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Keywords
distributed robotics, group behaviors, multi-robot cooperation, multi-robot systems, robot soccer

Comments
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Object Closure and Manipulation by Multiple Cooperating Mobile Robots

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Abstract

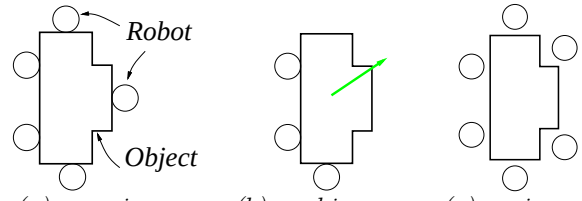
We address the manipulation of planar objects by multiple cooperating mobile robots using the concept of *Object Closure*. In contrast to Form or Force Closure, Object Closure is a condition under which the object is trapped so that there is no feasible path for the object from the given position to any position that is beyond a specified threshold distance. Once Object Closure is achieved, the robots can cooperatively drag or flow the trapped object to the desired goal. In this paper, we define object closure and develop a set of decentralized algorithms that allow the robots to achieve and maintain object closure. We show how simple, first-order, potential field based controllers can be used to implement multirobot manipulation tasks.

1 Introduction

Previous work on object manipulation by multiple robot mechanism can be categorized into three types (see Fig.1). The first type manipulation is the most popular one, specially in multiple finger or multiple arm manipulation [1][2][5][11][16][22][26]. All robots are arranged so that the total robots system is grasping the object during the manipulation(Fig.1-(a)). In this case, Form Closure or Force Closure condition should always be satisfied strictly. There are several research groups that have developed control strategies for coping with distributed control requirements and distributed sensing errors in such systems[6][13][21][23][24].

The second class of manipulation tasks requires *conditional closure manipulation*. This type does not guarantee Form Closure or Force Closure when we just consider robots in the system. By including gravity force, inertia, friction force, etc as an extra closure component, Force Closure is realized. In 2D manipulation, the most typical example of *conditional closure manipulation* is box pushing demonstration by two robots[14][3]. Lynch and Mason showed results on controllability in such manipulation tasks[8]. Tasks such as lifting objects[12] and throwing objects[9] could be viewed as examples of such *conditional closure*, but in a dynamic setting.

This paper is based on the notion of *caging* defined and studied in [15][19][20]. The key issue is to introduce a bounded movable area for the object. Then, the contact between object and robotics mechanism need not be maintained by robot's control. This makes motion planning and control of each robotic mechanism become simple and robust. We call this condition *Object Closure*. When a group of robots can establish object closure, the object can be transported to the desired target set by simply flowing a rigid formation of robots [18]. However, for multirobot cooperation (in contrast to multifingered grasping), decentralized algorithms are essential for such tasks. In this paper, we show a new approach for manipulation based on maintaining object closure with multiple robots. The proposed method has distinct advantages, especially when the number of robots increases, and when the object geometry cannot be determined precisely.



(a) grasping *(b) pushing* *(c) caging*

Figure 1: Three type manipulations by multiple robotic mechanism

2 Manipulation via Object Closure

The target of manipulation is to generate some desired motion on the object so that it can reach its target position and orientation even under certain constraints, e.g. contacting with environment or limitation of manipulating force of each robot. Then keeping contacts between robots and object in all the time is not a necessary condition for manipulation. In this paper, we study the problem of this type manipulation, and discuss properties and check conditions for *Object Closure*.

2.1 Assumptions

In this paper we will make the following assumptions about our task.

1. All robots have the same size circle shape body(discs) which be able to contact with the object in any direction. The object is star-shaped [1].

