An Investigation on a Robot System for Disassembly Automation

P. Dario, M. Rucci, C. Guadagnini, C. Laschi
ARTS Lab, Scuola Superiore S. Anna
via Carducci 40, 56127 Pisa, Italy

Abstract

The traditional approach to automation and robotics has focused so far mainly on assembly problems, whereas the managing of manufactured products at the end of their life cycle has been almost entirely neglected. However, disassembly and recycling are becoming important factors as the ecological and economical implications of manufacturing rise increasing concerns

As an initial investigation of the very general problem of disassembly, in this paper we outline first the motivations and the potentially very important perspectives of this approach for robotics and automation research and for industrial application. Then we present a robotic system for the extraction, recognition and sorting of individual objects from an "agglomerate". Such operations are of crucial importance in several disassembly tasks, such as recycling and raw materials recovering. The system is based on the integration of different sensory modalities with motor actions. An example of application of the system is described and experimental results are discussed.

1. Introduction

The concept of assembly has become important since the beginning of the Industrial Revolution in the second half of the XVIII century. The financial driving forces which promoted the manufacture of goods in large quantities and at low cost encouraged the development of automated machines and processes for assembly tasks. In the last decades, the extrapolation and the generalisation of some of the concepts and technologies associated with industrial automation contributed to the development of modern Robotics and of some aspects of Artificial Intelligence [1].

Recently, different priorities, that complement those associated with assembly, have emerged. In contrast to the past ones, 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 like the present one which is increasingly sensible to the reduction of economic wastes and to the possibility of recovering raw materials, are far too evident. In fact one could even speculate that a systematic development and exploitation of disassembly techniques could lead in the future to the birth of sort of *"inverse" factories* that, by operating in symbiosis with the more traditional factories, would close the loop of the production cycle (design - assembly - utilisation), open new perspectives of development for industrial automation and eventually affect even some macro-economic aspects of the industrial world. The inverse factory could lead to the full implementation of the concept of *"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.
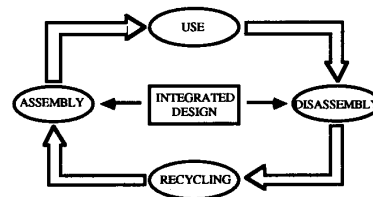

Figure 1. The integrated design concept.

Disassembly problems imply several fundamental distinctions in respect to corresponding assembly tasks. A crucial difference is that in disassembly problems objects have a past "life", which could have modified them unpredictably both in their aspect and in their internal structure. As a consequence, in general, an automated disassembly system should deal with environments characterised by a higher degree of uncertainty than in the case of assembly tasks. Integrated design is a powerful tool for reducing such uncertainty: if a specific product has been designed properly, an automated system for disassembly could be considered as operating in a partially structured environment. For various reasons, however, integrated design is not always possible. For example, integrated

design efforts are useless with those goods (such as common garbage) which typically undergo large modifications during their life. In such cases, disassembly involves tremendous difficulties, mainly related to scene understanding. In fact, a general disassembly system should be able to correctly understand the world and to interact with it efficiently. Before that fully automated, large scale plants for disassembly become a reality, it is interesting and could be useful to develop robotic workstations that disassemble and sort objects on a small scale, making use of some degree of intelligence. Unfortunately, the state-of-the-art of artificial perception is not advanced enough to allow the development of general disassembly systems. For this reason, the few existing approaches to robotic disassembly [2] [3], have been based on a large *a priori* knowledge of the environment, which allow to operate in the presence of a certain degree of uncertainty (in fact, one could even argue that "disassembly" rather than assembly should be regarded and investigated as "the" real problem for artificial perception in robotics!).

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 present approach to the development of a robot 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

The major problems of disassembly on a small scale are associated with perception. In fact, artificial perception seems far from being able to replicate biological capabilities within a short time. As a result, at the moment the final goal of scene understanding has been put aside by researchers on perception, who have focused their efforts toward the comprehension of how specific tasks (such as feature extraction) can be accomplished. This is particularly true even for the case of computer vision, which is, with no doubt, the field of artificial perception which has received most attention in recent years.

