An Experimental Multisensorial Robotic System for Disassembly Automation

P. Dario, C. Guadagnini, C. Laschi, M. Rucci

ARTS Lab, Scuola Superiore S.Anna
via Carducci 40, 56127 Pisa, Italy

Abstract

Disassembly and recycling are becoming increasingly important in our society, especially for their ecological implications.

In this paper we present an approach to disassembly problems, which is essentially based on the concepts of multisensory integration and fusion and on the use of purposive actions to simplify perceptual tasks. We present a robotic system for the recognition and sorting of individual objects from a group, operations that are extremely important in most disassembly tasks.

An example of application of the system is described and experimental results are discussed. The effectiveness of the system in operating in a partially structured environment, shows how problems which are difficult to manage by using a single sensory modality can be solved by integrating multisensory data.

1. Introduction

The traditional approach to automation and robotics has been focused on assembly problems whereas the management of manufactured products at the end of their life cycle has been almost entirely neglected [1].

Recently, different priorities, complementary to assembly tasks, have emerged. These new priorities are related to the concept of *environmental conscious manufacturing* and, even more, to the notion of disassembly, and to such tasks as dismantling and recycling. The economic implications of the problem of disassembly, in a world increasingly sensible to the reduction of economic wastes and to the possibilities of recovering raw materials, are far too evident. In fact one could speculate that a systematic development and exploitation of disassembly techniques could lead in the future to the birth of *"inverse" factories* that, by operating in symbiosis with the more traditional factories, would close the loop production cycle (design-assembly-use), open new perspectives of development for industrial automation and might eventually affect some macro-economic aspects of the industrial world. The inverse factory could lead to the full implementation of the concept of the so called *"integrated design"*, that is the design of products that are conceived not only to be assembled and used, but also to be totally and efficiently disassembled and recycled. A scheme of this possible closed-loop industrial cycle is depicted in Figure 1.

Beyond its fundamental role in recycling industry, disassembly is also a useful learning tool. In fact, disassembly leads to object "apprehension", that is the determination of the properties of an object and of the relations among them [2].

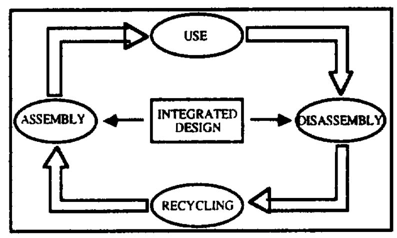


Fig.1 The integrated design concept.

In robotics research, disassembly introduces new aspects, in respect to more traditional assembly problems, especially as disassembly tasks deal with environments that are characterised by a higher degree of uncertainty. For this reason artificial perception becomes extremely important in order to explore the environment so to reduce such uncertainty.

Unfortunately, the state-of-the-art of artificial perception is not advanced enough to allow the development of general disassembly systems. So almost all the existing applications [3] [4], have been based on a large *a priori* knowledge of the environment which let them operate in the presence of a certain degree of uncertainty.

Based on these considerations, and in the framework of a long term project on "closed-loop" manufacturing automation, we have started to investigate the basic problem of sorting and identifying objects in a partially unstructured environment.

Our belief is that integration of different sensory modalities is a powerful tool for reducing environment uncertainty in disassembly tasks. So our present approach to the development of a robotic system for disassembly automation involves the integration of different sensory modalities (vision and touch) and the use of purposive actions to simplify perceptual tasks

2. Active integration of sensory modalities for scene understanding

Perception is extremely important in humans, while dealing with unstructured environments; vision is no doubt the most powerful sensory modality, as it provides a large amount of knowledge about the environment. However artificial vision alone can be ineffective for a robotic system in unstructured environments. For example scene segmentation cannot be achieved by only vision, unless the objects are physically separated or a large amount of *a priori* knowledge is available. When such *a priori* knowledge is not available, multi-sensory exploratory procedures and motor interactions become particularly useful.

Multi-sensory data-fusion concerns the fusion of data available by different sensory modalities [5]: the simultaneous use of more than one sensory modality could result in a great simplification of perceptual goals. Things that are difficult to understand with one sense can become obvious with others: thus all the senses should co-operate toward the final understanding of the scene.

