Design of Distributed End-effectors for Caging-Specialized Manipulator

(Design Concept and Development of Finger Component)

Rui Fukui, Keita Kadowaki, Yamato Niwa, Weiwei Wan,
Masamichi Shimosaka and Tomomasa Sato

Abstract In this paper, we propose a novel design of end-effectors that is specialized in caging manipulation. Caging manipulation has several advantages comparing with traditional grasping manipulation. For example, caging can allow small gap/margin between end-effectors and a target object, making the manipulator relieved from constant contact and precise control. Therefore, caging manipulator can avoid many problems from dynamics. Regardless of its advantages, intelligent caging manipulators have not be realized. This is because, for one thing, it may demand many actuators to realize flexible geometrical constraint (caging), for the other thing, kinematic constraints of a general purpose manipulator prevents us from applying direct caging approaches. We address this problem by introducing a novel design/framework of end-effectors that is inspired by ROBOTWORLD. The framework utilizes permanent magnet inductive traction method. The method is suitable for coexistence of multiple robots and for reduction of actuator number by sharing the same actuators. We discuss the concept and the basic framework of the proposed caging manipulator and development of a finger component prototype. After that we conduct basic experiments to evaluate the feasibility of caging manipulation and to reveal the obstacles (challenges) for our manipulator.

1 Introduction

Our research group aims to realize a manipulation robot in logistics as shown in Fig. 1. We are especially focusing on stable manipulation of packed objects. As an example of market products for logistical use, KIVA Systems Corp. developed an automatic object transfer robot system[3]. In that system, robots can manipulate stockers, but the item-level manipulation is executed by human workers. We would

Rui Fukui, Keita Kadowaki, Yamato Niwa, Weiwei Wan, Masamichi Shimosaka, Tomomasa Sato
The University of Tokyo, 7-3-1 Hongo Bunkyo-ku Tokyo Japan, e-mail: fukui@ics.t.u-tokyo.ac.jp

like to realize an item-level manipulation robot for logistical use. The right-below text area shows the target specifications of our manipulator.

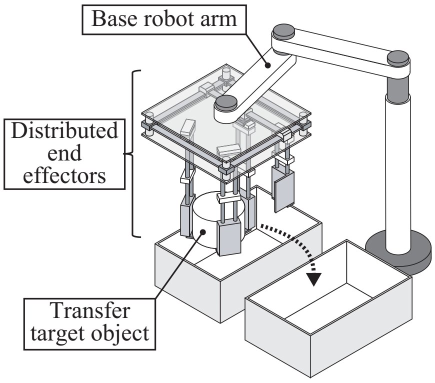


Fig. 1 Conceptual sketch of a caging manipulator in logistics applications.

- Target objects (Packed daily-use objects are assumed)
  - Shape : hexahedron family and cylinder family
  - Size : maximum is A4 size (210×297 [mm]), minimum is cylinder from 30 to 50 [mm] in diameter. [a]
  - Weight : less than 1 [kg]
- Entire weight : less than 5 [kg]
  ⇒The end-effectors are supposed to be installed on a general-purpose robot arm.
- Time to transfer an object : within 10 [s]

[a] The maximum size is determined by considering the previous work[4] and the minimum size assumes objects such as a PET bottle.

1.1 Related work

To realize stable object manipulation, there are two major problems. The first is difficulty in acquisition of a precise geometrical model for the target object, while the second is difficulty in precise recognition of the surface properties for the target object.

As for the first problem, thanks to the recent technology improvement of stereo cameras or depth imagers, it becomes feasible to acquire geometrical information from sensors and control a robot based on the acquired information[12]. However, they suffer from problems of eye direction and occlusion and cannot get full and precise information. To overcome the model insufficiency, some researchers compare the acquired information with data-base, and construct a manipulation strategy based on the limited information[5, 2, 1].

Regarding the second problem, in traditional robotic manipulation, ”Force Closure” is the basis of the manipulation, but the simplified model is too fragile to address practical problems. In contrast, some researches developed tactile contact sensors to realize human-like haptic sense[8, 6]. But the human haptic sense is so complex that it is still far from full imitation of the human capability.

