

論文の内容の要旨

Efficient Caging Planning Under Uncertainty Based on Configuration Spaces of Target Object and Finger Formation (対象物体と指配置のコンフィギュレーション空間を用いた 不確かさを扱える効率的なケーシング計画)

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This thesis discusses the planning algorithms of a novel type of grasping closure – namely caging. In the author's view, this is the first literature which systematically discusses caging planning algorithms and their applications in robotics. Although the idea of caging is not proposed by the author himself, he further develops the geometric definition of caging and extends caging to robotic applications to challenge the difficulties caused by perception uncertainty and control uncertainty. Major contributions of this thesis involves three aspects. The thesis contributes in three aspects. Firstly, in caging theory, the thesis initially explains the relationship between caging and traditional research in grasping. Namely, caging is the extension of immobilization. Secondly, in caging planning algorithms, the thesis initially employs caging to deal with uncertainty. It on the one hand proposes efficient algorithms to deal with caging test while on the other hand further proposes efficient algorithms to deal with caging optimization. Both caging test algorithms and caging optimization algorithms are explored in the configuration space of target object and the configuration space of finger formation. Thirdly, in the aspect of applications, the thesis applies the proposed caging planning algorithms to robotic hands and multi-robot cooperative transportation. It discusses how to select proper algorithms according to requirements of real-world applications. Results show that the algorithms are not only robust to various uncertainty but also helpful to reduce the number of fingers or mobile robots.

The thesis has 8 chapters. In Chapter 1, the author introduces the basic concepts of robotic manipulation and the basic structure of an end-effector developed by some students from the author's group. Along with the introduction, the author explains how he started his research in caging and why he thinks caging is promising. The author claims that caging can be used to deal with uncertainty and can be a good supporting tool for the end-effector. He defines the caging test and caging optimization problems and gives an overview of thesis organization in this chapter.

Chapter 2-7 are the main body of the thesis. It is divided into three parts. They are as following.

Part I, Basic Concepts of Caging. This part introduces the basic concepts of caging and its recent development. The author in this part reviews historic works in grasping, contemporary work in caging and initially builds up the relationship between caging and traditional robotic grasping research (Fig. 1). He demonstrates both traditional grasping concepts and caging in the configuration space of target object, namely C^{obj} and visualizes the shift between caging and traditional concepts in grasping in this space. This Part I includes Chapter 2.

Part II, Caging in C^{obj} and Its Applications. In this part the author discusses in detail of how to deal with the caging problems in C^{obj} (Fig. 2) and presents some applications based on the proposal. C^{obj} is an intuitive tool to analyze caging. It is intuitive because it is directly connected to traditional topics in grasping. By employing C^{obj} the author provides in-depth review of the caging problems and certain solutions to them.

Specifically, the author in this part firstly revisits, improves and implements a previous work which aims to find the caging region of the third finger given a 2D convex target object and two boundary contacts. Then, the author explores how to push through the limitations of given fingers and extend his implementation to general cases. The author proposes to push through the limitation by fixing the two boundary contacts alternatively and reduce the computational complexity of that algorithm by decomposing caging into translational constraints and rotational constraints. The author demonstrates the performance of his proposal and evaluates the robustness of finger formations with WEBOT simulation software. Along with the exploration and evaluation, the author also discusses how to apply the algorithm in C^{obj} to real robotic hands.

Applications in this part include the distributed end-effector (Fig. 3 and Fig. 4) and multi-robot cooperative transportation (Fig. 5 and Fig. 6). The applications work well on 2D objects with convex boundaries.

This Part II includes Chapter 3 and Chapter 4. The drawback of the proposal in this part is that it can only work with convex boundaries. This drawback motivates the author to explore into another tool, namely the configuration space of finger formation, or C^{frm} .

Part III, Caging in C^{frm} and Its Applications. This part views the caging problems in the configuration space of finger formation, namely C^{frm} (Fig. 7). The center of consideration of C^{frm} is finger formation and it is independent from object shapes. Consequently, the caging algorithms in C^{frm} complement the drawbacks of C^{obj} . They can be used to deal with any 2D objects, ranging from concave ones and even hollow ones.

Specifically, the author in this part firstly compares C^{frm} and C^{obj} . He discusses both the advantages of C^{frm} and the difficulties of implementing caging algorithms in C^{frm} . The author

proposes to overcome the difficulties by introducing the space mapping idea (Fig. 8). Raw space mapping and especially its faster version, the improved space mapping, make it possible to update the whole space of C^{frm} completely and efficiently. Based on the updated C^{frm} , the algorithm can quickly find the caging candidates in the updated C^{frm} and locate the optimal caging configuration.