Sensorimotor procedures are very important in order to achieve a better comprehension of the scene; in fact, by means of an active interaction with the environment it is possible to gather further information from the scene by actively modifying it. The use of sensorimotor procedures has become increasingly popular after the observation that several ill-posed problems can be transformed in well-posed and stable problems, if an active approach is undertaken. As a result, the paradigm of active perception [6] and its sensorial diversifications such as active vision [7], active touch [8][9], and so forth, have been recently formalised and discussed.

3. Methodology and system architecture

The general problem of disassembly of objects on a small scale should probably be approached by using two hands to separate assembled parts. However, as a first step, we have considered the problem of extracting and recognising different individual objects among agglomerates and we have assumed some degree of a priori knowledge. Such a sorting problem is crucial in several disassembly operations, such as recycling of common garbage. The ultimate goal of the system is to achieve a full understanding of the scene by separating different objects and by identifying each of them [10].

The experimental scenario we have considered is shown in Figure 2.

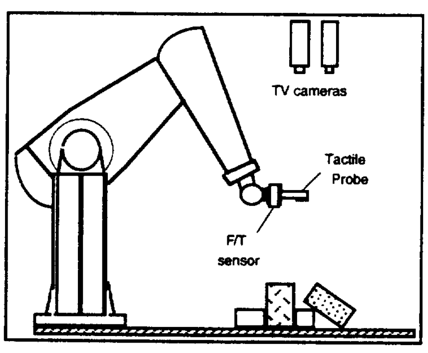


Fig.2 The robotic system used in the experiments on disassembly.

Several objects are located in front of a PUMA 562 manipulator, and within the visual field of 2 b/w TV cameras. The cameras are located above the scene and provide 3D visual information. Tactile data are provided by two devices: a 6 axis F/T sensor and a multifunctional tactile probe (figure 3). The F/T sensor is located at the wrist of the PUMA manipulator, just before the tactile probe. The tactile probe, developed in our laboratory [8][11], is a composite fingertip provided with multiple sensing capabilities.

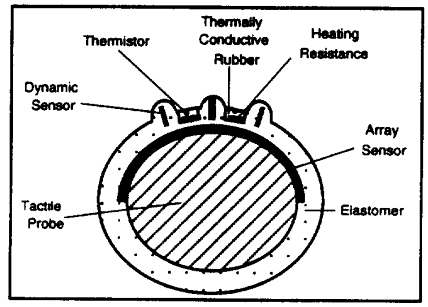


Fig.3 Section of the multifunctional tactile probe.

At first the visual analysis of the scene is executed. Images are processed in order to build up a representation of the explored objects with the goal of finding objects separated from the others. This is accomplished by looking for "standard" shapes, that is boundaries which can be classified as geometrical shapes corresponding to objects whose existence is known "a priori" (boxes, circles, etc.). These boundaries are more likely to be actually composed of a single object and for this reason they have been chosen. The visual analysis of the scene consists of a sequence of basic operations which allow the object occluding boundaries to be detected; each boundary is then described as a geometric shape. A detailed description of the visual analysis phases, in particular of the contour following algorithm, has been presented in [12]. In Figure 4 the main phases of visual analysis are shown.

The results of image processing are then analysed on the basis of semantic rules, and the set of curves which best fit the data while building up a closed boundary is singled out.

A peculiar feature of our approach is that, rather than processing or reasoning further on the visual image, the system makes use of active exploration. The robot manipulator is used for refining a situation iteratively by moving ("pushing" [15][16]) some objects so as to modify the geometry of the scene [17]. The main goal of motor interaction with the scene is to introduce modifications in the relative position of the objects so as to gather more information and to reduce uncertainties in the scene representation.

In order to execute sensorimotor procedures the system needs spatial information about the scene, which is provided by stereo vision processing. On the basis of the available visual data and on the hypotheses currently formulated by means of previous interactions with the scene, the system determines which part of the scene to focus on, and how to interact with it. Pushing an agglomeration of objects is likely to move different objects relatively to each other; in this way a large boundary detected by visual analysis can be subdivided into several smaller boundaries and/or it can modify its shape by revealing that it is actually composed of more than one object. All the parameters of the pushing action, such as the pushing direction and displacement, are determined in real-time based on the effect to induce.