[1]To star-shaped object, any half line connecting between the

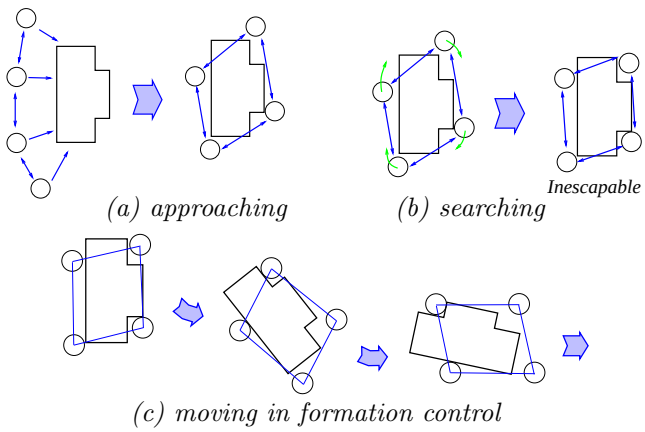


Figure 2: Two stages on caging the object and formation based manipulation

2. All robots know n, the number of robots attempting to maintain object closure, and can estimate the geometric properties (shape and center) of the object.
3. All robots can measure distance and direction toward any other robot and the object in its sensor range. This is easy to realize if a vision or ring sonar sensing system is installed on each robot.
4. n is sufficiently large to guarantee object closure is feasible and each robot's sensor range is large enough to guarantee that each robot can see its closest neighbors while maintaining object closure[2].
5. All robots are holonomic and the controller dynamics can be reduced to a single integrator:

$$\dot{\boldsymbol{x}} = \boldsymbol{u}.$$

2.2 Approach

Our proposed approach to caging or trapping the object is realized in two stages: (a) All robots approach to the object independently (See Fig.2-(a)); and (b) The robots search for an inescapable formation (See Fig.2-(b)). When the second step is successfully completed, a simple formation control strategy[4] can be used to drag the object to the designated goal destination. See Fig.3.

Step (a): Approaching to the object

For realizing distributed control on approaching to the target object, a potential field based motion control method is applied to the robot system. Each robot is guided by a 2D force vector $\boldsymbol{\beta}_i$ which is composed by two components, a potential force $\boldsymbol{\beta}_{obj_i}$ from the object and attracting or repelling forces $\boldsymbol{\beta}_{ij}$ to other robots .

object's mass center and infinite point only has one intersection point with the outline of the object. It can be concave.

[2]This condition can be eliminated if the sensors have a sufficiently large field of view.

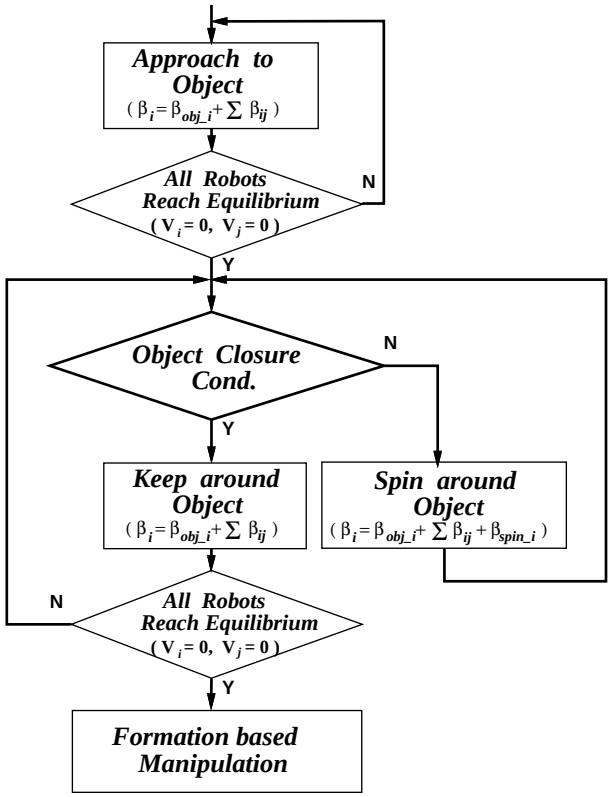


Figure 3: The control flow chart in each robot

$$\dot{\boldsymbol{x}}_i = \boldsymbol{\beta}_i \tag{1}$$

$$\boldsymbol{\beta}_i = \boldsymbol{\beta}_{obj_i} + \sum_{j=0}^{n} \boldsymbol{\beta}_{ij} \tag{2}$$

Under the effect of $\boldsymbol{\beta}_i$, all robots form a closed-chain formation around the object finally and separations between any neighbor robot pair will be the same. Proofs of equilibrium and stability are derived in [17].