The caging algorithms in C^{frm} are applied to the design and implementation of a gripping hand (Fig. 9 and Fig. 10). The algorithms play role in both design and implementation procedures. During design, the algorithms are employed to simplify and evaluate design models. During implementation, the algorithms are employed to control the hand to cage and grasp objects. The design and implementation demonstrate advantages of caging.

This Part III includes Chapter 5 and Chapter 6.

Part IV, In-depth the Relationship between C^{obj} and C^{frm} . C^{frm} is sometimes a more powerful tool comparing with C^{obj} . However, it is unwise to discuss which is better. Both algorithms in C^{obj} and C^{frm} have their advantages and disadvantages. The fourth part of the thesis proves that at different orientations C^{frm} is the linear transformation of C^{obj} . Consequently, the metrics used in C^{frm} and C^{obj} are different. Both the two tools and their correspondent algorithms have reasons to exist. They therefore should be treated equally.

Actually, the two tools and their algorithms correspond to different solutions of geometric modeling. The algorithm in C^{obj} uses wireframe modeling while the algorithm in C^{frm} uses solid modeling. Both modeling technology plays important roles in geometric modeling and either algorithms in C^{obj} and C^{frm} should exist. I treat them equally and compile them into Part II and Part III of this thesis.

In real world, the algorithms in C^{obj} and C^{frm} should be chosen according to mechanical structure of robots and tasks. If all capture points are distributed and target objects are convex (like the distributed end-effector and multi-robot cooperative transportation), it is wise to do caging planning with the algorithms in C^{obj} . If capture points can be represented by certain formations or target objects have various shapes (like the gripping hand), it is wise to do caging planning with the algorithms in C^{frm} .

This Part IV includes Chapter 7.

In the last chapter, the author concludes the thesis. He firstly summarizes the whole thesis, especially the algorithms in C^{obj} and C^{frm} . Then, the author makes clear the three contributions. The author also proposes some future directions in the last chapter. In the aspect of algorithms, the author points out that future works could be the discussion of 2.5D/3D objects and the discussion of how to pre-define representative finger formations. In the aspect of applications the author points out that future works could be the deployment onto macro/nano manipulation and in-hand re-grasping systems.

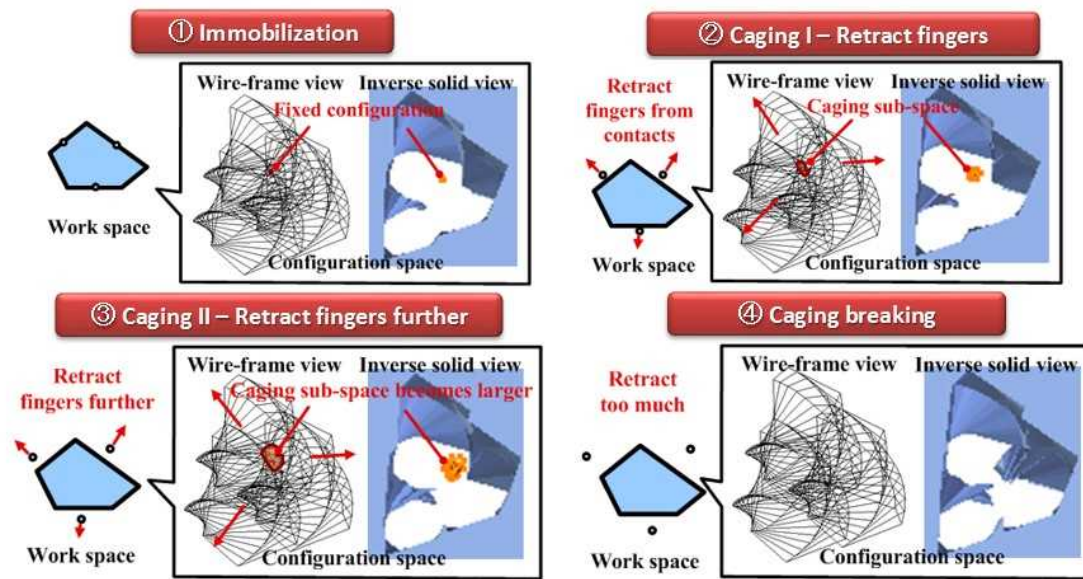


Fig. 1 The shift from immobilization (1) to caging (2,3) and caging breaking (4)