Consequently we focus on more flexible manipulation framework ”Caging”[9, 7, 10]. As shown in Fig. 2, caging can constrain an object in its ”cage” geometrically. The caging condition can allow small gap between the robot hand and the object. That means the caging manipulation can escape from the force control. In addition, the caging condition is independent from the object’s surface properties.

1.2 Problem statement

If we develop an anthropomorphous caging hand as shown in Fig. 3, the number of actuators is **16**. Comparing with a simple gripper hand that needs only one actuator, 16 actuators are too redundant. Therefore, this paper discusses design of more sophisticated and concise framework for the caging manipulator.

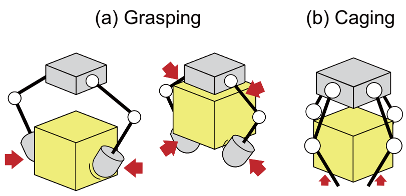


Fig. 2 Conceptual images of grasping and caging.

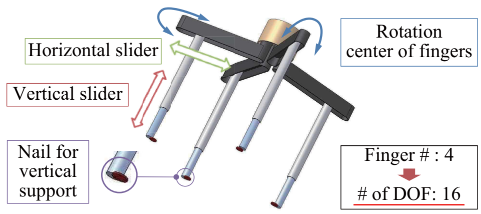


Fig. 3 Conceptual image of anthropomorphous caging hand.

2 Technical Approach and Basic Design

First of all, in the caging condition, constant contact between the end-effectors and an object is unnecessary. To utilize the advantage of its loose restriction, our manipulator surrounds the object gradually by moving constraint structures one by one. The basic idea of the framework is inspired by Robotworld[14]; where several robots work in the shared workspace. To realize a caging operation, following functions are required.

Function 1: To measure the position and shape of the target object.
Function 2: To plan the alignment of the constraint structures that leads to caging condition.
Function 3: To locomote the constraint structures one by one.
Function 4: To constrain the object in required directions.
Function 5: To transfer the object while keeping the caging condition.

It is effective to reduce the required number of actuators in Function 3 for a concise framework. To realize the reduction, permanent magnet inductive traction method [13] can be a powerful key technology. Fig. 4 shows the proposed framework. In the framework, each function is assigned to each component. We designate this framework as "distributed end-effectors". The end-effectors comprise following three components.

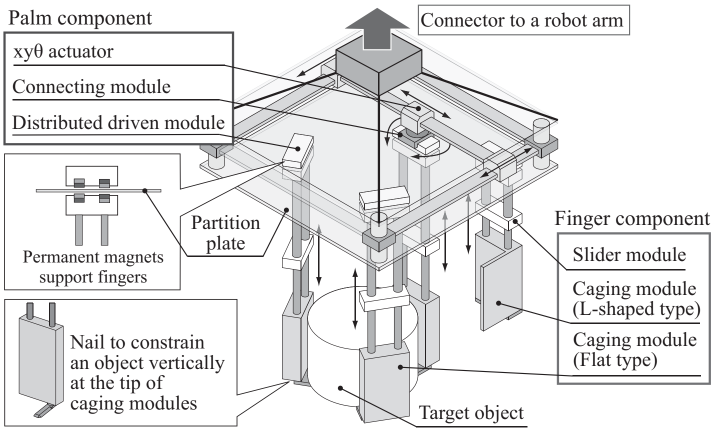


Fig. 4 Framework of the proposed end-effectors (caging manipulator).

(1) Sensing component

A depth imager (e.g. Microsoft Kinect, Swiss Ranger) and two dimensional code (2D-Code) reader are the main instruments of this component. They acquire the shape and position of target object.

(2) Palm component

This component consists of a $xy\theta$ actuator, distributed driven modules and a connecting module. The distributed driven modules support the finger components under the partition plate with permanent magnet pairs. The connecting module is installed at the motion part of the $xy\theta$ actuator, and it makes connection with the distributed driven module by inserting connection pins. The connecting module also drives the vertical motion of the slider module in the finger component. This palm component is the key part to save the number of required actuators.