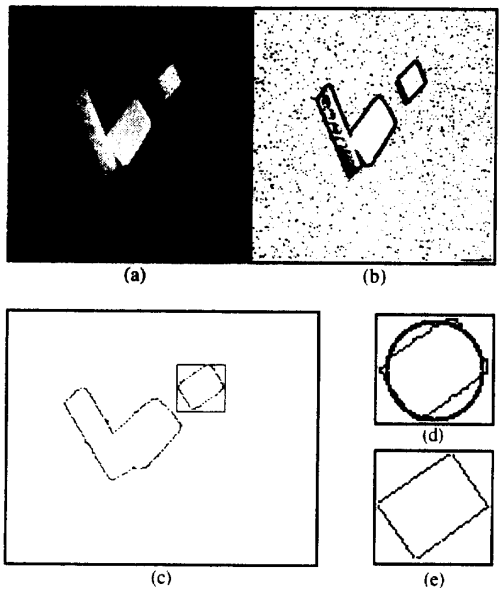


Fig.4 (a) Grey level image; (b) binary image of the edges as detected by a gradient local operator [13]; (c) result of a contour following operation; (d) circle detected by Hough method [14] on the smaller boundary; (e) segments extracted on the lines detected by Hough method on the same boundary: the boundary is described as a rectangle.

A pushing action is performed in order to achieve one of the following tasks:

1. verifying if an object is separated from others;
2. separating the objects of a same group to allow future recognition.

After that an object has been separated and its shape has been recognised using vision, it can be explored by means of tactile procedures, which can add further information toward the final recognition. Tactile exploration is also carried out on the basis of the hypotheses produced by means of visual analysis. Usually, different tactile features are examined subsequently in order to reduce the set of possible objects.

Tactile exploration is guided by vision in two ways: on one hand, the system executes a specific exploratory procedure on the basis of the shape detected by vision; on the other hand, vision provides the spatial parameters the system needs for reaching the object to explore.

As far as tactile analysis is concerned, the data provided by the F/T sensor are mainly used to control in real-time the exploratory procedures and to estimate material hardness/softness. Also, monitoring forces plays a crucial role in order to avoid damages to the system. The information provided by the F/T sensor is important both during the exploratory and the recognition phases.

On the contrary, the data acquired by the thermal sensor are used mainly for object recognition, after that the objects occluding contours have been already determined. Thermal data are aimed to determine object material by means of an appropriate sensorimotor procedure. The detail of different exploratory procedures used to recognise object material "hardness" and "thermal properties" have been presented and discussed in detail previously [18].

The conceptual components of the system are shown in Figure 5.

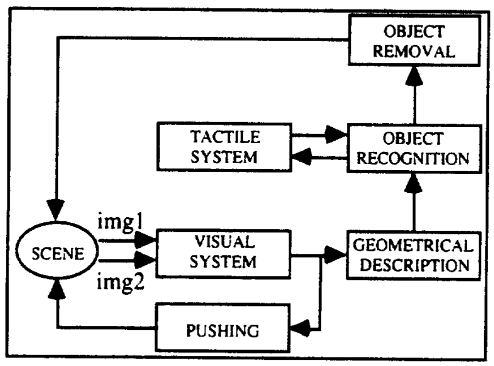


Fig.5 The system modular scheme.

4. Experimental results

In order to test system performances, we have investigated the problem of the sorting of ordinary use objects, such as those which can usually be found in a shopping-bag. Due to the virtually unlimited number of dimensions and shapes of this type of objects, this problem is extremely complex but yet well suited for testing our approach. Actually, the shopping-bag case is quite significant in the perspective of disassembly because ordinary household garbage is composed of such objects, after their use.

A list of the objects used in our experiments is shown in Table 1. As demonstrated by the analysis of the properties of each object, none of them can be recognised using either vision or touch alone. Therefore, a combination of visual analysis (and of "pushing" actions) and tactile exploratory procedures is required. Examples of the implemented procedures, which allow to identify all the objects of the set we considered, are given in Figure 6.

	SHAPE					MATERIAL THERMAL PROPERTIES					MATERIAL HARDNESS		
	bottle	cylinder	regular parallelepiped	long parallelepiped	small parallelepiped	good conductor	conductor	bad conductor	insulator	good insulator	very soft	soft	hard
glass bottle	√						√						√
plastic bottle	√									√			√
soft drink can		√				√							√
jam jar		√					√						√
barley-coffee box		√						√					√
pasta box			√						√			√	
milk carton			√					√				√	
sugar box			√						√				√
spaghetti box				√					√			√	
cotton wool				√						√	√		
soap bar					√					√			√
sponge					√					√	√		

Table 1 The set of objects used in the experiment with their different geometric, material and surface properties.