In order to overcome the present limited capabilities of analysing perceptual data, our approach to disassembly is essentially based on the concepts of multi-sensory data fusion, active interaction with the scene and adaptability.

Multi-sensory data fusion concerns the fusion of data available from different sensory modalities [4]: the, simultaneous use of more than one sensory modalities could result in a significant simplification of perceptual

goals. Problems that are difficult to understand by means of one sense can become obvious by others: thus all the senses should co-operate toward the final understanding of the scene. With the term "data-fusion" we indicate also the co-operative use of different features obtained by a single sensory modality. Our interest for "intra-sensory" data fusion derives from the fact that typically, due to the high specialisation of processing algorithms, only a small part of the total amount of information present at the input can be efficiently processed [5]. The remaining information is not only neglected, but even acts as noise. Furthermore, these algorithms are not conceived for working in co-operation with others, so that their unification into a single general-purpose algorithm is extremely difficult.

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 further information can be gathered 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 used. As a result, the paradigm of active perception [6] and its sensorial diversifications such as active vision [7], and active touch [8], have been recently formalised and discussed.

3.   Methodology   and   system architecture

The general problem of object disassembling should be approached on a small scale 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 the 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 [1].

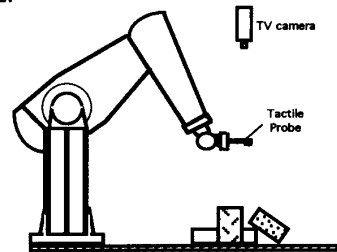The experimental scenario we have considered is shown in Figure 2.

Figure 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 a b/w TV camera. The camera is located above the scene and provides 2D visual information. Tactile information is also acquired actively and integrated with the results of visual analysis. The procedure followed to explore, disassemble and recognise objects is depicted in the block diagram of Figure 3.
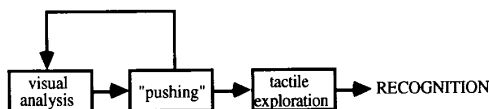

Figure 3. Sequence of the procedure for disassembling and recognising objects.

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, cylinders, etc.). These boundaries are chosen because they 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 operations. First, the edges of the images are extracted by means of a gradient operation. It is well known that this is an extremely complex task due to the large number of noisy features typically present in the image. In fact real objects usually have printed characters and different collars which introduce meaningless edges often sharper than the occluding contours of the objects. (With the term occluding contour we indicate the image edge due to depth discontinuities [9]). The resulting image is then binarised by introducing a suitable predetermined threshold. A very low threshold value is used in our case so as to avoid the loss of too many edges. This facilitates subsequent operations. The thresholded edges are linked by a contour following operation providing a boundary image where each boundary is one pixel wide and its area exceeds a given threshold. The threshold has been introduced so as to remove small boundaries, which are usually given by noise in the edge extraction. An important feature of the algorithm is that, if several boundaries are found, one enclosed in the other, only the outer one is left in the image. This process does not guarantee that all the boundaries singled out have a physical correspondence with the occluding contours of the objects. It may well happen that a large boundary is due to a collection of objects whose specific boundaries are all included in the larger one. In Figure 4 the main phases of visual analysis are shown. Finally, the Hough method [10] is applied to find the straight line and circle equations

describing each boundary. It is well known that the Hough method, which is based on the concept that a point belongs to a curve if it verifies its equation, is applicable to every parametric curve. We applied the Hough method to detect lines and circles with a bi-dimensional and a three-dimensional accumulator array, respectively. The results of the Hough method 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.
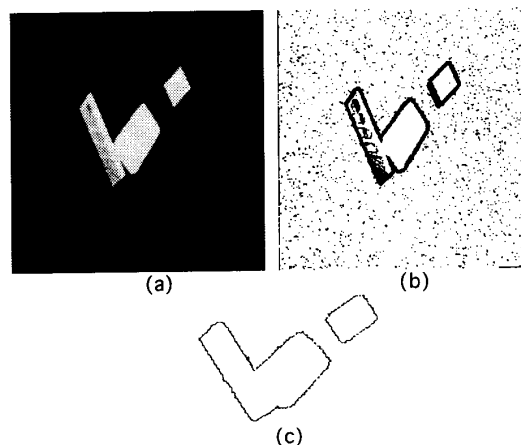