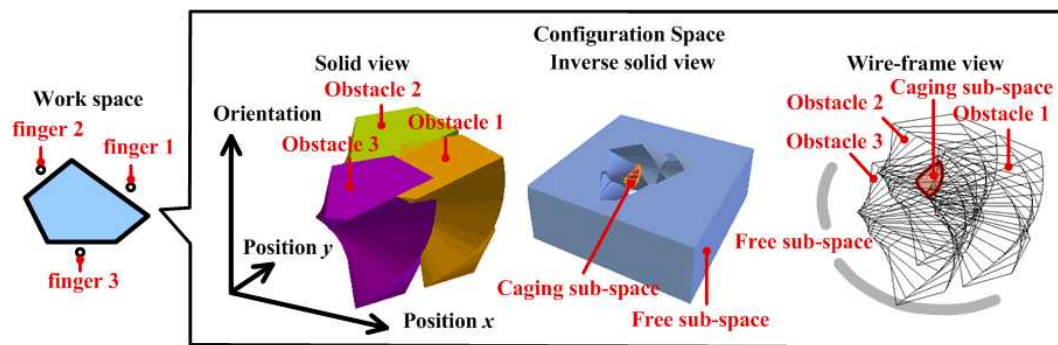


Fig. 2 Caging in C^{obj} means that the configuration obstacles enclose an caging sub-space