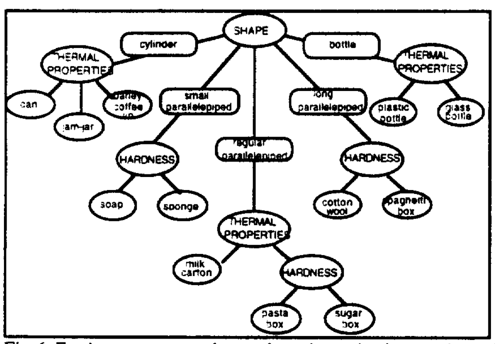


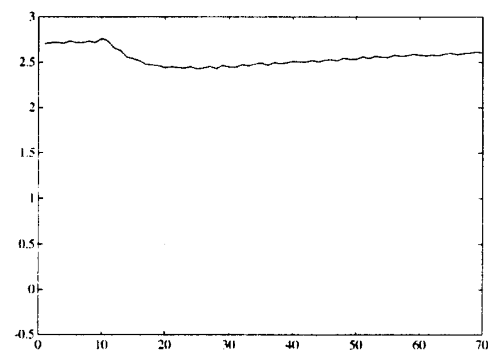
Fig.6 Exploratory procedures (based on the integration of visual and tactile information) used for identifying all the objects of Table 1.

Once an object has been isolated by integrating visual data with pushing interactions and its shape has been recognised by reasoning on the results of the image processing, the system plans and executes the appropriate tactile exploratory procedure. Visual data provide the spatial parameters the system needs for physically reaching the object to explore. During each movement of the robotic arm the output of the F/T sensor is monitored in order to avoid collisions due to errors.

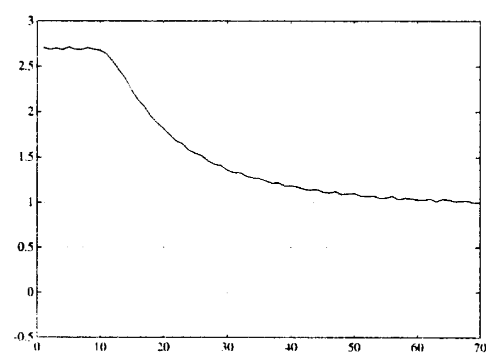
In order to extimate the "hardness" of object, the finger is moved towards the object until contact; in this phase the F/T sensor is used as a contact sensor. The contact is then refined towards a certain force value, that is the same for every object. From this position the finger is moved downwards for a certain displacement and the new force value is read. This value is directly proportional to the hardness of the object. As to thermal explorations, the system uses the same procedure for obtaining the appropriate contact, since the thermal conduction is proportional to contact pressure, too. The contact is kept for a given time, then the voltage of the thermal sensor is measured. This value is inversely proportional to the thermal conductivity of the explored material. Figure 7 shows the sensor voltage behavior from 10 s before contact to 70 s later, in the cases of an insulator (a) and of a conductor (b), respectively.

In Figure 8 (a) and 8 (b) the results of several thermal and hardness tests are shown respectively. For each kind of exploration a number of test have been carried out.The objects have been divided into several classes, trying to determine threshold values capable of identifying them. Every object the system explores can be associated to one of the hardness classes and to one of the thermal classes, so to determine the choice of the right arch on the recognition tree, as shown in Figure 6.

An example of the overall system performance is given in Figures 9, 11 and 12.

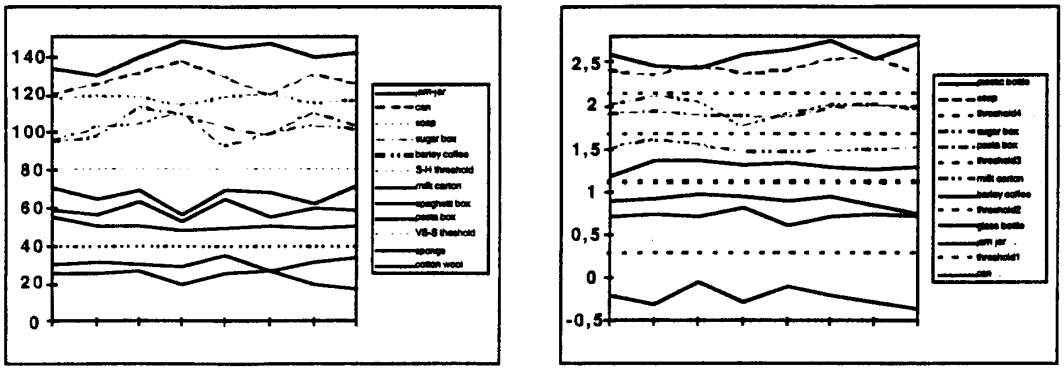


(a)