Step (b): Searching for inescapable formation

When Step (a) is completed, the object may not be completely contained. In Step (b), the robots search for a condition of Object Closure. A configuration where the object cannot escape, *i.e.* an *inescapable* formation, can be found by moving the robots along the perimeter of the object looking for conditions that might satisfy the requirements of object closure. The vector $\boldsymbol{\beta}_i$ is set as follow:

$$\boldsymbol{\beta}_i = \boldsymbol{\beta}_{obj_i} + \sum_{j=0}^{n} \boldsymbol{\beta}_{ij} + k_{spin_i}\boldsymbol{\beta}_{spin_i} \tag{3}$$

Here

$$k_{spin_i} = \begin{cases} 1 & \textit{object is escapable} \\ 0 & \textit{object is inescapable} \end{cases}$$

Notice we are yet to formulate the conditions under which the object can escape.

We discuss components of potential based control for both these stages. The vector

$$\boldsymbol{\beta}_{obj_i} = -||\boldsymbol{p}_i - \boldsymbol{p}_d(\theta_i)||^{(2k-1)}(\boldsymbol{p}_i - \boldsymbol{p}_d(\theta_i)) \quad (4)$$

constructs an attracting potential field toward to the surface of the object. Here, $k \geq 1$. $\boldsymbol{p}_d$ is the vector to the closest point on the object perimeter. It is set as the equilibrium point to robots for realizing Object Closure without contacting with the object.

Second, we set attraction and repulsion among all robots which are in robots' sensor range(L_{sen}) as follow:

$$\boldsymbol{\beta}_{ij} = \begin{cases} \mathbf{0} & ||\boldsymbol{p}_i - \boldsymbol{p}_j|| > L_{sen} \\ -\frac{||\boldsymbol{p}_i - \boldsymbol{p}_j||^{2k} - {P_d}^{2k}}{||\boldsymbol{p}_i - \boldsymbol{p}_j||}(\boldsymbol{p}_i - \boldsymbol{p}_j) & else. \end{cases} \quad (5)$$

For keeping same distances among all pair neighbor robots around the object, the value of P_d is set as $S(\boldsymbol{p}_d)/n$. Here, $S(\boldsymbol{p}_d)$ is the length of path $\boldsymbol{p}_d$ and n is the total number of robots.

Finally, the potential force $\boldsymbol{\beta}_{spin_i}$ is set to each robot to spin around the object. Its direction is perpendicular to attractive force toward the object.

$$\begin{cases} \boldsymbol{\beta}_{spin_i} \cdot \boldsymbol{\beta}_{obj_i} = 0 \\ ||\boldsymbol{\beta}_{spin_i}|| = \beta_{spin} > 0 \end{cases} \quad (6)$$

3 Definitions

The problem of checking for *Object Closure* is equivalend to the problem of finding a path from current configuration to a infinite point (free space). To solve this problem, we map the robots and the object in configuration space and consider the subset of configuration space which is connected to the object's current configuration. A few definitions help to crystallize the basic ideas.

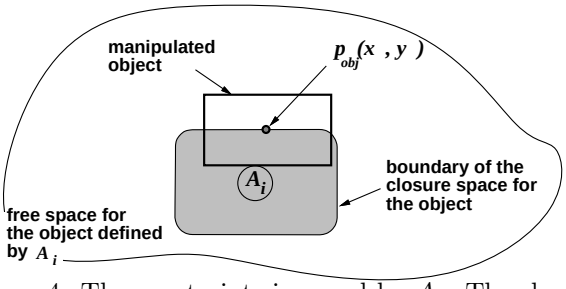


Figure 4: The constraints imposed by A_i. The shaded area denotes $\mathcal{C}_{cls_i}$, *C-Closure Object*.