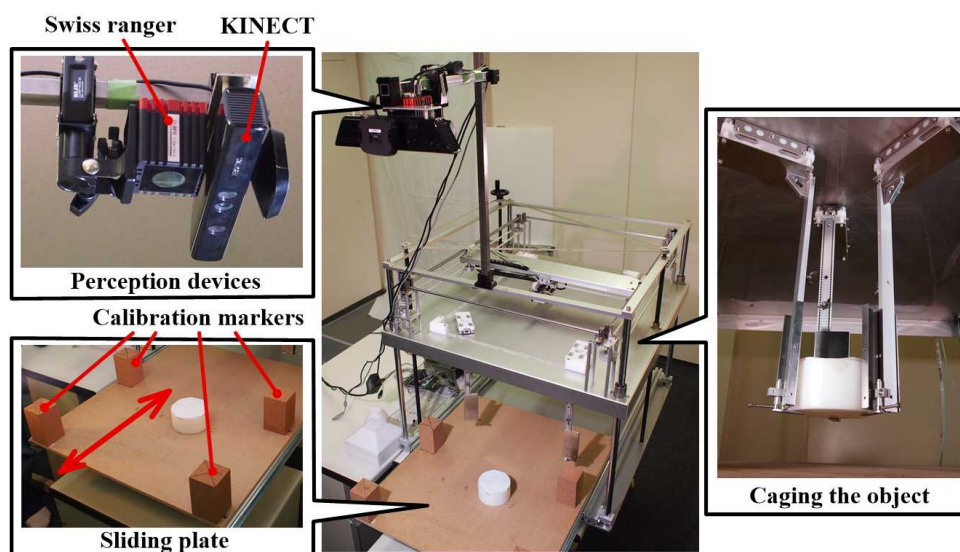


Fig. 3 The distributed end-effector

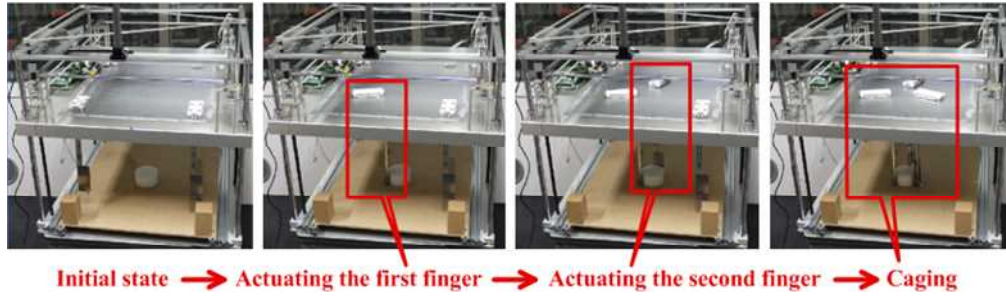


Fig. 4 Workflow of the distributed end-effector with algorithms in C^{obj}

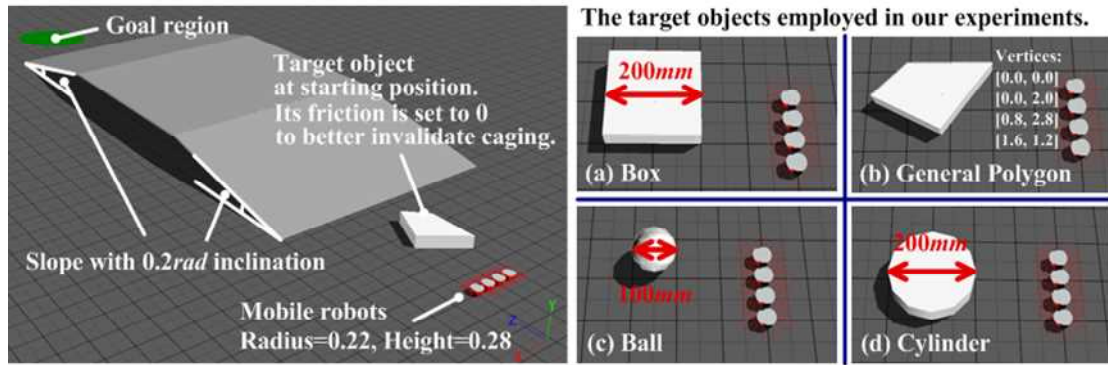


Fig. 5 Simulation environment of the multi-robot cooperative transportation

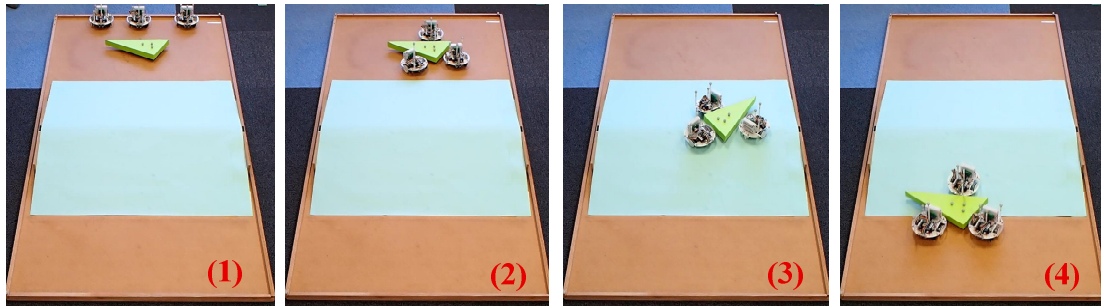


Fig. 6 Real-world implementation of the multi-robot cooperative transportation

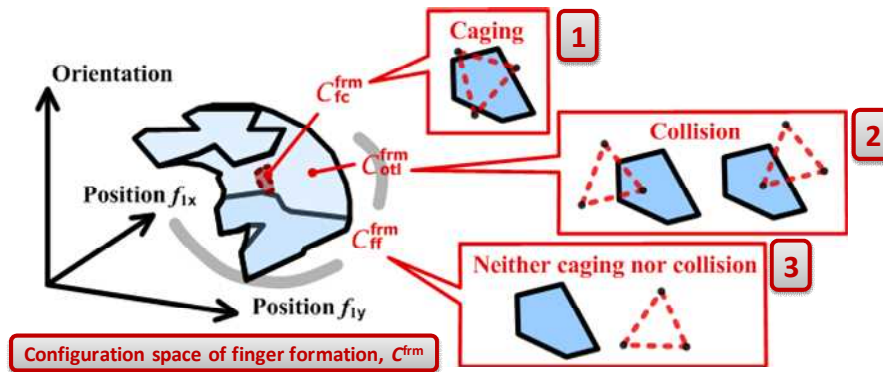


Fig. 7 The C^{frm} can be divided into three sub-spaces. Caging in this space means the existence of 2

