Robotica (1997) volume 15, pp 693–700. Printed in the United Kingdom © 1997 Cambridge University Press

A reliable parts-picking system with an active and multi-sensor visual system

Nobuhiro Okada,* Tadashi Nagata,† and Tsutomu Hasegawa‡

(Received in Final Form: March 27, 1997)

SUMMARY

We constructed a high reliability parts-picking device with an active and multi-sensor visual system, that picks up a part from randomly stacked parts. The system determines the orders in which to pick up the parts. To determine the order, we introduce concepts of risks of collapsing a stack by picking, and the ease of manipulator operations. The system examines if the risks exist and estimates the ease. We show that the parts-picking system can achieve high reliability by determining the orders, using the effects of the examination and the estimation. We also give some experimental results.

KEYWORDS: Visual system; Multi-sensor; Parts-picking; Manipulators.

1 INTRODUCTION

Many industrial robots have been introduced into factories. Many of them are only playback types that can perform programmed operations. Nowadays, such programming becomes tedious for human operators. Thus, robots that can perform tasks autonomously are greatly required.

As an example of a task that can not be performed by playback type robot, we choose parts-picking tasks. In a parts-picking task, a robot picks up a part from a bin or a belt-convey. Since parts are randomly stacked in or on them, a play-back type robot that does not have the ability to cope with their random positions cannot pick them up.

To have the ability to operate autonomously and to be used in parts-picking tasks, robots must have sensors to obtain information about their environment and operation targets. Tella et al. used a vacuum gripper with tactile sensors to detect the normal vectors of the top surface of the part, as well as a vision sensor, and achieved parts-picking.[1] However, in general, tactile sensing has a lower resolution and takes longer than visual sensing. Furthermore, tactile sensing may collapse a parts stack by touching it. In contrast to tactile sensors, visual sensors can obtain information rapidly without touching. Fukada et al. used a monocular camera to recognize cylindrical parts in a bin.[2] Since the system used only one camera, the 3-dimensional information gained about the locations of the parts was insufficient. Ikeuchi et al. used a visual sensor consisting of a photometric stereo system and a binocular stereo system, and models constructed in a computer to know the location and the orientation of the target.[3] Al-Hujazi et al. used range information obtained by a range finder to obtain the normal vector of the top surface of the target.[4] Although they[2–4] used some visual sensors that can obtain 3-dimensional information of targets, systems that process 3-dimensional information from such sensors will take a long time to do it. Kawai et al. combined gray image and a parse range image to shorten the time required to obtain 3-dimensional information about parts.[5] As mentioned above, many attempts have been made to accomplish correct and rapid measurements. We also constructed an active and multi-sensor visual system for parts-picking operations that efficiently obtains 3-dimensional information about parts.[6–9]

Furthermore, studies to realize reliable parts-picking operations have also been made. Baerveldt prevented collisions between fingers of a manipulator and parts using an optical range sensor fitted on the fingers.[10] However, the system could not know if a collision might occur before operations. Yanagihara et al. estimated the manipulability which was defined as how much space exists around the part to prevent such collisions.[11] However, cases where parts were stacked 3-dimensionally were not sufficiently considered in it.

Thus, the aim of this paper is to achieve high reliability of parts-picking operations using our active multisensor visual system.

Firstly, we define a high reliability parts-picking operation. Here, we define it as an operation that causes no damage to the parts or the manipulator. As examples of causes of damage to parts, the following may be given:

(i) Dropping of parts due to incomplete grasping.
(ii) Collapse of a stack of parts due to operation of the manipulator.

* Dept. of Intelligent Machinery and Systems, Faculty of Engineering, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka, 812-81 (Japan) e-mail: okada@mech.kyushu-u.ac.jp.
† Institute of Systems & Information Technology/KYUSHU, 2-1-22 Momochihama, Sawara-ku Fukuoka, 814 (JAPAN) e-mail: nagata@k-isit.or.jp.
‡ Dep. of Intelligent Systems, Graduate School of Information Science and Electrical Engineering, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka, 812-81 (JAPAN) e-mail: hasegawa@irvs.is.kyushu-u.ac.jp.

https://doi.org/10.1017/S0263574797000817 Published online by Cambridge University Press

And a cause of damage to both parts and manipulator.
(iii) Collision between the parts and the manipulator

The first situation may occur when information about the location and alignment of parts obtained by a sensor or actions of the manipulator is incorrect. It can be avoided by improving their accuracy. In this paper, we describe a system that can prevent situations (ii) and (iii) above.

A collapse of parts stack such as (ii) will alter the locations of parts in a wide area. In parts-picking operations, if such a collapse does not occur, the area around the part which has been picked up is the only area where changes are involved. Therefore, a sensor system can learn the new status of parts by merely investigating the area around the part which has been picked, provided collapses of the stack do not occur. If collapses occur, however, the sensor system has to re-examine the whole stack every time, and the overall performance will be lowered. Additionally, a collision between parts and a manipulator as in (iii) necessitates various error recoveries, and will also degrade the performance. To construct a system that can prevent situations such as (ii) and (iii) is, then, to build a system that achieves a higher performance.