(3) Finger component

This is the main component to constrain the target object. Horizontal constraint is realized by a body plate of the finger front. In contrast, vertical constraint is realized by a nail installed at the bottom of the component. When an object is too close to a neighbor object, another nail is inserted at the edge of the target object and the palm component pushes the object to make enough space for inserting the caging module (i.e. the distributed fingers) as shown in Fig. 5.

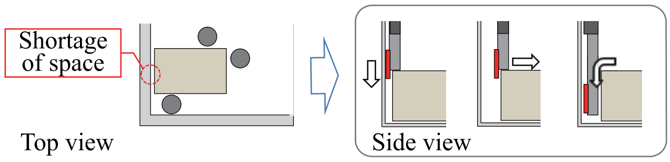


Fig. 5 Conceptual image of drag function.

Summary of the end-effectors' framework

We use names "palm" and "finger" to make it easy to understand the framework, however, the structure itself is quite different from human hand. Especially almost all motion axes are orthogonal to each other, therefore, it is very easy (intuitive) to design the finger alignment strategy. Fig. 6 shows the task flow. In this framework, the number of actuators is **nine** (one in each four fingers + five in the palm). This is drastically concise comparing with the anthropomorphous caging hand that has 16 actuators.

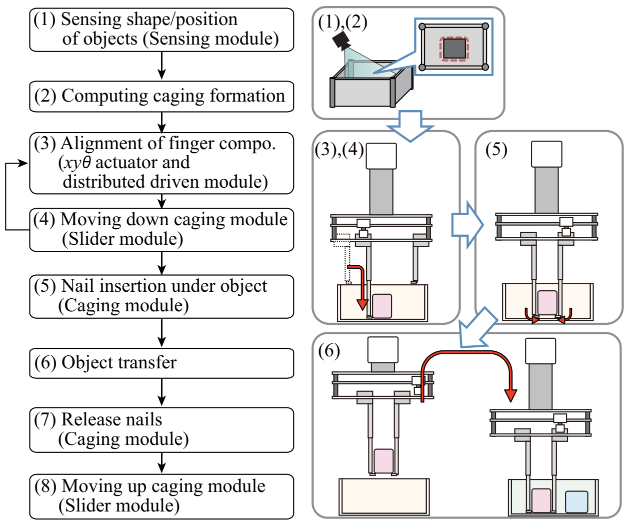


Fig. 6 Task flow of the caging manipulator.

3 Development of Finger Component Prototype

Fig. 7 shows the developed finger component. Its weight is 300 [g], and the thickness of the caging module is 10 [mm]. The caging module gives geometric constraint to a target object , and the slider module drives the caging module vertically.

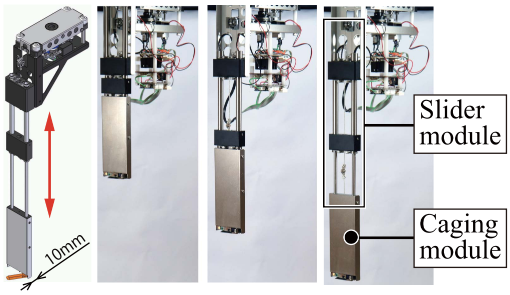


Fig. 7 The developed finger component.

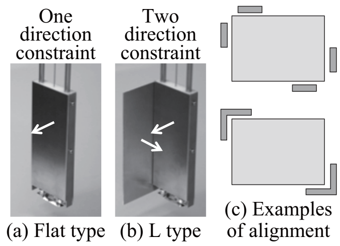


Fig. 8 Variations of caging module.

3.1 *Design details of the caging module*

The caging module has three functions; (a) To give horizontal geometric constraint, (b) To give vertical geometric constraint and (c) To drag the object horizontally.

The side body plate of the caging module realizes function (a). The plate has two variations as shown in Fig. 8. If the object is hexahedron family, it can be caged with two L type caging modules. Because the L type caging modules is equivalent to two flat type caging modules, but it is faster and easier to operate. A horizontal nail realizes function (b). The nail is installed at the bottom of the caging module and it is rotated and inserted under an object to support weight of the object. Function (c) is realized by inserting a thin nail between the wall of a box and an object (or between objects), and by dragging the object horizontally as shown in Fig. 5.