(a)   (b)

(c)

Figure 4. (a) Grey level image; (b) detected edges; (c) resulting boundary.

A peculiar feature of our approach is that, rather than processing or reasoning further on visual image, the system makes use of active exploration. That is, the robot manipulator is used for refining a situation iteratively by moving ("pushing") some objects so as to modify the geometry of the scene. The main goal of the 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. Simple actions, like pushing or pulling an object far from another, or manipulating, can be often much more effective than lengthy and sophisticated reasoning and processing of visual scene. 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. As proposed also by Balorda [11], and by Accordino et al. [12], the basic motor action that we have considered is the action of *pushing*. 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 in to 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 on the basis of the effect to induce. Once that a certain boundary has been selected for pushing, the co-ordinates of the point to push are evaluated by means of the images provided by the camera. The pushing direction and the displacement are determined by choosing the larger free area adjacent to the boundary. As shown in Figure 3, the phases of the procedure are executed iteratively until an object is extracted from the group, that is, until it is possible to single out a standard shape which does not change with a motor action (Figure 5).
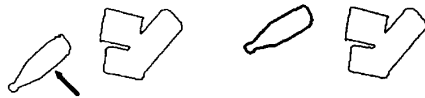
Figure 5. The bottle does not change its shape with a motor action.

After that objects have been separated and some of them possibly recognised using vision, the remaining objects can be explored by means of tactile procedures, which can add further information toward the final recognition [13]. 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 data are provided by two devices: a 6 axis F/T sensor and a multi-functional tactile probe. 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][14], is a composite fingertip provided with multiple sensing capabilities. Basically, the probe incorporates a tactile 16x16 piezoresistive array sensor based on semiconductor polymer technology [15], a 3-element dynamic sensor and 4 thermal sensors. The dynamic sensors comprise thin film strips of piezoelectric polymer material embedded in a soft elastomer layer. The piezoelectric strips are included in three protuberances that simulate the ridges of the fingertip skin, and enhance sensor sensitivity to the shear strains induced when the finger slides along the object surface. Typical sensor performances have been discussed in [16]. Also the thermal sensors are incorporated in the elastomer layer, but they are surrounded by an elastomer with different properties (thermally conductive and electrically insulant). Each sensor consists of a SMD-type resistance and a thermistor located immediately above it.

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 to avoid damages to the system. Thus, 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 tactile probe are used

mainly for object recognition, that is when the objects occluding contours have already been determined. This information is used for detecting shape as well as for estimating material thermal properties and surface texture. In particular, the tactile image detected by the piezoresistive array provides information on local geometrical features (smooth surfaces, edges, corners), whereas the dynamic sensor provides an estimation of surface roughness by means of a gentle rubbing action, and the thermal sensor contributes to identify object material by means of an appropriate sensorimotor procedure. The details of different exploratory procedures used to recognise object material "hardness", and "thermal properties", and "surface texture", have been presented and discussed in detail previously [16].
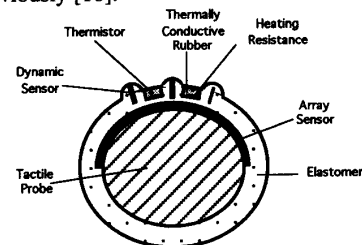

Figure 6. Section of the multi-functional tactile probe.