Let $\mathcal{C}$ denote the C-space of the object and robots, $\mathcal{A}_{obj}$ denote the object and $\mathcal{A}_i$, $i = 1$ to n, denote the robot i in the working space. n is the total number of robots. A configuration $\boldsymbol{q}$ of $\mathcal{A}$ is a specification of robot's or object's position and orientation $(\boldsymbol{p}^T, \theta)^T$ in the working space.

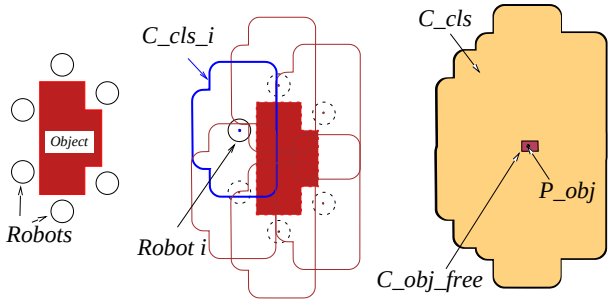


Figure 5: An example of *C-Closure Object* and *C-Closure Object Region* while six robots cage an object.

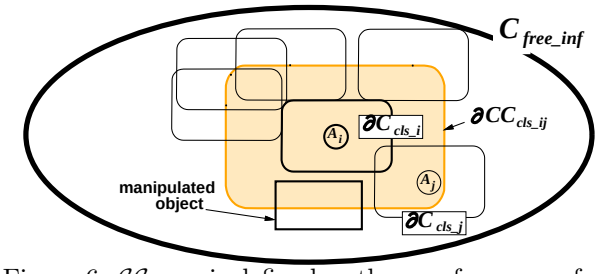


Figure 6: $\mathcal{CC}_{cls_ij}$ is defined as the non free space for an object with the shape $\partial\mathcal{C}_{cls_j}$ associated with an obstacle with the shape $\partial\mathcal{C}_{cls_i}$.

First, we define a subset *C-Closure Object* as:

$$\mathcal{C}_{cls_i} = \{\boldsymbol{q}_{obj} \in \mathcal{C} \mid \mathcal{A}_{obj}(\boldsymbol{q}_{obj}) \cap \mathcal{A}_i(\boldsymbol{q}_i) \neq \emptyset\} \quad (7)$$

which means that each robot $\mathcal{A}_i$ in the working space maps in $\mathcal{C}$ as a closure region to object's motion. This is shown schematically in Fig.4 when the configuration space is limited to R^2. The union of all the *C-Closure Objects*:

$$\mathcal{C}_{cls} = \bigcup_{i=1}^{n} \mathcal{C}_{cls_i} \quad (8)$$

is called the *C-Closure Object Region*. This is shown in Fig.5. Also $\mathcal{C}_{cls_i}(\theta_0)$ and $\mathcal{C}_{cls}(\theta_0)$ is the subset (a slice) in the $\mathcal{C}_{cls_i}$ and in the $\mathcal{C}_{cls}$ respectively while $\theta_{obj} = \theta_0$.

Next, we define a new C-space of the *C-Closure Object* and denote it as $\mathcal{CC}$. A C-Object of a *C-Closure Object* in $\mathcal{CC}$:

$$\mathcal{CC}_{cls_ij} = \{\boldsymbol{q}_j \in \mathcal{CC} \mid \mathcal{C}_{cls_i}(\boldsymbol{q}_i) \cap \mathcal{C}_{cls_j}(\boldsymbol{q}_j) \neq \emptyset\} \quad (9)$$

is called *CC-Closure Object* which indicates the C-Obstacle of ith *C-Closure Object* to jth *C-Closure Object*(Fig.6). Here, $i \neq j$. Also, $CC_{cls_ij}(\theta_0)$ is the subset in the CC_{cls_ij} while $\theta_j = \theta_0$.