(b)

Fig.7 The thermal sensor output when contacting (a) a plastic bottle and (b) a glass bottle; the X-axis represents the time (in s) and the Y-axis the sensor output (in V). At time t=10 the contact begins.



(a) (b)

Fig.8 Experimental results of exploration as detected by (a) the F/T sensor and (b) the thermal sensor; the X-axis represents successive different explorations and the Y-axis represents for each test (a) the force measured by the F/T sensor in µF (1 µF = 113.3674 N) and (b) the voltage output of the thermal sensor after the contact with the object.

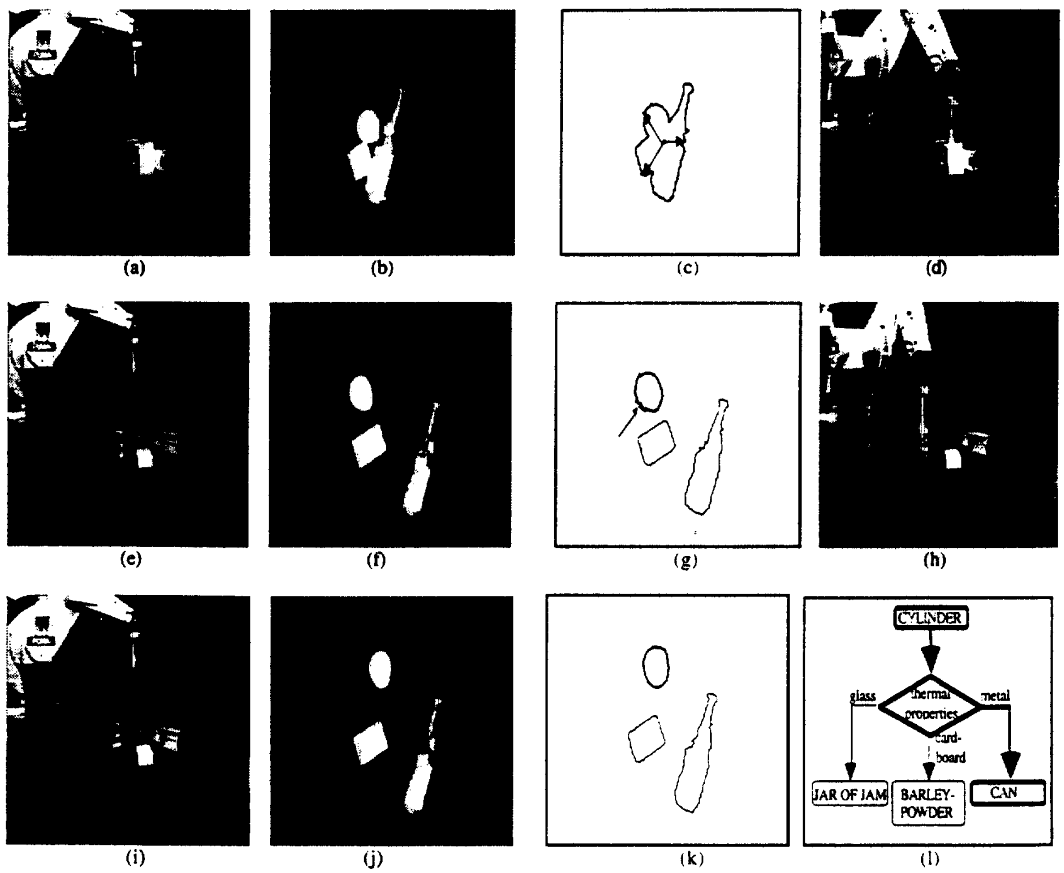


Fig.9 Sequences of operations: (a) initial scene; (b) image of the objects from above; (c) boundary of the cluster of objects and pushing directions; (d) pushing action; (e)(f) scene after pushing; (g) selected boundary and new pushing directions; (h) pushing action on the can; (i)(j) the can has been moved; (k) a circle is recognised by comparing two boundaries in different positions; (l) tactile exploratory procedure for the final recognition of the selected object (the cylinder).

