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Research Article

Whole arm manipulation planning based on feedback velocity fields and sampling-based techniques

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ABSTRACT

Changing the configuration of a cooperative whole arm manipulator is not easy while enclosing an object. This difficulty is mainly because of risk of jamming caused by kinematic constraints. To reduce this risk, this paper proposes a feedback manipulation planning algorithm that takes grasp kinematics into account. The idea is based on a vector field that imposes perturbation in object motion inducing directions when the movement is considerably along manipulator redundant directions. Obstacle avoidance problem is then considered by combining the algorithm with sampling-based techniques. As experimental results confirm, the proposed algorithm is effective in avoiding jamming as well as obstacles for a 6-DOF dual arm whole arm manipulator.

1. Introduction

Whole arm manipulation (WAM) is a type of manipulation that engages all surfaces of the links to manipulate an object or environment. Salisbury et al. [1] classified tasks that can be accomplished by a WAM robot into pushing, searching, enclosure and exclusion. Enclosure of an object by a robotic hand or multiple arms, also known as 'enveloping grasp' [2] or 'power grasp' [3], is a significant application of WAM, since it provides a more stable and robust grasp while enabling the robot to hold larger and heavier objects.

Regarding the manipulation of an object or body, many researchers have focused on the link tip level manipulation [4–6], since a dexterous motion can be anticipated by controlling many degrees of freedom in the system. Such manipulation, however, may easily fail in grasping an object due to an external disturbance or fault occurrence. On the other hand, manipulation under the enveloping style results in more robust grasp comparing to the grasp by link tips. Furthermore, this type of manipulation greatly contributes in reducing the required torque by distributing the gravitational force to each contact point. In a humanoid robot, manipulation under enveloping style may provide the only feasible solution to accomplish certain tasks which has opened up some important applications in assistive robotics in recent years [7].

Despite of WAM benefits in providing a safe grasp, moving the grasped object or changing the grasp configuration is challenging [8]. In general, unlike in link tip level manipulation where there exist many DOFs for controlling each contact forces, in whole arm manipulation there is an one-to-multiple mapping from joint torques to contact forces. Therefore, since contact forces cannot be uniquely determined, exact control of object motion is generally impossible in rigid body model [9] and risk of jamming is increased, i.e. the robot and object are stalled in a position while the internal forces between the object and robot's arms are increasing.

To cope with this problem, some researchers have studied whole arm manipulation with assumption that robot jacobian is invertible and therefore contact forces can be uniquely determined and controlled [10,11]. However, this assumption is limited to manipulators in which number of DOFs for each link is more than number of force transmitting directions at its contact points.

Another approach to generally solve the problem of contact force indeterminacy is upgrading the rigid body model to compliance model in whole arm manipulation [12]. In this case, contact forces can be determined by knowing infinitesimal motions of manipulator and

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object and the robot stiffness matrix for linear transformation. Although in this framework, exact control of object requires sensing or calculating contact force preload, the risk of jamming can be reduced without force feedback by preplanning manipulator motions.

Motion planning for dexterous link tip manipulation have been extensively considered in literature [13–15]. In [13] planning for global dexterous manipulation motions for reconfiguring 3-D smooth objects by fingertip grasps is presented. The algorithm is based on a two-level scheme: a global level that expands a tree of subgoals, and a local level that solves for instantaneous quasi-static motions of the entire fingertips-object system between adjacent subgoals. In [14], dexterous manipulation planning problem is solved based on a new search space structuring that relies on definition of the grasp subspaces, i.e. the subspaces of all the configurations corresponding to a k-finger grasp. Consequently, a resolution method builds a graph which nodes are chosen in the grasp subspaces. A review of other various approaches can be found in [15].

Despite of dexterous link tip manipulation, few approaches have been introduced for whole arm manipulation planning. In [11] this problem is solved by randomized techniques with the consideration that contact types may change during manipulation. By assuming manipulation system is kinematically determinate and manipulable, the object can not only be manipulated along the desired trajectory by the motion of the multi-fingered hand, but also a class of feasible contact modes can be chosen by using the redundant degrees of freedom. In [16], grasp quality is considered during manipulation to guarantee a robust and stable grasp configuration. Three efficient quality measures are proposed to rate different possible configurations during manipulation. Consequently, randomized kinodynamic planning [17] is used to switch between these configurations by considering local kinematic constraints imposed by the object.