The most important design key point is how to actuate the two nails by one actuator. As shown in Fig. 9, the both nails are driven by gear transmission mechanisms. The center gear (b) has half non-toothed part, and the part makes it possible to select/switch a driving nail.

3.2 *Design details of the slider module*

The slider module realizes height control of the caging module. Generally speaking, precise height control is essential because the height of the caging module has a large effect to the nail insertion force. However, it is very difficult to detect precisely the bottom boundary of an object. That means precise vertical mechanisms such as lead screw and rack & pinion are useless.

The caging module hangs via a wire, and is driven vertically by winching the wire as shown in Fig. 10. The connecting module rotates a pulley to winch the wire via a magnet coupling. This crane mechanism needs a tensioner to keep the wire tension constant, and the tensioner can detect a contact with the floor or an object. The crane mechanism is suitable for making a coherent state between the caging module and the floor. Therefore, it does not need precise height control to align the nail at the boundary.

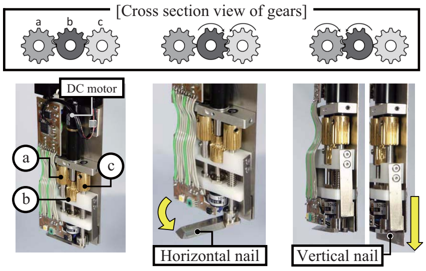


Fig. 9 Motion of horizontal and vertical nails.

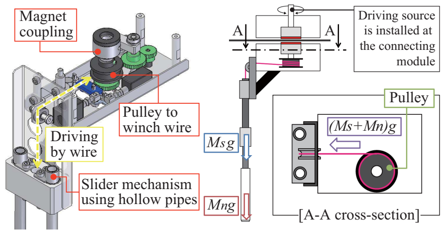


Fig. 10 The crane mechanism using wire and magnet coupling

4 Experiments

4.1 Feasibility test of caging manipulation

Fig. 11 shows the experimental test bench to evaluate the feasibility of caging manipulation. The test bench can imitate a vertical pick-up motion (One DOF) of a robot arm that is equipped with the distributed end-effectors. As a driving source of the distributed driven modules, a manual $xy\theta$ table was implemented. One developed finger component and two dummy fingers are used for constraining an object. The dummy finger has the same dimension (size) and hangs under the partition plate with permanent magnets. But it is not installed with the actuators and sensors, therefore, the dummy finger needs to be actuated by human hands.

Eight kinds of daily-use objects are selected as manipulation target objects. Fingers' alignment is designed empirically as shown in Fig. 12. As a basic idea, formation (a) is applied for cylinder shape, formation (b) for general hexahedron and formation (c) is applied for hexahedron with high aspect ratio (thin box). In the future, we will use the our developed algorithm [16] to realize automatic planning.

The experimental procedure is as follows; (1) To align the finger component and dummy fingers around the object, (2) To control the height of slider module and insert the horizontal nail under the object, (3) To brake the slider and simulate the arm vertical motion, (4) To check the robustness of the caging by applying external force from the outside of the cage. By executing this experiment, it was confirmed that all eight objects can be caged and resist against external force even if there are 5 [mm] margins between the caging module and the object. Fig. 13 shows the experimental results.

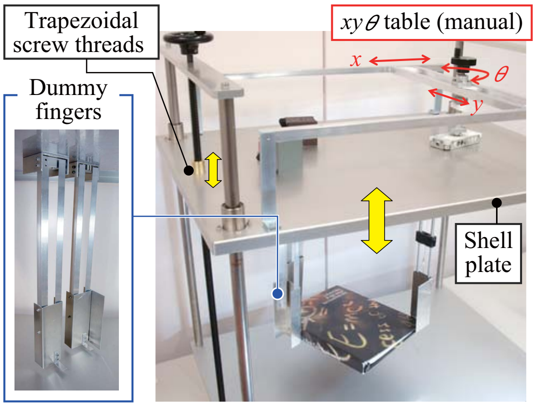


Fig. 11 Experimental environment.