Finally, the subset of configuration space in which the object does not contact or intersect any robot is:

$$\begin{aligned} \mathcal{C}_{free} &= \mathcal{C} \backslash \mathcal{C}_{cls} = \mathcal{C} \backslash \bigcup_{i=1}^{n} \mathcal{C}_{cls_i} \quad (10) \\ &= \{\boldsymbol{q}_{obj} \in \mathcal{C} \mid \mathcal{A}_{obj}(\boldsymbol{q}_{obj}) \cap (\bigcup_{i=1}^{n} \mathcal{A}_i(\boldsymbol{q}_i)) = \emptyset\} \end{aligned}$$

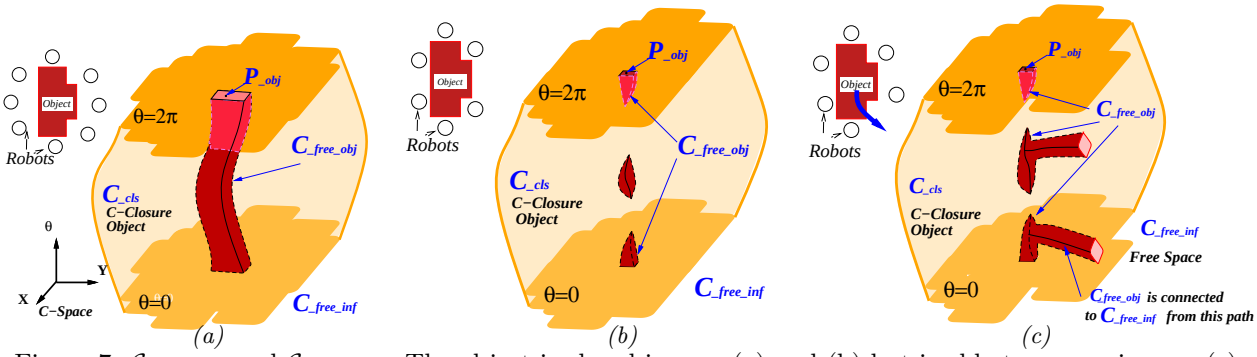


Figure 7: $\mathcal{C}_{free_obj}$ and $\mathcal{C}_{free_inf}$: The object is closed in case (a) and (b) but is able to escape in case (c).

the *Free Space* for the object. From the first assumption in Section 2, the following properties can be derived:

$$\mathcal{A}_i(\boldsymbol{p}) = \mathcal{A}_i(\boldsymbol{p}, \theta_i), \quad \mathcal{A}_i(\boldsymbol{p}) = \mathcal{A}_j(\boldsymbol{p}) \tag{11}$$

$$\mathcal{C}_{cls_i}(\boldsymbol{p}, \theta_i) = \mathcal{C}_{cls_j}(\boldsymbol{p}, \theta_i) \tag{12}$$

$$\mathcal{CC}_{cls_ij}(\boldsymbol{p}, \theta_i) = \mathcal{CC}_{cls_ik}(\boldsymbol{p}, \theta_i) \tag{13}$$

Here, $\theta_i \in [0, 2\pi)$ is any given orientation of the object, and $i, j, k = 1$ to n and $i \neq j$, $i \neq k$. Eq.12 and Eq.13 show that any $\mathcal{C}_{cls_i}$ and $\mathcal{CC}_{cls_ij}$ have the same shape and orientation with all other *C-Closure Object* and *CC-Closure Object* respectively while θ_i is the same.

4 Object Closure

The object and robots are in a condition of Object Closure if and only if there is no feasible path connecting the current object configuration to any point in $\mathcal{C}_{free_inf}$, a pre-defined subset of the C-space. In this paper, we will be concerned with the problem of keeping the position of the caged object contained but not the orientation. Thus we only consider Object Closure in R^2. Thus $\mathcal{C}_{free_inf}$ will have the structure of a generalized cylinder.