As an example of a case where a collapse happens, we direct our attention to the situation where a manipulator picks a part which is supporting another part. We make the system check whether a part supports another, i.e. if the *risk* of collapse exists, using information obtained by the visual system. We also introduce a concept of the *ease* of picking, which means the probability of the collision between parts and a manipulator. The visual system estimates it to prevent the collision. By ordering the parts to be picked in a sequence, using the results of the check and the estimation, the parts-picking system can perform reliable and efficient operations.

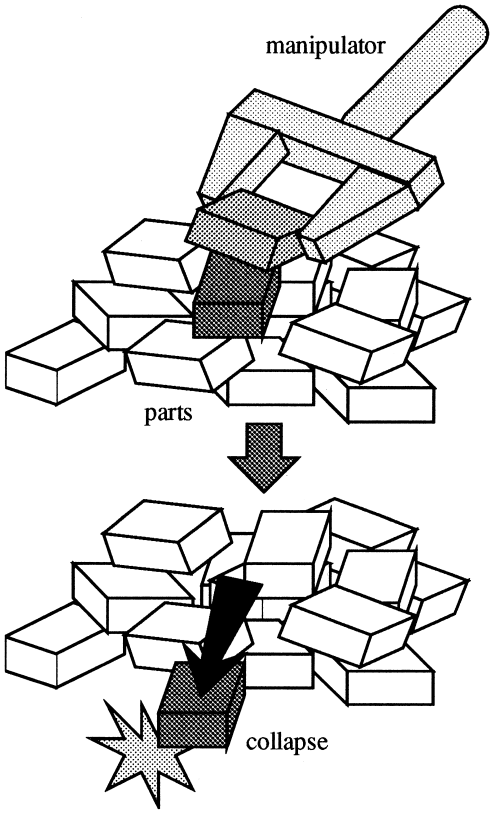


Fig. 1. A collapse of a stack by parts-picking.

2 DETERMINATION OF THE ORDER OF PARTS-PICKING

We believe that a part which can be safely picked up from randomly stacked parts by a manipulator should satisfy the following:[9] It should be on top of other parts and not under other parts, or be isolated from other parts. However, the condition is derived by examining whether it can be picked up by paying attention to only the part itself. We believe that the system should determine if the part can safely be picked up and decide the order of picking, taking note of the area around the part for the following reasons:

There have been cases where a collapse of a parts stack was caused by the parts-picking operation. They are the cases where the picked parts were supporting others, or the cases where the picked parts were holding others as counterweights (see Figure 1). Furthermore, collapses will change the status of a parts stack over a broad area.

Additionally, collisions between parts and a manipulator may damage both of them and collapse the parts stack (see Figure 2). The collision may change the trajectory of the manipulator and move the part to be picked up, and make the operation result in a failure.

So, the system has to determine the order of parts-picking before operations by the examination of the risk of breaking down the stack by picking, and by the estimation of the ease of picking. By determining a sequence in this way, we believe that the probability of the above situations will be reduced. We can also expect that a part that carries a risk or low ease will reduce the risk or higher ease after another part has been picked.

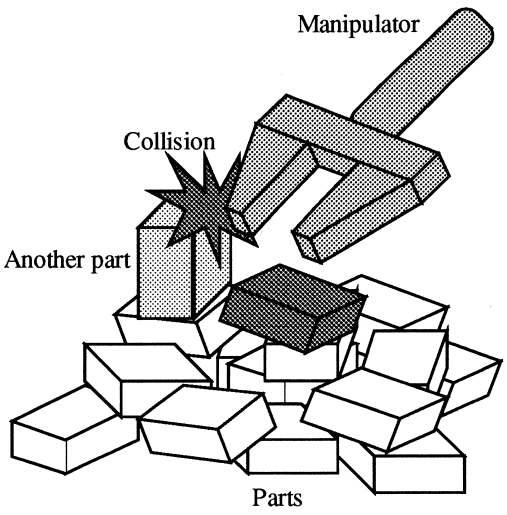


Fig. 2. Collision between a manipulator and another part.

https://doi.org/10.1017/S0263574797000817 Published online by Cambridge University Press

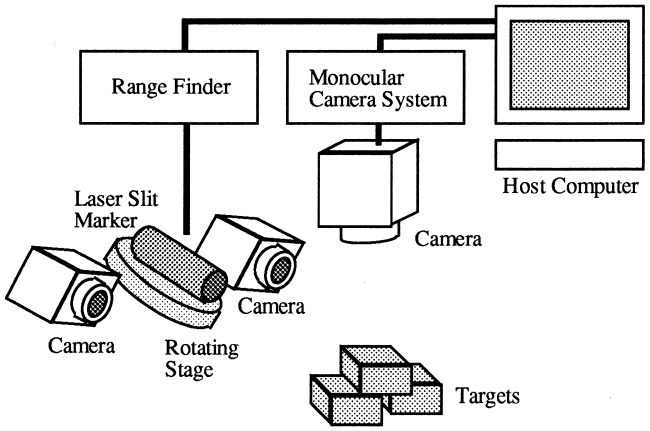


Fig. 3. The outline of the active and multisensor visual system.