When an arbitrary group of objects is presented to the system (Figure 9 (a)), visual analysis is performed in order to look for a "standard shape" (Figure 9 (b)(c)). If such a shape cannot be found, the system realises the boundary refers to a group of objects and plans a pushing action aimed to separate them, on the basis of available visual data (Figure 9 (c)(d)). The scene modified after pushing (Figure 9 (e)(f)) is analysed again and a circular "standard" shape is detected (Figure 9 (f)(g)). A pushing action is executed on the same shape (Figure 9 (h)) in order to verify if it really refers to a single object. If the same shape can be detected in the successive scene, the system has found a single object (Figure 9 (i)(j)(k)) and plans the exploratory procedure for its final recognition (Figure 9 (l)). In the example presented in Figure 9, a thermal exploration is performed with the results shown in Figure 10. The sensor voltage at the end of the contact (usually after 70 s) allows to identify a conductor material and to recognise the soft drink can.

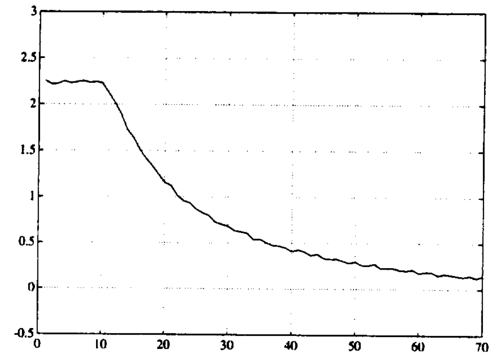


Fig.10 Voltage vs. time plot in the case of the thermal exploration of the can.

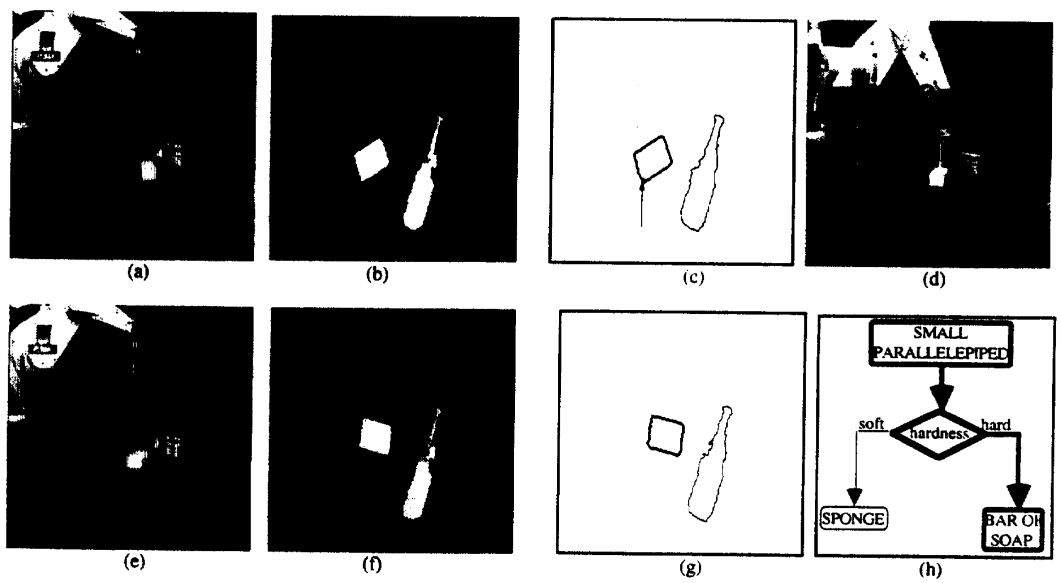


Fig.11 More sequences of operations: (a)(b) scene after that the recognised object has been removed; (c)(d) a new boundary is selected for pushing; (e)(f) the scene after pushing the parallelepiped and recognising (g) by shape and(h) by tactile exploration.

