of the formation to a desired configuration cannot be guaranteed.

With the leader following strategy, some robots are considered as leaders, while others act as followers. [10]. The leader pursues some group objectives, while the following robots track transformed coordinates of the leader with some prescribed offsets. However, this approach has some disadvantages. Particularly, the chain structure of the approach leads to a poor disturbance rejection property and additionally, the leader's motion is independent of the followers, i.e., there exists no explicit feedback from the followers to the leader. Furthermore, the formation does not tolerate leader faults.

Virtual structures consider the entire formation as a rigid body. The control law for a single vehicle is derived by defining the dynamics of the virtual structure and then translates the motion of the virtual structure into the desired motion of each vehicle. The team motion-planning/control problem now reduces to a well-known single-agent motion planning/con-

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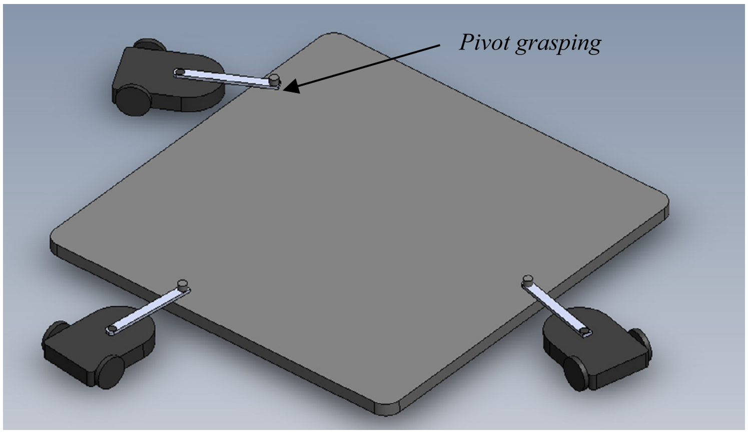

Fig. 1. Several wheeled mobile robots manipulate a large object.

trol problem from which the respective strategies for the individual agents are derived. The formation paradigm has also evolved to allow prescription of parameterized formation maneuvers [13] and group feedback [2,11]. This approach shows the greatest promise for scalability and is a proper method for formation regulation once the desired arrangement of the robotic team is not changing.

Before controlling the robots' formation, the best formation of robots should be found. However, although the problem of formation control has been well studied, finding the best arrangement of robotic members has been less studied [14,15]. As a result, in this paper, this important issue is first addressed. To this end, numerical approaches such as Particle Swarm Optimization (PSO) method and Genetic Algorithm (GA) can be utilized as it has been done in this paper. As in the object manipulation tasks by multiple arms, the formation of the robots does not change, hence a useful formation control approach is virtual structure as it has been utilized in the current work.

In order to control the interaction forces between the robots and payload and hence controlling the desired formation, a control scenario is utilized which, is called Multiple Impedance Control (MIC), [16]. The Multiple Impedance Control (MIC) has been developed for several cooperating arms manipulating a common payload while the internal forces between the arms and payload can also be tuned [17]. The MIC enforces reference impedance on both the manipulator end-points and the manipulated object. This means that both the manipulator end-effectors and the object are controlled to behave like designated impedance in reaction to any disturbing external force on the object.

The organization of this paper is as follows: Section 2 discusses about the dynamics of the system that contains kinematics and dynamics model of a constrained nonholonomic robot and dynamics of an object. In Section 3, a virtual structure method is described to determine the formation of a group of robots. The cost function of a group of robots for payload transportation is derived and then numerical methods are presented to obtain optimum configuration of the robotic team in Section 4. In Section 5, MIC controller is designed to overcome the nature of cooperative interactions between robots and object. In Section 6, a system of three mobile robots with an object is simulated, in which a Remote Center Compliance is attached to each end-effector. The obtained results of computer simulations illustrate the correctness of the suggested method. Finally, Section 7 concludes the paper with a discussion of the results.

2. System dynamics

In this section, the dynamics of a group of wheeled robots that cooperatively manipulate a common object will be derived. To this end, the system is first decomposed into two parts, mainly the robotic members and the manipulated object, and the dynamics of each part is then derived considering the interaction between the robots and the object as it will be described in the next sub-sections.

2.1. Kinematics and dynamics model for a mobile robot in a group

In Fig. 2a, one of the members of a robotic team, which pivotally grasped an object, like that in Fig. 1, has been considered. As it can be observed, a massless solid rod is attached to the robot for manipulation purposes, whose interaction forces due to contact with the object have also been addressed. To model this system, the mobile robot depicted in Fig. 2b is taken into consideration, which is a typical example of a nonholonomic mechanical system. It consists of a vehicle with two driving standard wheels mounted on the same axis, and a front passive wheel. The robot is actuated through two independent DC motors providing the necessary torques for the rear wheels.

The pose of the ith robot in an inertial Cartesian frame $\{X, Y\}$ is completely specified by the vector $\mathbf{q} = [x\, y\, \varphi]^{\mathrm{T}}$, where (x, y) and φ are the coordinates of the point P, and the orientation of the platform with respect to the inertial basis,

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