Let $\boldsymbol{q}_{obj} \notin \mathcal{C}_{cls}$ be a free initial configuration of the object and $\boldsymbol{q}_{inf}$ be the infinite point in $\mathcal{C}$. We define two sets $\mathcal{C}_{free_obj}$ and $\mathcal{C}_{free_inf}$ as follows:

$$\mathcal{C}_{free_obj} = \{\boldsymbol{q} \in \mathcal{C}_{free} | \ connected(\boldsymbol{q}, \boldsymbol{q}_{obj})\} \tag{14}$$

We will define $\boldsymbol{q}_{inf} \in \mathcal{C}_{free_inf}$ as a generic point that is sufficiently far away from the object. Then we have the following property:

$$(\mathcal{C}_{free_obj} \bigcup \mathcal{C}_{free_inf}) \subseteq \mathcal{C}_{free}. \tag{15}$$

An object can escape from robots only when the $\boldsymbol{q}_{obj}$ connects to the $\boldsymbol{q}_{inf}$ in C-space. Then *Object Closure* condition can be expressed as follow:

Proposition 1: *Let $\boldsymbol{q}_{obj}$ is the current configuration of the object. The object is in Object Closure iff the following conditions are satisfied.*

$$\begin{cases} \mathcal{C}_{free_obj} \neq \emptyset, \ \{\boldsymbol{q}_{obj}\} \\ \mathcal{C}_{free_obj} \bigcap \mathcal{C}_{free_inf} = \emptyset \end{cases}$$

The first condition guarantees the existence of an initial grasping or caging configuration and the second condition removes the case which $\mathcal{C}_{free_obj}$ only contains the point $\boldsymbol{q}_{obj}$, the object grasping case. The last one describes the Object Closure. When Object Closure is achieved, there is a bounded free space($\mathcal{C}_{free_obj}$) around the $\boldsymbol{q}_{obj}$, which is entirely kept inside of the $\mathcal{C}_{cls}$, as shown in Fig.7-a and Fig.7-b. On the other hand, Fig.7-c shows the case that there is a connection path between $\mathcal{C}_{free_obj}$ and $\mathcal{C}_{free_inf}$. In this case, the object is able to escape from robots' formation by this path.

As Fig.7 suggests, we must consider two cases of Object Closure. First, the free space around the $\boldsymbol{q}_{obj}$ is connected in the θ direction and the object can rotate while being completely contained (Fig.7-a). This case is an artifact of our loose definition of Object Closure, which emphasizes containment in R^2 and ignores orientations. The second case is shown in Fig.7-b. The free space $\mathcal{C}_{free_obj}$ only has limited range in the θ direction from $\boldsymbol{q}_{obj}$, and consists of disjointed subsets. We check the conditions for *Proposition 1* by taking slices in the configuration space. Following the definitions in Eq.14 , we define their slices along $\theta = \theta_0$ to be $\mathcal{C}_{free_obj}(\theta_0)$ and $\mathcal{C}_{free_inf}(\theta_0)$. The conditions for *Proposition 1* can now be expressed as follows:

Proposition 2: *Let θ_0 satisfy*

$$\begin{cases} \mathcal{C}_{free_obj}(\theta_0) \neq \emptyset, \ \{\boldsymbol{q}_{obj}\} \\ \mathcal{C}_{free_obj}(\theta_0) \bigcap \mathcal{C}_{free_inf}(\theta_0) = \emptyset. \end{cases}$$

The Object Closure condition is satisfied iff for a small $\Delta\theta$, if θ is replaced by $\theta_0 \pm i\Delta\theta$, $(i > 0)$

$$\begin{cases} \mathcal{C}_{free_obj}(\theta) \neq \emptyset & (Con.2 - A) \\ \mathcal{C}_{free_obj}(\theta) \bigcap \mathcal{C}_{free_inf}(\theta) = \emptyset & (Con.2 - B) \end{cases}$$

are satisfied. The conditions can be satisfied in two ways:

(1) *Con.2-A and Con.2-B are satisfied in all $\theta \in [0, 2\pi)$*

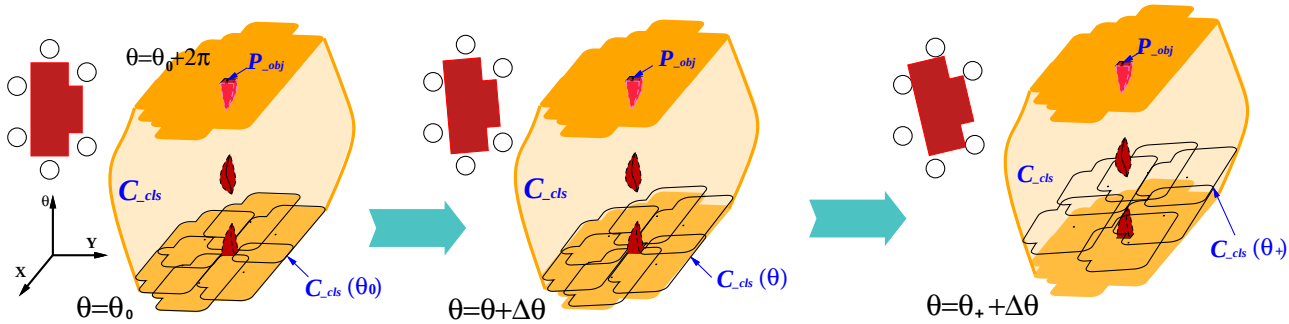


Figure 8: Test for *Object Closure* can be realized by checking conditions of Con.2-A and Con.2-B in each $\Delta\theta$ step on θ direction.

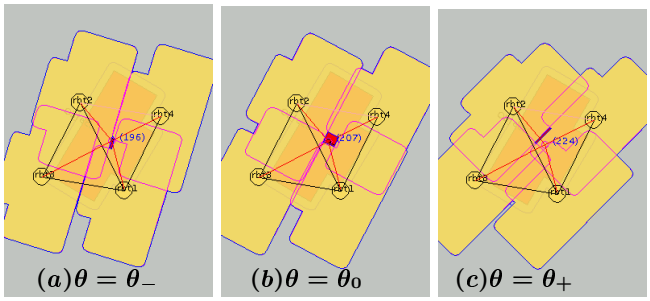


Figure 9: Boundaries of $\mathcal{C}_{free_obj}$ exist on θ direction.

(2) *There is a pair of θ_+ and θ_- so that conditions Con.2-A and Con.2-B are satisfied in all $\theta \in [\theta_+,\ \theta_-]$ and following conditions are satisfied.*

$$\begin{cases} \mathcal{C}_{free_obj}(\theta_+) \neq \emptyset, & \mathcal{C}_{free_obj}(\theta_+ + \Delta\theta) = \emptyset \\ \mathcal{C}_{free_obj}(\theta_-) \neq \emptyset, & \mathcal{C}_{free_obj}(\theta_- - \Delta\theta) = \emptyset \end{cases}$$

5 Efficient Test for Object Closure

Because the check for Object Closure must run in real time, the computation cost should be low. But calculations involved in computing $\mathcal{C}_{cls_i}$ and checking the condition in Proposition 1 directly are hard, especially when n is large and the shape of the object is complicated. We propose a new algorithm based on the results of Proposition 2. There are two basic steps: (A) checking existence of object's configuration which is out of the set of *C-Closure Object Region* $\mathcal{C}_{cls}$(Fig.9) and (B) checking each pair of neighboring *C-Closure Objects* intersect so that the *C-Closure Objects* divide the configuration space into two disjoint sets.

It turns out both (A) and (B) can be performed efficiently in a decentralized setting in which each robot uses information about the object geometry and the poses of the two nearest neighbors. Details are provided in a longer version of the paper at [25].

6 Simulation Results

A Simulation system is developed in Java2 package. The dynamics of the object and friction between object and supporting ground are implemented in the system. A compliance based contacting force model which includes friction and sliding model are introduced to simulate contacts between the robot and the object.