The soft drink can is removed from the scene and a similar process is performed on the new scene (Figure 11 (a)(b)(c)). As in the example of Figure 9, by integrating vision and pushing, the system singles out a small rectangular shape (Figure 11 (d)(e)(f)(g)) and executes the appropriate exploratory procedure towards the recognition of the bar of soap (Figure 11 (h)).

Once the bar of soap has been removed from the scene, the system describes the shape of the last object as a bottle (Figure 12 (a) to (g)) and executes a thermal exploratory procedure. The glass bottle is recognised and removed.

Ultimately the system is able to separate and recognize the objects as an arbitrary group, by integrating visual data and pushing interactions for scene segmentation, and by integrating vision and touch for the final recognition of each object.

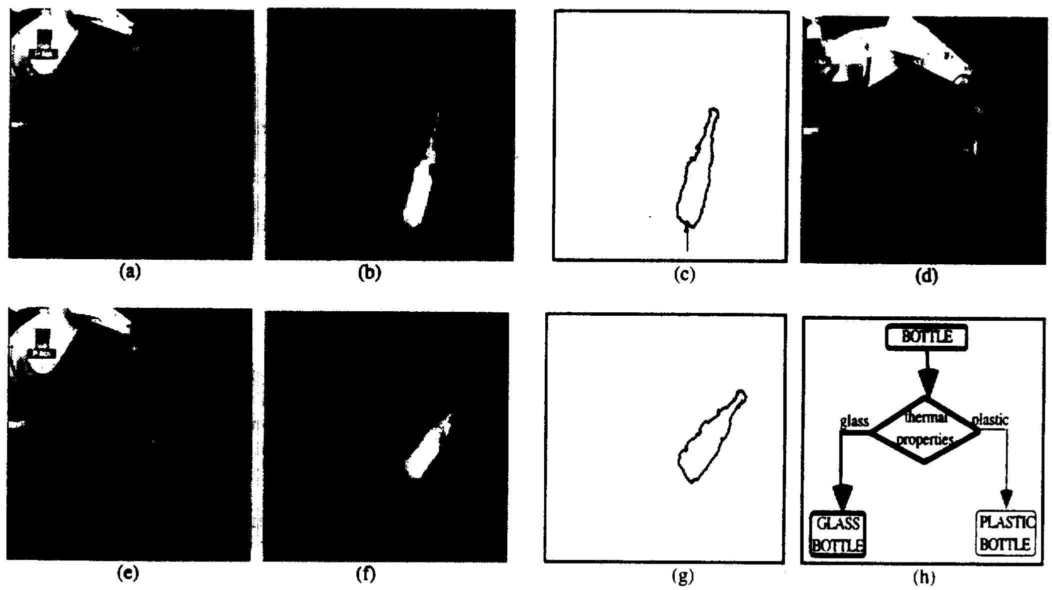


Fig.12 Additional sequences of operations: (a)(b) the last object in the scene after that the previously recognised object has been removed; (c)(d) pushing action on the bottle; (e)(f) the bottle in a different position and (g) its recognition by shape comparison; (h) the final tactile exploratory procedure to identify the glass bottle.

5. Conclusions

In this paper we have proposed a general approach to the problem of disassembly automation, and pointed out that many factors contribute to make disassembly an extremely promising field for research on automation and on robotics. (In fact, perhaps even more than the traditional and overwhelmingly investigated problem of assembly). Nevertheless, tremendous difficulties arise in the development of general disassembly systems.

The initial approach we have discussed in this paper is based on the simultaneous use of different kinds of information and on a tight link between sensory processing and the execution of motor actions. The integration of tactile and visual data with active exploration ("pushing") procedures has been examined and the application to the shopping-bag case has been described. Experimental results indicate that a problem like the one we have addressed, which is extremely complex if a single and static sensory modality is used, can be reduced to a tractable level by using multisensory data and, above all, active sensorimotor strategies.

A very interesting consideration concerns the advantages of allowing the system to learn during its operative life. In general learning means to increment the stored knowledge, that is the inclusion in the memory of new models, or parts of models, or the modification of those already acquired. A different aspect of learning is the discovery of new exploratory strategies which can be used to understand the scene.

Both are appealing when working in unstructured environments, in the presence of uncertainty. In fact, by means of learning procedures the system can adapt itself to work also in presence of varied conditions.