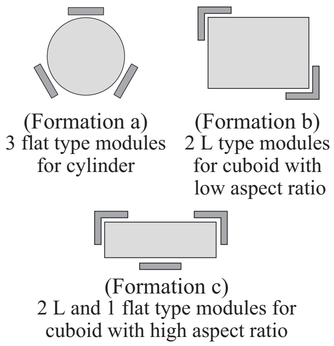


Fig. 12 Caging formations.

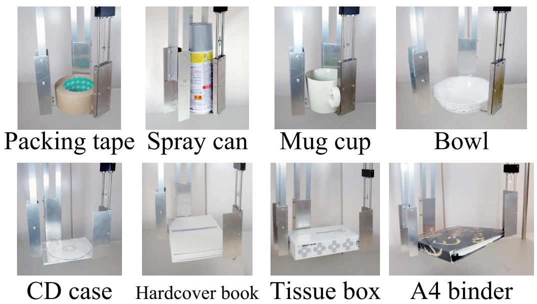


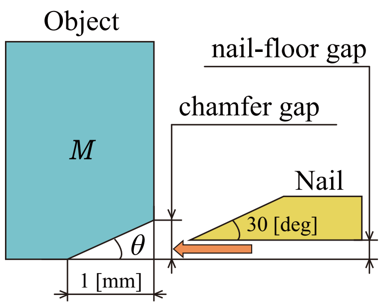
Fig. 13 Experimental results (Snapshots of constrained target objects).

4.2 *Performance experiment of horizontal nail insertion*

The horizontal nail insertion is the most uncertain process in the task flow. We evaluated its performance by experiments. Fig. 14(a) shows the experimental setup where θ is the angle of chamfer and M is the object mass. Chamfered distance is fixed at 1 [mm], meanwhile the angle of chamfer is varied. The horizontal nail is actuated by a DC motor. Each configuration is examined five trials, and each success rate is counted.

Fig. 14(b, c, d) is the results of the nail insertion when the object mass (M) is 100 [g], 500 [g], and 1 [kg] respectively. In the table, each box is painted in deep orange where the nail insertion succeeded in all five trials, in light orange where it succeeded from one to four trials, and white where all trials failed.

A gap made by chamfer (chamfer gap) is the allowable limit of nail-floor gap to insert the nail. Blue lines (insertion limit line) are boundary lines between an area where the nail-floor gap is smaller/larger than the chamfer gap. In Fig. 14(b), the nail was inserted over insertion limit line, and this is because the object was lift up by the insertion force. In Fig. 14(c), the insertion limit line has enormous



(a) Experimental setup of nail insertion

θ [deg] \ nail-floor gap [mm]	0	0.1	0.2	0.3	0.4	0.5
0	5/5	0/5	0/5	0/5	0/5	0/5
10	5/5	5/5	5/5	5/5	5/5	1/5
20	5/5	5/5	5/5	5/5	5/5	5/5
30	5/5	5/5	5/5	5/5	5/5	5/5
40	5/5	5/5	5/5	5/5	5/5	5/5
50	5/5	5/5	5/5	5/5	5/5	5/5
60	5/5	5/5	5/5	5/5	5/5	5/5
70	5/5	5/5	5/5	5/5	5/5	5/5
80	5/5	5/5	5/5	5/5	5/5	5/5

(b) Success number of times (M=100 [g])

insertion limit line

θ [deg] \ nail-floor gap [mm]	0	0.1	0.2	0.3	0.4	0.5
0	0/5	0/5	0/5	0/5	0/5	0/5
10	5/5	4/5	3/5	0/5	0/5	0/5
20	5/5	5/5	3/5	2/5	0/5	0/5
30	5/5	5/5	5/5	2/5	0/5	0/5
40	5/5	5/5	5/5	5/5	5/5	5/5
50	5/5	5/5	5/5	5/5	5/5	5/5
60	5/5	5/5	5/5	4/5	2/5	2/5
70	5/5	5/5	4/5	2/5	1/5	0/5
80	0/5	0/5	0/5	0/5	0/5	0/5