It is important to observe that sensor performances are inherently related to sensorimotor control. For example, the array sensor works well at certain contact force levels and relative position, which largely depend on the specific object feature; the dynamic sensor provides edge enhancement when slid at a certain velocity and low contact force; the thermal sensor is effective when the finger is pressed quite hardly on a flat surface (in fact so hard to flatten sensor ridges). Work is in progress in our laboratory to obtain such adjustment, with no or little a priori knowledge of object characteristics, by means of learning procedures [17] [18].

4. Experimental results

In order to test system performances, we have investigated the problem of sorting common 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, 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 the experiment is given 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

(combined with "pushing") and tactile exploratory procedures is required. Examples of these procedures, which allow to identify all the objects of the set we considered, are given in Figure 7.

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

	SHAPE					MATERIAL THERMAL PROPERTIES					MATERIAL HARDNESS				TEX-TURE	
	bottle	cylinder	regular parallelepiped	long parallelepiped	short parallelepiped	metal	glass	plastic	waxed cardboard	cardboard	very soft	soft	hard	very hard	smooth	grooved
glass bottle	√						√							√	√	
plastic bottle	√							√							√	
soft drink can		√				√								√	√	
tomato tin		√				√								√		√
coffee tin		√				√		√						√		√
jam jar		√					√							√	√	
barley-coffee box		√							√					√	√	
pasta box			√							√			√		√	
flour paper bag				√						√			√		√	
milk carton				√					√				√		√	
sugar box				√						√				√	√	
spaghetti box					√					√			√		√	
biscuits packet					√				√			√				√
cotton wool					√				√		√				√	
soap bar			√					√					√		√	
sponge				√							√	√			√	

Figure 7. Exploratory procedures based on the integration of visual and tactile information, leading to the identification of all of the objects of Table 1.
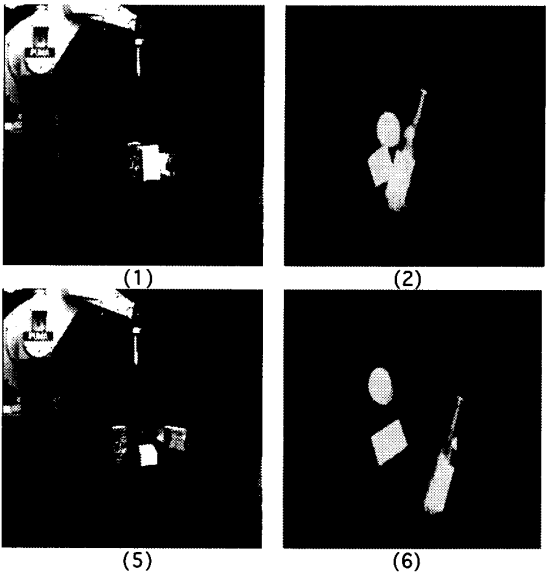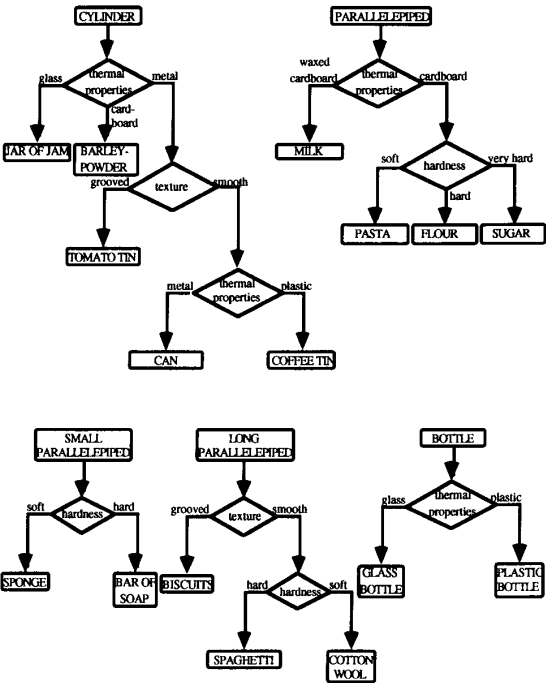