3 AN ACTIVE AND MULTI-SENSOR VISUAL SYSTEM

The outline of our active and multi-sensor visual system is shown in Figure 3. We used it as the sensor system for our parts-picking system.[6–9,12]

The visual system consists of a range finder and a monocular camera system. The range finder was fabricated in our laboratory. It has two CCD cameras and a laser slit marker. It is a binocular stereo system and resolves the stereo matching problem by illuminating targets with the laser slit. It measures the 3-dimensional positions of points in realtime, and has about 1.5[mm] resolution for the depth value in our experimental environment. The monocular camera system uses a CCD camera and processes gray images obtained from it. It can process gray images quickly using a image processor (nexus nexus600). The range finder sees the parts obliquely, and the monocular camera system sees them from above.

Each of the visual sensors adjusts its behavior using information from the other to improve performance. Thus, they compose an active and multi-sensor visual system.

4 PROCESSES TO DETERMINE THE ORDER

We will now discuss how processes for the examination of risk, the estimation of ease, and planning to determine the order are performed.

4.1 Examination of the risk of collapse

There are some cases where picking a part up from randomly stacked parts collapses the stack. Some of them are situations where the part to be picked up supports or holds another by its weight. These cases are illustrated in Figure 4. In the figures, part 'A' supports or presses part 'B'. Figure 5 shows the cases that are similar to the cases shown in Figure 4 but differ from them because picking 'A' will not affect 'B'. Here, we exclude the cases where several parts support one part.

Birnbaum et al. checked whether a parts stack is stable using a visual system and physical constraints.[13] However, the method could only be applied into situations where all parts are visible to the visual sensor,

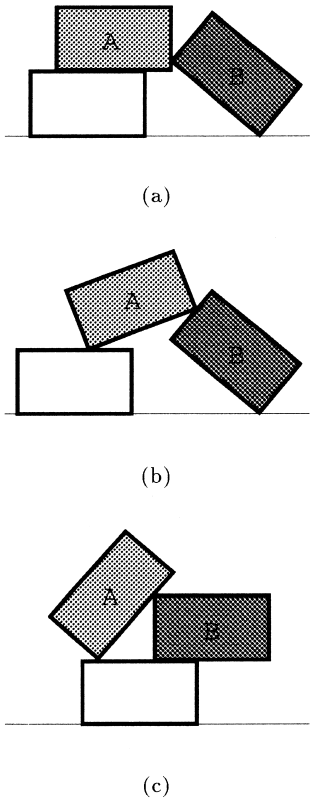


Fig. 4. Cases where parts-picking a part will collapse the stack.

and could not be adapted to cases where occlusions occurs. Although Schmult constructed a system that disassembles blocks (*Duplo Structures*) keeping them stable,[14] the system also had to be previously given status of all parts. Among situations where collapses occur, cases where parts to be picked up are supporting others cannot be previously detected without knowing the status of all parts. It is almost impossible to know them using visual sensors that see parts only from outside. Therefore, it cannot wholly be known if picking a part will collapse the stack when it holds another.

In this paper, our purpose is to detect the risk of collapse for only the case where a part supports another. In contrast to Birnbaum et al. and Schmult, the system is able to check the risk of performing tasks while occlusions reside, though the system cannot correctly know whether or not the stack is stable.

We define the situation where a part supports another as follows: Here, we use rectangular solids whose sizes are roughly known as parts. As shown in Figure 6, if part 'B' is in contact with a side of part 'A' which is to be picked up, and if the distance between the fulcrum of 'B' (the contact point of 'B' and its base) and the contact point is shorter than the distance between the mass center of 'B' and the contact point measured in the **x**–**y** plane, we say that part 'A' supports part 'B'. Figure 6 illustrates a side view, and bold lines in the figure illustrates the areas which are visible to the visual system.

To examine the conditions, the visual system finds part 'B' as a part that contacts part A (the part to be picked up). It measures the top surfaces of the parts, and finds the centers of the surfaces $m_a, m_b,$ and the normal

https://doi.org/10.1017/S0263574797000817 Published online by Cambridge University Press

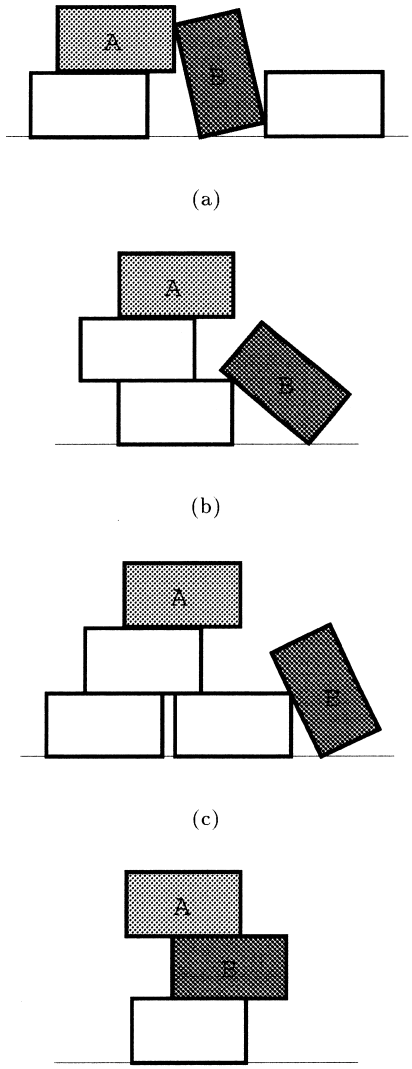


Fig. 5. Cases where parts-picking a part will not pull down the stack.

