論 文 の 内 容 の 要 旨

論文題目　Cooperative Non-Prehensile Manipulation by Multiple Mobile Robots for Transportation
（複数移動ロボットによる搬送のための協調非把持マニピュレーション）

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Robots play a vital role in society. They are responsible for executing a number of different tasks, among which the transport manipulation of objects is imperative. For large-scale objects, a useful transport method is to load the object onto autonomous mobile robots that can transfer it to a target area. However, for large-scale objects in restricted areas (especially with obstacles), it is almost impossible to apply large industrial manipulators to load said objects onto mobile robots by prehensile methods. Instead, small-sized mobile robots are preferable due to their motion flexibility in restricted environments. By operating as a coordinated system, small-sized mobile robots can work collaboratively to manipulate large-scale objects with non-prehensile methods. In this study, we adopt two types of simple-structure mobile robots to realize the transport manipulation of a targeted object: mobile robot mounted with a manipulator to conduct push manipulations and a non-manipulator robot that can still load and transport objects.

When applying multiple mobile robots to cooperatively execute non-prehensile manipulations, the motion of each robot should be well-planned. Defining a mode as a series of states that hold the same constraint, the manipulation planning itself is known to be a multi-modal problem, which means that the planner should be able to probe not only the state space of each mode but also the feasible paths among the modes in the modal space. The manipulation sequences in the modal space are important because they guide the searching task in the configuration space and reduce the number of computations. Without determining the mode sequences, the restraint on the geometry and kinematics of the object–robot system would restrict the sample-based planner in probing the configuration state space.

In this study, a mode is defined as a contact state. To obtain the mode sequences in the manipulation planning, the possible contact states of the object that would occur during manipulation must be identified and the transitions of the contact states investigated. However, when an object makes contact with both the

robot and the environment, many possible modes exist due to the various contact combinations. The number of possible modes increases if the number of robots engaged in the manipulation is not definite. To the manipulation itself, the, an undetermined number of robots results in contact states with inadequate constraint to hold objects. Thus, to identify the feasible modes, it is vital to determine the number of robots. Furthermore, when considering mode transitions, changes in environment and robot contact must be considered. In manipulations executed by mobile robots, the way in which a robot makes contact with an object also complicates the mode transition because mobile robots can make contact actively or passively. Therefore, investigating the mode transition is a difficult task in planning multiple robot manipulation. In addition, even if manipulation is well-planned, precise control is also required to maintain the contact state between the object and the robots. Otherwise, unforeseeable mode transitions will occur, and the robots will fail to implement the manipulation tasks. Thus, the kinematic model of object–robot contact is expected to be as simple as possible in facilitating manipulation planning.

If prior conduct the gross planning in the modal space to investigate the transition of contact state and determine the number of robots, the planning would become more efficient and the mode paths could be used to guide the configuration-space probing. Thus, we adopt a method to generate the possible modes with the determined number of robots and to investigate the mode transitions.

Firstly, modal planning is conducted where we reduce the number of possible modes by determining the necessary number of robots for each manipulation state. The modes are generated to describe an object's contact sets from the robots and the environment while ignoring their exact configurations. Each multi-contact set exerted by the robots and the environment satisfies the necessary condition for force closure on the object along with gravity. Based on the created modes, we list every possible transition between the modes by determining whether the given robot can actively change the contacts with geometrical feasibility. Specially, we separated the mode transition induced by the robot contact, as the manner that the robot makes a contact with the object could either be active and passive. Two simulations are conducted to validate the proposed method, the results of which suggest that it is effective in various non-prehensile-manipulation cases with mobile robots. The mode-transition graph generated by our method can be used to efficiently sequence the manipulation actions before executing the detailed robot motion planning.

Secondly, to realize the object–robot contact with a simple kinematic model, we design the transporter-robot mechanism behind object contact. The modal planning requires a definite contact state, but this results in a nonnegligible problem with respect to robot control and maintaining object–robot contact. We apply a mobile robot with equivalent point–face contact with the manipulated object, since point–face contact does not change with object movement. Passive joints are adopted on the end effectors of the mobile robots, thereby enabling the manipulation to change object orientation while maintaining rigid contact with the robot, which, in turn, improves the inflexible face–face contact. In this study, we develop a mobile robot for transport manipulation, which has a flexible loading unit which makes an equivalent point–face contact with the object. We use three transport robots to hold the object. This is because three non-collinear points are adequate to support a surface; using any more is redundant and makes it difficult to confirm the object–robot contact state when the object moves. Furthermore, to guarantee the flexible movement of the robots in transporting the object, each robot is designed with omni-directional wheels so that, in the object–robot system, the group of robots can move as a three-wheeled omni-directional unit.

Finally, the mobile-robot system executes a manipulation task on a large-scale object for transportation, applying the proposed modal-planning method to determine the mode sequences in the process. Based on the modal-planning method, fine manipulation planning is conducted to determine the action sequences of the robot system in cooperative non-prehensile manipulation. In essence, the selected modal path is used to guide the searching work in the configuration space of the object–robot system. The valid states are prior determined for some selected modes, which are then treated as milestones in the state space to guide the searching of feasible action sequences of robot manipulation. The method used to handle invalid selected modal paths is also proposed, which involves cutting the invalid transitions in the current path and searching for new paths from the interrupted nodes. Compared with quitting the current path directly, said method preserves the valid part in the selected modal path and avoids insignificant looping in the newly selected path. The successful manipulation by the mobile robot prototypes demonstrate the feasibility of the proposed modal-planning method and the advantages of the developed mobile-robot system.

In this research, the manipulation of large-scale objects for transport is realized by the collaboration of simple-structured mobile robots with non-prehensile methods. To facilitate the application of the sampled-based method to plan the cooperative manipulation, modal planning is prior conducted to determine the manipulation sequences, wherein we propose a method to identify the possible modes with the determined number of robots as well as to investigate the mode transitions. Considering that a simplified object–robot contact model facilitates the implementation of the planned motion sequences for the robots, we design a transporter robot with an object loading unit that can make equivalent point contacts with the object. Indeed, extra costly controls are not necessary to maintain the contact state between the object and the robot. The proposed modal-planning method is applied to roughly plan the robot motion sequences, the results of which suggest that, in the fine planning, the geometrically feasible action sequences of the object–robot system can realize object manipulation.