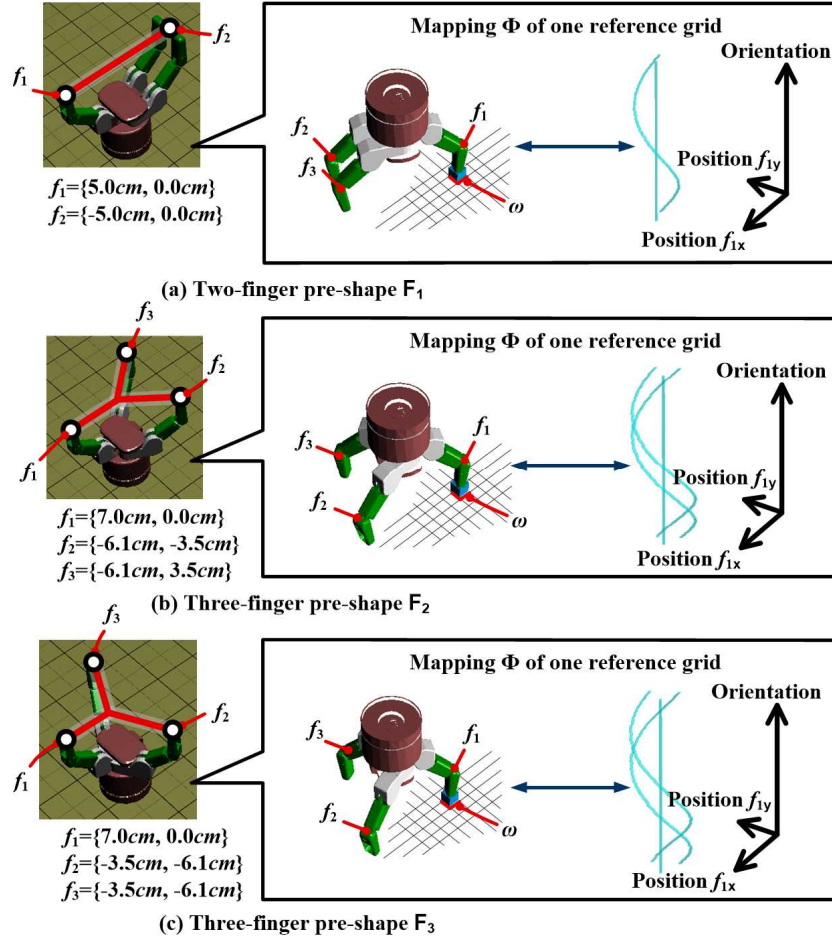


Fig. 8 The mapping from W space to C^{firm} – A grid in W space is mapped to a helical structure in C^{firm}

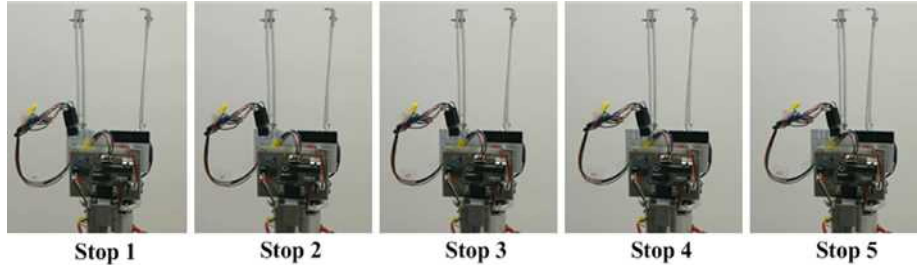


Fig. 8 The robotic gripper

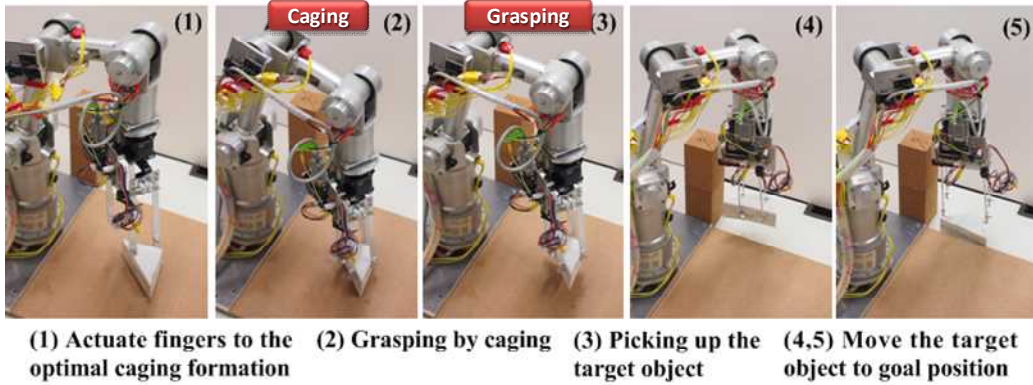


Fig. 9 Work procedure of the robotic gripper with caging algorithms in C^{firm}