vectors of them $\vec{n}_a$, $\vec{n}_b$, then finds the point nearest to m_a in the top surface of 'B' as the contact point c_b. It also calculates the mass center of 'B' m_b', and its fulcrum c_b' using m_b, c_b, $\vec{n}_b$ and the given size of the part. Then, the system determines that part 'A' supports part 'B' or a risk exists when the following conditions are met:

(i) c_b is under m_a in the direction of $\vec{n}_a$
(ii) c_b is above the bottom surface of 'A' in the direction of $\vec{n}_a$
(iii) the distance between c_b and m_b' is shorter than the distance between c_b and c_b' in the **x**–**y** plane

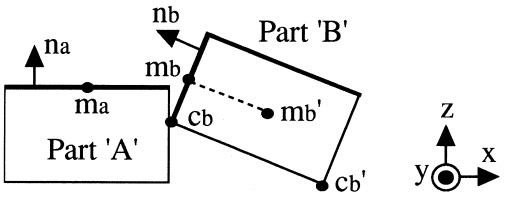


Fig. 6. Definition of a case where a part supports another.

When part 'A' hides a portion of the top surface of part 'B' the system cannot find the correct locations of m_b' and c_b' (see Figure 7). In such cases, the system will need to know them by using, for instance, higher level model matching.

4.2 Estimation of the ease of picking

In paragraph 4.1, we divide parts into two groups: Parts that can be picked up by a manipulator, and parts that cannot be, by paying attention to the risk of collapsing the parts stack by picking. It is usual, however, that more than one part that can be picked up exists. Hence, it is necessary to determine the picking order among them.

As a standard to determine the order, we use the ease of measuring for the visual system.[15] Since the range finder sees parts obliquely in our active and multi-sensor visual system, it may happen that the range finder is affected by occlusions and cannot adequately measure parts. In such a case, errors of measurements can grow and cause manipulation errors. So, the system gives higher priority to parts that can be easily measured by the range finder. We could also expect that parts that had lower ease of measuring would become less awkward after picking the parts that had the higher ease. However, collisions between parts and a manipulator were not to be taken into consideration. Baerveldt checked whether such a collision occurs using optical range sensors attached to fingers of a manipulator.[10] However, the system could not know if collisions would occur before operations. Though Yanagihara et al. used the manipulability of manipulator operations to determine the picking order,[11] and used the estimation of how the part is isolated from others (isolation factor) as the manipulatibility, such considerations for 3-dimensionally stacked parts were not enough.

We adopt the ease of manipulation as a standard to determine the order of picking,[9,12] in this paper. We define how much free space for fingers of a manipulator exists around the part as the ease of manipulation. The visual system estimates it to examine if collisions between parts and fingers may occur. Since a manipulator approaches the part along the direction of the normal vector of the top surface of it in our partspicking system, the system introduces a weight along the direction into the estimation, and estimates the ease 3-dimensionally.

The process to estimate the ease of picking and to determine the order of picking is shown as follows:

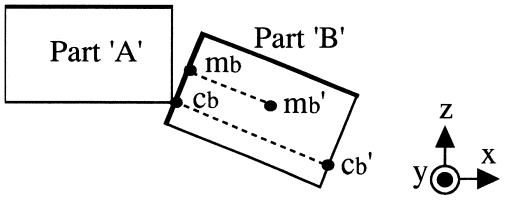


Fig. 7. A case where a system cannot know the correct m_b' and c_b'.

https://doi.org/10.1017/S0263574797000817 Published online by Cambridge University Press

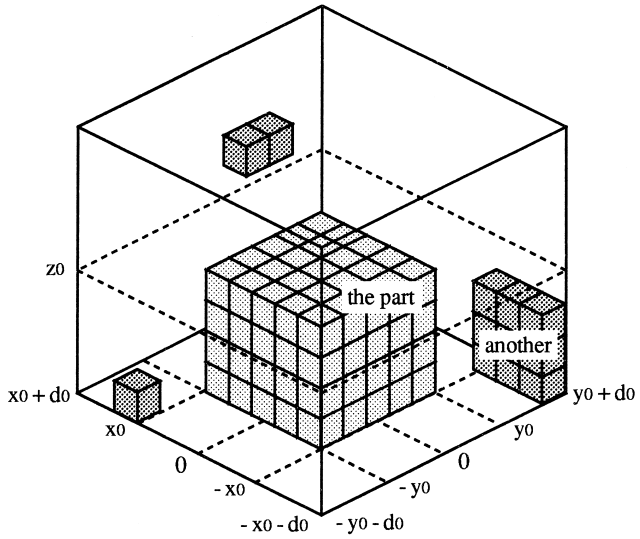


Fig. 8. Voxel data for an esitmation of the ease of picking.