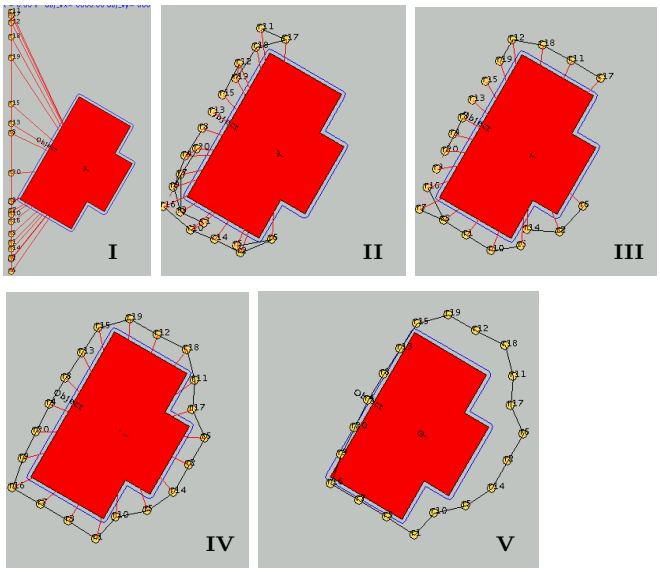


Figure 10: A simulation result of object closure by twenty robots. Since the number of robots is large, the object closure is constructed immediately without spinning robots around the object.

Fig.10 and Fig.11 show simulating results of the Object Closure by multiple mobile robots. In Fig.10, same controller which is based on the above mentioned algorithm is implemented in twenty robots. Without loosing generality, all robots are starting from random positions on the left side of the field. Because the number of robots is relatively large, the Object Closure is realized directly from approaching stage (IV), without the robots having to search around the perimeter. On the other hand, in the case which is shown in Fig.11, the four robots approach the object (II-III) and trap the object only for the current object orientation (IV). The search by moving around the perimeter eventually yields Object Closure (V). Finally the object is pushed

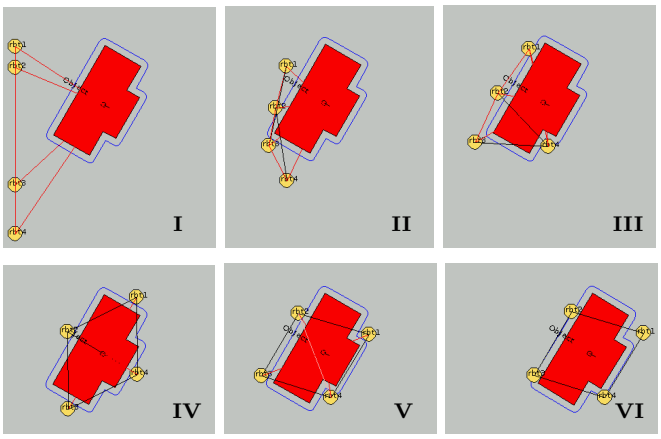


Figure 11: A simulation result of four robots' object closure which need to search inescapable arrangement by spinning robots team(IV, V).

on horizontal direction (VI) using a formation control strategy. Notice while centralized search algorithms can be guaranteed to yield Object Closure, our approach is decentralized approach and it is difficult to show completeness.

7 Conclusion

In this paper, we developed a novel approach to multi-robot manipulation based on the concept of Object Closure. This work inspired by the work of Rimon [15], Ponce [20] and others in caging, Lynch and Mason [8] in controlled pushing, and Parker [14], Donald and Rus [3], and Mataric [10]. While previous approaches have required form or force closure or variations on this theme, we use Object Closure, a condition where the object is trapped between the robots. We described algorithms for: (a) robot motion control that allow the robots to achieve and maintain object closure; and (b) testing for a condition of object closure. Our algorithms run in real-time on any browser with Java, with reasonably good performance. The main limitations are our inability to handle heterogeneous robots and the lack of guarantees on completeness of the Object Closure Test.

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