(c) Success number of times (M=500 [g])

θ [deg] \ nail-floor gap [mm]	0	0.1	0.2	0.3	0.4	0.5
0	0/5	0/5	0/5	0/5	0/5	0/5
10	0/5	0/5	0/5	0/5	0/5	0/5
20	0/5	0/5	0/5	0/5	0/5	0/5
30	0/5	0/5	0/5	0/5	0/5	0/5
40	0/5	0/5	0/5	0/5	0/5	0/5
50	0/5	0/5	0/5	0/5	0/5	0/5
60	0/5	0/5	0/5	0/5	0/5	0/5
70	0/5	0/5	0/5	0/5	0/5	0/5
80	0/5	0/5	0/5	0/5	0/5	0/5

(d) Success number of times (M=1 [kg])

Fig. 14 Results of the horizontal nail insertion experiment.

influence, and the nail insertion becomes impossible outside of it. In addition, the angle of chamfer (θ) also has influence on the nail insertion, and its influence is remarkable when the nail-floor gap is large. Smaller nail-floor gap makes it easier to insert the nail especially when θ is between 10 [deg] and 70 [deg]. Unfortunately, the nail insertion under the 1 [kg] object was impossible, although the motor has theoretically sufficient power to insert the nail.

5 Conclusion

Thorough this work, we have two main experimental insights as following.

(1) What are OBSTACLES for our caging manipulator?

Through the development and experiments, we have found four obstacles for our manipulator.

(1) Size/Dimension of the horizontal nail in the caging module
(2) Stiffness of the slider module and the partition plate
(3) Three dimensional rotation of the target object with high aspect ratio
(4) Too small gap or chamfer between the target object and the floor

(1) Size/Dimension of the horizontal nail : The horizontal nails are important parts to support weight of the target object. However the size is restricted by the thickness and width of the caging module. In addition, the size of the horizontal nail has large relation to the allowable margin/gap between the caging module and the target object. Consequently in the experiment A, we needed more number of fingers comparing with initial intuition. That is, we used three finger components to constrain the objects with high aspect ratio.

(2) Stiffness of the slider module and the partition plate : When inserting the horizontal nail under the target object or lifting up the object, vertical force is applied to the tip of caging module. To reduce the unintended deformation of the caging module, not only the slider module but also the partition plate should be stiff enough. This is because the bend of the partition plate can induce the misalignment of the caging module. In current condition, we selected aluminum plate for the partition, but in the next prototype we will try more stiff material such as non-magnetic stainless steel.

(3) Three dimensional rotation of the target object : In the feasibility experiment, two L type caging modules and one flat type caging module are necessary to cage an object with high aspect ratio. If we use only two L type caging modules, the end-effectors need to support the vertical force (weight) at the opposing corners. However in this condition, the object rotates in the axis of the diagonal line. Consequently we need to introduce a sensing process and a finger alignment algorithm that is suitable for manipulating an object with high aspect ratio. Or we can introduce the

”grasping by caging”[11, 15] technology to build a loose-contact-based grasping by starting from contact free caging.

(4) Too small gap or chamfer : The horizontal nail insertion is the only process that needs to consider the effect of friction. In the experimental result (Fig. 14(d)), it is found that the motor requires more power than expected. There is tiny round part at the tip of the horizontal nail, consequently the round part may collide with the chamfer at the bottom of the target object. To overcome the problem, we need to execute more experiments and estimate the uncertain effect of the friction between the nail and target object.

(2) Advantages and disadvantages of caging manipulation

Table 1 summarizes the advantages and disadvantages of our proposed caging manipulator compared with the traditional grasping manipulator. The grasping approach has a large advantage in its versatility, hence many researchers adopt this strategy. In contrast, the caging manipulator doesn’t need force control and it is robust against the surface properties of the target object. Unfortunately a caging manipulator may not be good at operation of a soft and deformable object. Human-like robot hand has a large potential to realize versatile manipulation, in contrast, the proposed caging manipulator is promising to perform stable object manipulation that cannot be realized by human-like robot hand.