After measurements, the active and multi-sensor visual system acquires the positions of the top surfaces of the parts that can be picked up, the normal vectors of the surfaces, and range data around the parts.[6–9] The system estimates the ease of each part using them.

At first, the system calculates the transformation that transforms the center of the top surface into the origin, the normal vector of it into the **z** axis, and the vector of a line segment of it into the **x** axis. Then the system transforms the range data, and changes them into voxel* form (see Figure 8).

The system performs the estimation in the area:

$$-x_0 - d_0 < x < x_0 + d_0$$
$$-y_0 - d_0 < y < y_0 + d_0$$

where (x_0, y_0) is the position of a corner of the top surface rectangular after the transformation ($x_0 > 0$, $y_0 > 0$), and d_0 is the value that defines the size of an area to be estimated. For each (x, y) in the area, except for the area of the top surface:

$$\begin{cases} -x_0 < x < x_0 \\ -y_0 < y < y_0 \end{cases}$$

the system searches a voxel from higher z. If a voxel is found, the system obtains the distance between the voxel and the part in the **x**–**y** plane d, and the height of the voxel in the direction of the normal vector of the top surface z, and then calculates the evaluation function $e_{(z,d)}$ for the voxel. The evaluation function $e_{(z,d)}$ is defined as follows: Since there must be space for fingers of the manipulator into account, we define it as

$$e_{(z,d)} = \frac{z}{d_1} \cdots (z < -g) \tag{1}$$

$$e_{(z,d)} = \frac{w(z+g) - g}{d_1} \cdots (z \geq -g) \tag{2}$$

* Voxel denotes a volume cell that quantizes a 3-dimensional volume into cubics, while a pixel refers to a picture cell that quantizes a 2-dimensional picture into squares.

for $d < d_1$, and define it as

$$e_{(z,d)} = \frac{z}{d} \tag{3}$$

for others, where d_1 and g are the tolerances for fingers in lateral and vertical directions respectively, and w is a weight ($w > 1$). By the definitions, the value of $e_{(z,d)}$ becomes large if the voxel is near the part and if the height of the voxel is high. Then the system calculates the ease of picking E as the sum of $e_{(z,d)}$,

$$E = \frac{\sum e_{(z,d)}}{n} \tag{4}$$

where n is the number of found voxels. We also define the validity of the ease V using the number of positions where the system could not find voxels m, as

$$V = \frac{n}{n+m} \tag{5}$$

If a near and tall part exists around the part to be picked up, then, the value of E becomes large. Therefore we can determine the order of picking in the order of small E. When some parts have the same E, the system gives the part that has a larger V a higher order.

Many studies have been done to correctly examine whether collisions occur.[16–18] Though our approach does not correctly check it, it can obtain estimates to determine the picking order easily because they use only simple calculations.

4.3 Planning to determine the picking order

The total process to determine the picking order by our active and multisensor visual system is shown in Figure 9.

At first, the visual system searches for free parts, i.e. parts that are not under other parts or parts that are isolated from others, using the monocular camera system, and measures range data around the parts using the range finder.[6–8] Next, the system checks the risk of collapsing the parts stack by picking, and it estimates the

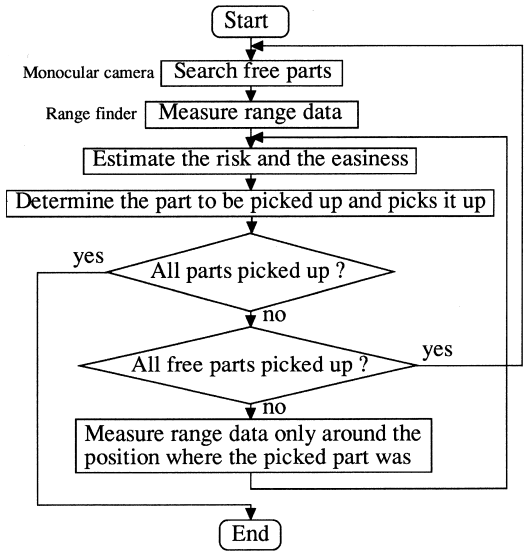


Fig. 9. The flow of the sensor system.

https://doi.org/10.1017/S0263574797000817 Published online by Cambridge University Press

ease of manipulation. Then, it gives the parts that can be picked up without causing a collapse the orders defined by the ease. After the determination, the parts-picking system picks the parts that has the highest order. Then the status of the area where the picked part changes shows the effects of the picking. If, around the area, there is a part that is given an order, the part is measured and the risk and the ease are estimated again. After picking all the parts that were given the orders, the visual system searches for free parts again, and it repeats the process until all parts have been picked up.

There are some cases where a parts-picking system cannot perfrom a task by using only one manipulator. For example, in the cases illustrated in Figure 4(b) and (c), a manipulator cannot pick any part up without collapsing the stack. In this paper, we assume that such cases do not occur.

Therefore, the parts-picking system can perform highly reliable and efficient operations by examining the risk and estimating the ease before the operations.