Figure 8. Sequences of operations: (1) initial scene; (2) image of the objects from above; (3) boundary of the cluster of objects and pushing directions; (4) pushing action; (5)(6) scene after pushing; (7) selected boundary and new pushing direction; (8) pushing action on the tomato tin;
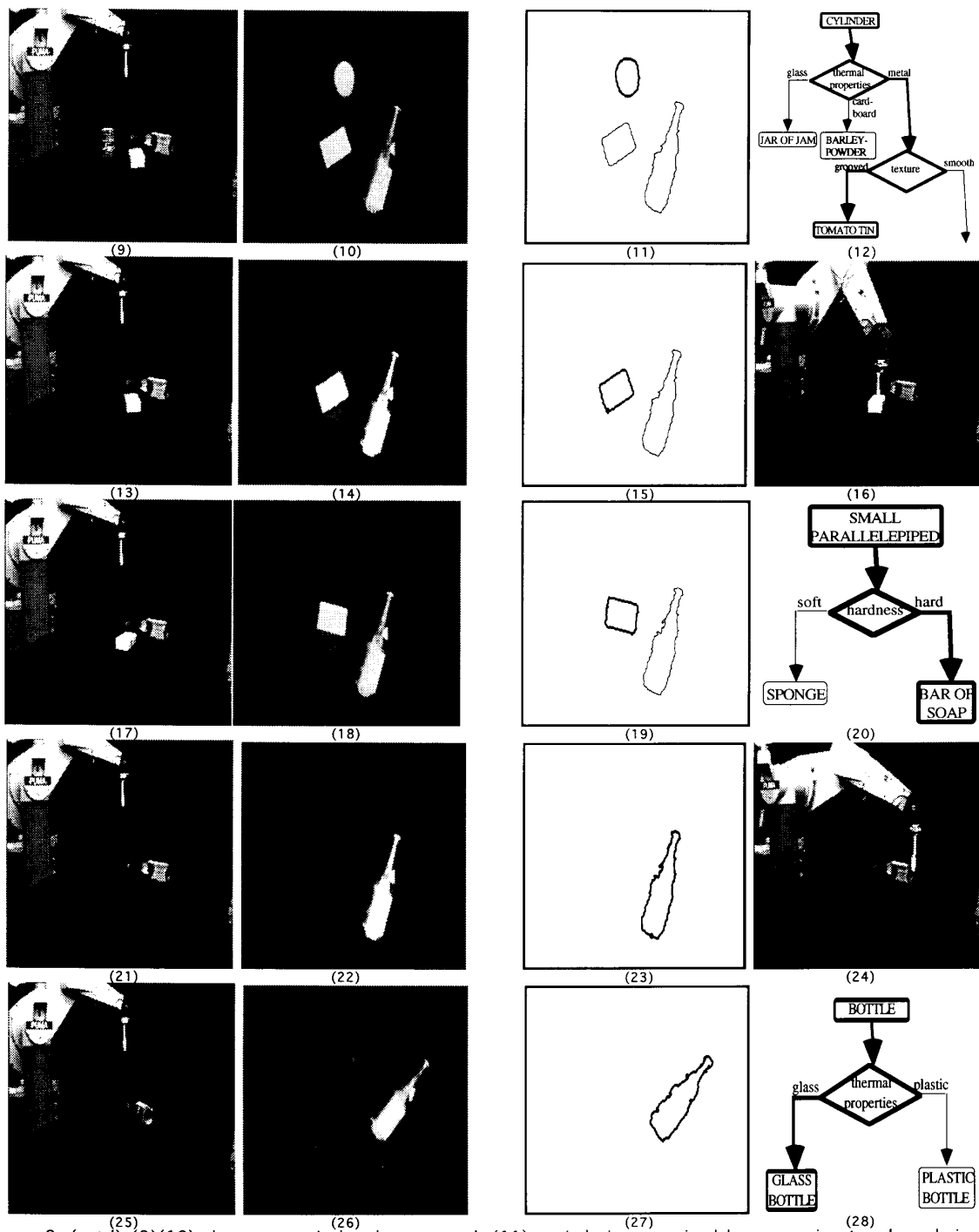
Figure 8. (cntd) (9)(10) the tomato tin has been moved; (11) a circle is recognized by comparing two boundaries in different positions (7 and 11); (12) tactile exploratory procedure for the final recognition of the object; (13)(14) scene after that the recognized object has been removed; (15)(16) a new boundary is selected for pushing; (17)(18) the scene after pushing the parallelepiped and recognizing it (19) by shape and(20) by tactile exploration; (21)(22) the last object in the scene after that the recognized object has seen removed; (23)(24) pushing action on the bottle; (25)(26) the bottle in a different position and (27) its recognition by shape comparison; (28) tactile exploratory procedure to identify the object as 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 much 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.