Table 1 Summary of qualitative comparison in grasping and caging manipulators.

Approach	Grasping (Force Closure)	Caging
Principle	Force constraint by grasping force or frictional force	Geometrical constraint by Caging
Advantages	•Can control object posture inside the hand •Can be realized with small number of actuators only for power grasp (e.g. 1 DOF gripper) •Possible to manipulate soft/deformable objects	•Allow substantial error of a geometrical object model •Needless of constant contacts between end-effectors and an object •Needless of force control •Can manipulate a solid object regardless of its surface properties •Wide range of the manipulation target size (Large object) •Concise structures compared with anthropomorphic robot hands
Disadvantages	•Allow little error of a geometrical object model •Need sophisticated force control to realize constant contact •Difficult to configure optimal internal force •Difficult to evaluate manipulation stability in its operation	•Impossible to control its posture inside the hand •Difficult to manipulate soft/deformable objects •Need to prepare multiple structures to realize a solid cage •Complex structures compared with 1 DOF gripper

References

1. Bohg, J., et al.: Mind the gap - robotic grasping under incomplete observation. In: Proceedings of IEEE International Conference on Robotics and Automation, pp. 686–693 (2011)
2. Brook, P., et al.: Collaborative grasp planning with multiple object representation. In: Proceedings of IEEE International Conference on Robotics and Automation, pp. 2851–2858 (2011)
3. D'Andrea, R., et al.: Future challenges of coordinating hundreds of autonomous vehicles in distribution facilities. In: Proceedings of IEEE International Conference on Technologies for Practical Robot Applications, pp. 80–83 (2008)
4. Fukui, R., Mori, T., Sato, T.: Home-use object transfer/storage robot system with compliant strategy and mechanism (commodities management and its extended application of daily life support for the elderly). Journal of Robotics and Mechatronics **23**(4), 532–543 (2011)
5. Goldfeder, C., et al.: The Columbia grasp database. In: Proceedings of IEEE International Conference on Robotics and Automation, pp. 1710 –1716 (2009)
6. Hasegawa, H., et al.: Robot hand whose fingertip covered with net-shaped proximity sensor /-moving object tracking using proximity sensing-. Journal of Robotics and Mechatronics **23**(3), 328–337 (2011)
7. Makita, S., et al.: 3D multi-fingered caging: Basic formulation and planning. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 2697–2702 (2008)
8. Noda, K., et al.: A shear stress sensor for tactile sensing with the piezoresistive cantilever standing in elastic material. Sensors and Actuators A **127**(2), 295–301 (2006)
9. Pereira, G.A.S., Campos, M.F.M., Kumar, V.: Decentralized algorithms for multi-robot manipulation via caging. International Journal of Robotics Research **23**, 783–795 (2004)
10. Rodriguez, A., Mason, M., Ferry, S.: From caging to grasping. In: Proceedings of Robotics: Science and Systems (2011)
11. Rodriguez, A., Mason, M.T., Ferry, S.: From caging to grasping. International Journal of Robotics Research (2012. (To appear))
12. Rusu, R.B., et al.: 3D is here: Point cloud library (PCL). In: Proceedings of IEEE International Conference on Robotics and Automation, pp. 6500–6503 (2011)
13. Sato, T., Fukui, R., Morishita, H., Mori, T.: Construction of ceiling adsorbed mobile robots platform utilizing permanent magnet inductive traction method. In: Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 552–558 (2004)
14. Scheinman, V.: Robotworld: A multiple robot vision guided assembly system. In: Proceedings of the 4th International Symposium on Robotics Research (1987)
15. Wan, W., Fukui, R., Shimosaka, M., Sato, T., Kuniyoshi, Y.: Grasping by caging: A promising tool to deal with uncertainty. In: Proceedings of IEEE International Conference on Robotics and Automation, pp. 5142–5149 (2012)
16. Wan, W., Fukui, R., Shimosaka, M., Sato, T., Kuniyoshi, Y.: On the caging region of a third finger with object boundary clouds and two given contact positions. In: Proceedings of IEEE International Conference on Robotics and Automation, pp. 4154–4161 (2012)