5 EXPERIMENTAL RESULTS

The parts–picking system used in experiments is shown in Figure 10. In the figure, there is the active and multi-sensor visual system which consists of a range finder and a monocular camera system. The range finder is at the bottom left in the figure, and the camera of the monocular camera system is at the top middle. The figure also includes a manipulator (Kawasaki, PUMA560) on the right and parts on a table in the bottom middle. The front view of the range finder is also shown in Figure 11.

In the experiments, we show that the system can check the risk and estimate the ease.

The parts stacks used to examine the risks are shown in Figure 12. Here, we use blocks whose sizes were $27 \times 20 \times 11$[mm] as parts. Among the figures, picking

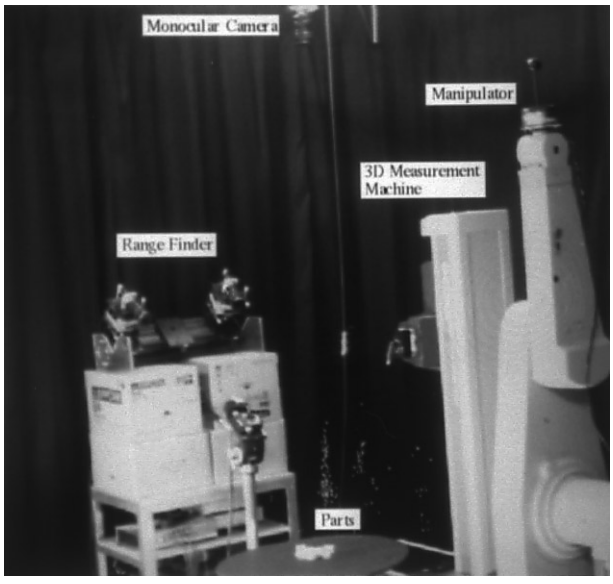


Fig. 10. The parts-picking system.

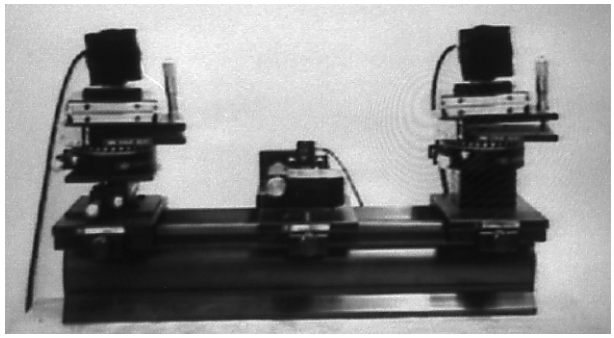
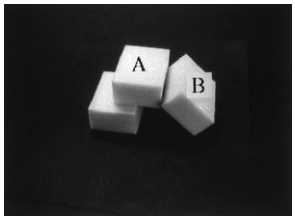


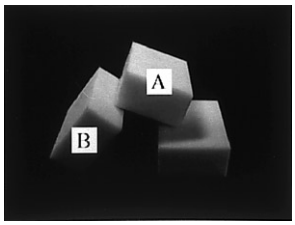
Fig. 11. The front view of the range finder.

'A' will disturb 'B', or a risk exists, in (a) and (b), and picking 'A' will not affect 'B', or there is no risk, in (c), (d), and (e).

A range image and a gray image of parts stack (a)



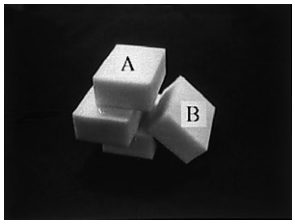
(a)



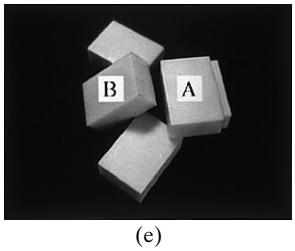
(b)



(c)



(d)



(e)

Fig. 12. Parts stacks used to check the risks.

https://doi.org/10.1017/S0263574797000817 Published online by Cambridge University Press

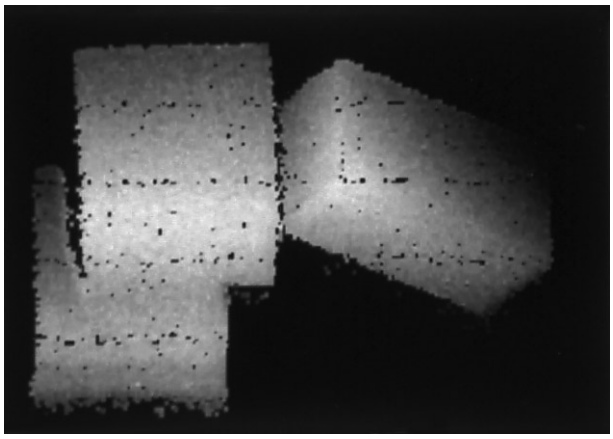


Fig. 13. A range image of parts stack (a).

taken by the range finder and the monocular camera system are given in Figures 13 and 14, respectively. In Figure 13 light points correspond to points near to the range finder, and dark points to points far from it. The height of the contact point c_b from the top surface of 'A' along the normal vector of the surface obtained from the range image was $h = -0.7$[mm]. The distance between c_b and the fulcrum of 'B' c_b', and the distance between c_b and the mass center of 'B' m_b' were $d_f = 3.19$[mm] and $d_m = 22.8$[mm] in the **x**–**y** plane, respectively. Since h was in the range of $0 \geq h \geq -h_0$ for the height of the part to be picked up ($h_0 = 11$[mm]), and since $d_f > d_m$, the system determined that picking 'A' would collapse the stack or that a risk existed.