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 macroeconomical 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.

Acknowledgments

References

[1] P. Dario, M. Rucci, "An approach to disassembly problems in robotics", *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp.460-467, Yokohama, Japan, July 26-30, 1993.

[2] D.Viescher, "Cooperating robot with visual and tactile skills", *Proc. IEEE Int. Conf. on Robotics and Automation.*, pp.2018-2025, Nice, France, May 1992.

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

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

[5] S. Grossberg, E. Mingolla and D. Todorovic, "A neural network architecture for preattentive vision", *IEEE Trans. Biom. Eng.*, 36, 1, 1989.

[6] R. Bajcsy, "Active perception", *IEEE Proceedings*, 76, 8, pp. 996-1005,August 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. IEEE Int. Conf. on Intelligent Robots and Systems, '91*, pp.1353-1356 Osaka, Japan, November 3-5, 1991,.

[9] D. Marr, *Vision*, W.H.Freeman and Company, New York, 1982.

[10] D.H. Ballard, and C.M. Brown *Computer Vision*, Prentice Hall, New Jersey, 1982.

[11] Z. Balorda, "Reducing uncertainty of objects by robot pushing" *Proc. IEEE Int. Conf. on Robotics and Automation*, pp.1051-1056, 1990.

[12] M. Accordino, F. Gandolfo, G. Sandini, M. Tistarelli, "Object understanding through visuo-motor cooperation", *Proc. 2nd International Symposium on Experimental Robotics*, Toulose, France, June 25-27, 1991.

[13] R. Howe and M.Cutkosky, "Touch sensing for robotic manipulation and recognition", in *The Robotics Review 2*, pp. 55-112, O. Khatib, J. Craig, T. Lozano-Pérez (eds), MIT Press, 1992.

[14] P.Dario, A.M.Sabatini, B.Allotta, M.Bergamasco and G.Buttazzo, "A fingertip sensor with proximity, tactile and force sensing capabilities", *Proc. IEEE Int. Conf. on Intelligent Robot and System*, pp.883-889, Tsuchiura, Japan, July 3-6, 1990.

[15] Force Sensing Resistor, Interlink Inc., Santa Barbara, California.

[16] P. Dario, P. Ferrante, G. Giacalone, L. Livaldi, "Planning And Executing Tactile Exploratory Procedures", *Proc. IEEE Int. Conf. on Intelligent Robot and Systems*, pp. 1896-1903, Raleigh, NC, July 7-10, 1992.

[17] M. Rucci and P. Dario, "Active exploration of objects by sensorimotor control procedures and tactile feature enhancement based on neural network," *Proc. IEEE/JSME '93 Int. Conf. on Advanced Mechatronics*, pp.445-450, Tokyo, Japan, August 2-4, 1993.

[18] M. Rucci, P. Dario "Autonomous Learning of Tactile-Motor Coordination in Robotics", *Proc. IEEE Int. Conf. on Intelligent Robots and Systems*, San Diego, CA, May 8-13, 1994,