Feedback motion planning is another interesting approach that can take local constraints into account [18]. The basic idea in this method of planning is assigning required robot velocity or acceleration as a vector at each configuration to guarantee robot convergence to the desired goal configuration. Robot motion will be its integral curve in the defined vector field. Unlike other motion planning approaches that generate open-loop trajectory for robot, this technique incorporates feedback from current configuration of robot in planning. This in turn, makes planning robust to uncertainties present in implementation. The good point is that as long as convergence property is maintained, this vector field can be defined according to local velocity constraints.

The contribution of this paper is introducing a velocity field planning approach for whole arm manipulation that guarantees reaching to the goal configuration while considering velocity constraints to avoid jamming. The algorithm is then extended to avoid obstacles in the task space by combining vector field and sampling-based approaches. The experimental results confirm the effective performance of the approach in avoiding jamming as well as obstacles in the task space.

The paper is organized as follows: In Section 2 velocity constraints for dexterous manipulation are reviewed. In Section 3 the proposed vector field that considers mentioned velocity constraints is presented and the general planning algorithm is introduced. In Section 4 obstacle avoidance problem is considered by combining sampling-based and feedback planning techniques. In Section 5 experimental set up and its control scheme is introduced and the experimental results are presented. Finally Section 6 concludes the paper.

2. Preliminaries

Consider a cooperative whole arm manipulator enclosing an object. An example of such system is shown in Fig. 1. The purpose of this section is developing necessary conditions for jamming and proposing the general approach for avoiding such situation.

2.1. Types of contacts

Regarding different configurations and contact forces, two types of contacts between the object and arms can be considered as follows.

2.1.1. Rolling contact

The relative twist v_i of the contact point i between robot and object is given by

$$v_i = G_i^T v_o - J_i \dot{q} \tag{1}$$

where G_i is the object grasp matrix and J_i is the robot jacobian for contact point i, v_o is the object velocity and $\dot{q}$ is the joint velocity of robot [19]. The contact is of rolling type if contact forces are constrained to be in the friction cone, i.e.

$$\sqrt{f_{i,x}^2 + f_{i,y}^2} \le -\mu f_{i,z}, \; f_{i,z} \le 0 \tag{2}$$

where $f_{i,(.)}$ are found according to contact frame and μ is the friction coefficient. In this case

$$v_{i,x} = v_{i,y} = v_{i,z} = 0 \tag{3}$$

2.1.2. Sliding contact

For sliding contact, the normal contact force is constrained by $f_{i,z} \le 0$ and the tangential components of the contact forces are constrained by

$$f_{i,x} = \tilde{\mu}_{i,x} f_{i,z}, \; f_{i,y} = \tilde{\mu}_{i,y} f_{i,z} \tag{4}$$

where $\tilde{\mu}_{i,(.)} = \mu v_{i,(.)} / \sqrt{v_{i,x}^2 + v_{i,y}^2}$. In this case, we have the constraint $v_{i,z} = 0$ for relative normal velocity and since tangential components of contact forces are not constrained to be inside the friction cone, there is no constraint for relative tangential velocities.

2.2. Redundant and motion-inducing movements

Assuming that quasi-static manipulation conditions are satisfied [20], the stiffness matrix K_x provides a linear relation between forces f and infinitesimal motions δx at contact points [12]

$$f = K_x \delta x = K_x (J \delta q - G^T \delta x_o) \tag{5}$$

where δq is infinitesimal motion of manipulator joints, δx_o is infinitesimal motion of the object G is the object grasp matrix and J is the robot jacobian. Object internal forces f_I should satisfy

$$G f_I = 0 \Rightarrow G K_x (J \delta q - G^T \delta x_o) = 0 \tag{6}$$

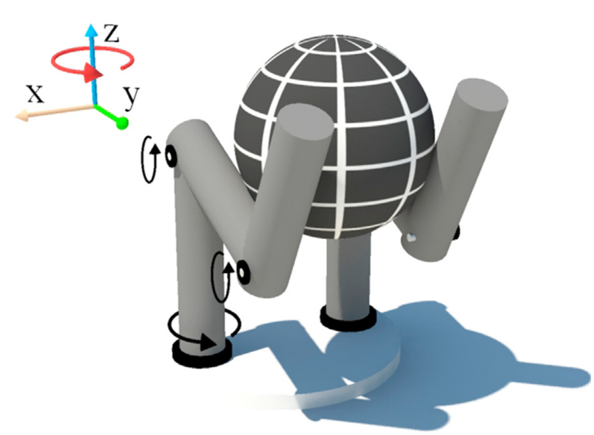

Fig. 1. A 6-DOF cooperative whole arm manipulator enclosing an object.