The system also determined that a risk existed for Figure 12(b). Because of $d_f < d_m$ in Figure 12(c), $-h_0 > h$ in Figure 12(d), and since 'B' does not touch 'A' in Figure 12(e), it correctly determined that 'A' did not support 'B' or that there was no risk.

Next, we will show some results of estimation of the ease. A range image of a parts stack taken by the range finder is shown in Figure 15. The parts that were found

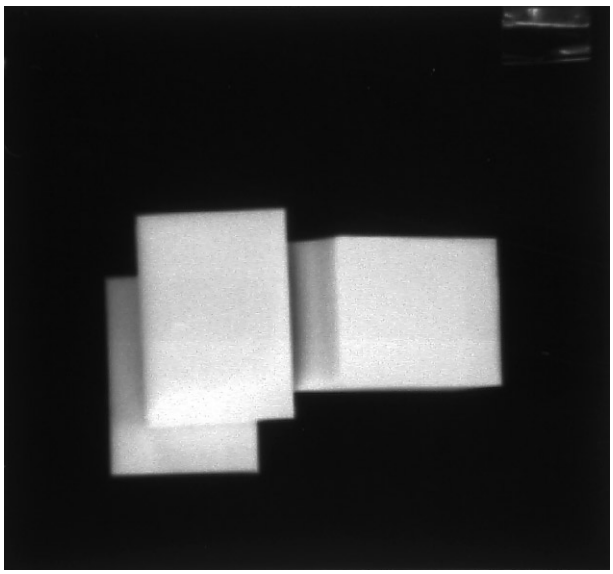


Fig. 14. A gray image of parts stack (a).



Fig. 15. A range image to estimate the ease of picking.

to be free parts by the monocular camera system are labeled in Figure 16.

Estimated ease E, validity V, and determined order are shown in Table I. Here, we used the following parameters: $d_0 = 30$[mm]; $d_1 = 10$[mm]; $g = 10$[mm]; $w = 2$. We also used cubes whose sizes were $2 \times 2 \times 2$[mm] as voxels. Since we adopted integers to calculate E for speed, and the values of E were multiplied by 1000 to avoid rounding off errors.

In the table, the parts that do not have a tall neighborhood (for example part No. 16, or part No. 12) are given higher orders. Therefore, we can say that the parts-picking system will be able to avoid collisions between parts and the manipulator using the order.

6 CONCLUSION

We developed a reliable and efficient parts-picking system that uses an active and multi-sensor visual system. The system determines the picking order with the aim of

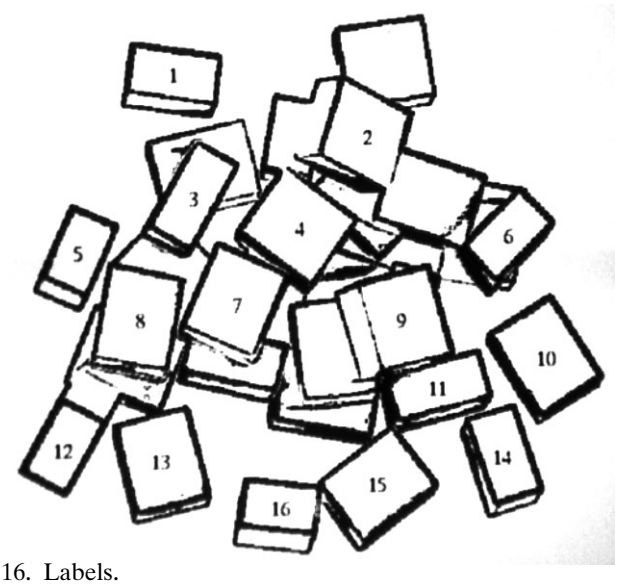


Fig. 16. Labels.

https://doi.org/10.1017/S0263574797000817 Published online by Cambridge University Press

Table I Estimation of the ease

Part No.	*E*	*U*	Order
1	937	0.214	12
2	590	0.452	6
3	699	0.585	7
4	759	0.685	10
5	861	0.455	11
6	482	0.485	4
7	559	0.691	5
8	748	0.623	9
9	193	0.716	3
10	2053	0.440	16
11	1137	0.757	14
12	166	0.730	2
13	1046	0.592	13
14	734	0.472	8
15	1478	0.593	15
16	130	0.512	1

avoiding the collapse of a parts stack. In this paper, we define situations where a manipulator picks a part that supports another, or situations where a manipulator collides with parts as cases where collapses occur. The system examine the risk of picking up such a part, estimates the ease of manipulation to prevent the collision, and determines the sequence of picking using the results. We mentioned that picking up parts in the given order would result in reliable and efficient parts picking operations, and experimental results showed that the system could check the risks and estimate the ease.