In our laboratory research on disassembly is proceeding along different directions: first of all, we are considering the general problem of the closed-loop factory for assembly-disassembly-recycling, and its macroeconomic implications. At a smaller scale, we are working to improve the proposed approach. On one hand we are investigating the processing of different visual features such as regions and motion; on the other hand we are trying to extend the capabilities of the robot system by including also adaptability (for example, fingertip orientation and force adjustment), which is a fundamental part of our approach. In particular we are considering the advantages of implementing a new version of the system by means of artificial neural network-based techniques so as to achieve on-line sensorimotor learning procedures [9].

Acknowledgments

This work was supported by the Special Project on Robotics of the National Research Council of Italy. One of the authors (M. Rucci) has been supported by a fellowship from "Istituto per la Ricostruzione Industriale" (IRI).

References

[1] P. Dario, and M. Rucci, "An approach to disassembly problems in robotics", *IEEE/RSJ Int. Conf. IROS'93*, Yokohama, Japan, July 1993.

[2] R. Bajcsy and S. Stansfield, "Object apprehension using vision and touch", *Workshop on Space Telerobotics*, JPL, Pasadena, CA, Gennaio, 1987.

[3] D.Viescher, "Cooperating robot with visual and tactile skills", *Proc. 1992 IEEE Int. Conf. on Robotics and Automation.*

[4] R. Bajcsy and C. Tsikos, "Assembly via disassembly: a case in machine perceptual development", *Proc. of 5th ISRR*, MIT Press, pp.303-309, 1989.

[5] G. D. Hager, "Task-directed sensor fusion and planning" Kluwer, Boston, 1990

[6] R. Bajcsy, "Active perception", *IEEE Proceedings*, 76, pp. 996-1005, 1988.

[7] M. Tistarelli and G. Sandini, "Dynamic aspects in active vision", *CVGIP: Image Understanding*, 56, 1, pp. 108-129, 1992.

[8] P. Dario, A.M. Sabatini, B. Allotta, M. Bergamasco and G. Buttazzo, "Object characterization and sorting by active touch", *Proc. of IROS '91*, pp. 1353-1356, Osaka, Japan, November 3-5, 1991.

[9] M. Rucci and P. Dario, "Active exploration of objects by sensorimotor control procedures and tactile feature enhancement based on neural networks", *Proc. of the 1993 JSME Int. Conf. on Advanced Mechatronics*, Tokyo, Japan, August 2-4, 1993.

[10] P. Dario, M. Rucci, C. Guadagnini and C. Laschi, "An investigation on a robot system for disassembly automation", *Proc. IEEE Int. Conf. on Robotics and Automation*, San Diego, CA, May 8-13, 1994 (Submitted).

[11] P. Dario, A. M. Sabatini, B. Allotta, M. Bergamasco and G. Buttazzo, "A fingertip sensor with proximity, tactile and force sensing capabilities", *Proc. of IROS '90*,Tsuchiura, Japan, pp. 883-889, July 3-6, 1990.

[12] P. Dario, M. Rucci, C. Guadagnini and C. Laschi, "Integrating visual and tactile informations in disassembly tasks", *Proc. IEEE 6th Int. Conf. on Acvanced Robotics*, Tokyo, Japan, pp.191-196, November 1-2, 1993.

[13] D. H. Ballard and C. M. Brown *Computer Vision*, Englewood Cliffs, NJ, Prentice-Hall, 1982.

[14] R. O. Duda and P. E. Hart *Pattern Recognition and scene Analysis*, New York, Wiley, 1973.

[15] Z. Balorda, "Reducing uncertainty of objects by robot pushing" *Proc. 1990 IEEE Int. Conf. on Robotics and Automation.*

[16] M. Accordino, P. Gandolfo, G; Sandini and M. Tistarelli, "Object understanding through visuo-motor cooperation" *Proc. 2nd. Int. Symp. on Experimental Robotics*, Toulose, France, June 25-27, 1991.

[17] P. Dario, M. Rucci, C. Guadagnini and C. Laschi, "An experimental robot system for investigating disassembly problems", *Proc. IEEE/Tsukuba International Workshop on Advanced Robotics*, Tsukuba, Japan, November 8-9, 1993.

[18] P. Dario, P. Ferrante, G. Giacalone, L. Livaldi, B. Allotta, G. Buttazzo and A. M. Sabatini "Planning and executing tactile exploratory procedures", *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Raleigh, NC, pp. 1896-1903, July 7-10, 1992.