The examination of the risks by the active and multisensor visual system is, however, so far useful for only limited situations. It cannot cope with cases where a part to be picked up holds another part as a weight, cases where the part is one of several parts that support another, etc. In particular, it cannot be previously known whether a part holds up another by using only observations from outside the stack. In such a situation, we think that some kind of an on-line process, for example a process that detects movements of parts using a fast visual system, would be required. Furthermore, a parts-picking system that uses more than one manipulator to support unstable parts will be needed in the future.

References

1. R. Tella, J.R. Birk and R.B. Kelley, ''General Purpose Hands for Bin-Picking Robots'' *IEEE Trans. on Systems, Man, and Cybernetics* **SMC-12,** 828–837 (1982).
2. Y. Fukada, H. Doi, K. Nagamine and T. Inari, ''Relationships-Based Recognition of Structural Industrial Parts Stacked in a Bin'' *Robotica* **2,** Part 3 147–154 (1984).
3. K. Ikeuchi, S. Nagata, B. Horn, and K. Nishihara, ''Determining Gripper Configuration in Bin Picking Tasks Using Photometric Stereo System and PRISM Stereo System'' *Trans.(D), I.E.I.C.E.,* (*in Japanese*) **J68-D,** 546–553 (1985).
4. E. Al-Hujaza and A. Sood, ''Range Image Segmentation with Applications to Robot Bin-Picking Using Vacuum Gripper'' *IEEE Trans. on Systems, Man, and Cyberentics* **20**, 1313–1325 (1990).
5. K. Kawai, M. Mutou, Y. Tanaka, K. Umeda and T. Arai, ''Bin Picking System Using Sparse Range Image and Gray Image'' *Proc. of the 10th. Conference of Robotics Society of Japan* (*in Japanese*) (1992) **2,** pp. 843–844.
6. N. Okada and T. Nagata, ''A Sensor System with a Range Finder and a Vision System for Parts Picking Operations'' *Proc. of the 3rd. International Conference on Automation, Robotics and Computer Vision* (*ICARCV '94*) **2,** pp. 894–898.
7. N. Kada, T. Nagata, Y. Nishikawa and T. Tanaka, ''Parts-Picking Using a Sensor System with a Range Finder and a Vision System'' *Proc. of the 12th. Conference of Robotics Society of Japan* (*in Japanese*) (1994) **3,** pp. 1131–1132.
8. N. Okada and T. Nagata, ''A Parts Picking System with a Range Finder and a Camera System'' *Proc. of the 1995 International Conference on Robotics and Automation* (*ICRA '95*) (1995) **2,** pp. 1410–1415.
9. N. Okada and T. Nagata, ''An Active Vision System with Heterogeneous Visual Sensors and its Application to Parts-Picking'' *J. Robotics Society of Japan* (*in Japanese*) **14,** 538–545 (1996).
10. A.J. Baerveldt, ''Singulation of Parcels with a Sensor-Based Robot-System'' *Proc. of the 1991 IEEE/RSJ International Workshop on Intelligent Robots and Systems* (*IROS '91*) (1991) **2,** pp. 523–528.
11. Y. Yanagihara and T. Kita, ''Parts-Picking in Disordered Environment'' *Proc. of the 1991 IEEE/RSJ International Workshop on Intelligent Robots and Systems* (*IROS '91*) (1991) **2,** pp. 517–522.
12. N. Okada, T. Nagata and H. Zha, ''Planning for Parts-Picking Tasks by Using an Active and Multi-Sensor Visual System'' *Proc. of the 1996 IEEE 22nd. International Conference on Industrial Electronics, Control, and Instrumentation* (*IECON'96*) (1996) **2,** pp. 737–742.
13. L. Birnbaum, M. Brand and P. Cooper, ''Looking for Trouble: Using Causal Semantics to Direct Focus of Attention'' *Proc. of the 1993 IEEE 4th. International Conference on Computer Vision* (1993) pp. 49–56.
14. B. Schmult, ''Autonomous Robotic Disassembly in the Blocks World'' *Int. J. Robotics Research* **11,** 437–459 (1992).
15. N. Okada, T. Nagata, T. Tanaka and Y. Nishikawa, ''Parts-Picking Using a Sensor System with a Range Finder and a Camera System'' *Proc. of the 13th SICE Kyushu Branch Annual Conference.* (*in Japanese*) (1994) pp. 357–358.
16. T. Lozano-Pérez and M.A. Wesley, ''An Algorithm for Planning Collision-Free Paths Among Polyhedral Obstacles'' *Communications of the ACM* **22,** 560–570 (1979).
17. T. Lozano-Pérez, ''Spatial Planning: A Configuration Space Approach'' *IEEE Trans. on Computers* **C-32,** 108–120 (1983).
18. I. Hara and T. Nagata, ''Describing Moving Obstacles in a Configuration Space'' *J. Robotics Society of Japan* (*in Japanese*) **11,** 255–262 (1993).

https://doi.org/10.1017/S0263574797000817 Published online by Cambridge University Press