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An Experimental Robot System for Investigating Disassembly Problems

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Abstract- **The traditional approach to automation and robotics has always been focused on assembly problems, whereas the managing of manufactured products at the end of their life cycle has been mostly neglected. However, disassembly and recycling are becoming important factors in a society like ours, which is increasingly concerned about the ecological and economical implications of manufacturing.**

In this paper we present a robotic system for the extraction and recognition of object agglomerates and sorting. 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 the obtained results are discussed.

1. INTRODUCTION

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

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 economic wastes and to the possibilities of recovering raw materials, are far too evident. In fact one could even speculate that a systematic development and exploitation of disassembly methodologies could bring in the future to the birth of a sort of *"inverse" factory* that, by operating in symbiosis with the more traditional manufacturing factories, will close the open loop production cycle (design - assembly - use) and might eventually affect even 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.

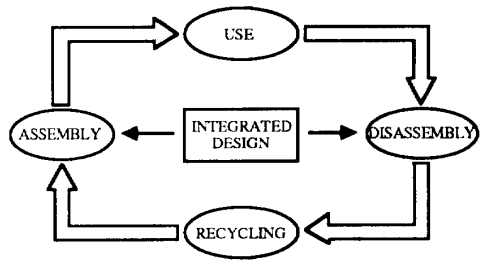

Fig.1 The integrated design concept.

The study of disassembly problems in the robotic field implies several fundamental distinctions with 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, a disassembly system should deal with environments characterized by a much higher degree of uncertainty than for 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.

However, integrated design is not always possible for various reasons. 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. Unfortunately, the state-of-the-art of artificial perception is not advanced enough to allow the development of general disassembly systems. For this reason, almost all the existing applications [1] [2], 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. 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 the 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.

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. In order to isolate the objects, after that a boundary has been selected, a motor action is planned based on vision analysis. As shown in Fig.2, these phases are executed iteratively until an object is extracted from the agglomerate, that is, it is possible to single out a standard shape which does not change with a motor action.

Then, if necessary, the object is 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 hypothesis produced by means of visual analysis. Usually, different tactile features are examined subsequently in order to reduce the set of possible objects.

The visual analysis of the scene consists of a sequence of basic 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 colors 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 [10]). The resulting image is then binarized by introducing a suitable predetermined threshold. A very low threshold 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.

A peculiar feature of our approach is that, rather than processing or reasoning further, we rely on active exploration. That is, we use the robot manipulator for refining this situation iteratively by moving ("pushing") some objects so as to modify the geometry of the scene.

Finally, the Hough method [11] is applied to find the straight line and circle equations describing each boundary. It is well known that 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 cumulator array, respectively. The results of the Hough method are then analyzed 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.

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. Simple actions, like pushing or pulling an object far from another, and manipulation 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 by Balorda [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 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 determinated in real-time on the basis of the effect to induce. Once that a certain boundary has been selected for pushing, the coordinates of the point to push are evaluated by means of the images provided by the two cameras. The positions of the cameras help to determine quite easily the absolute location of the point. The pushing direction and the displacement are determined by choosing the larger free area adjacent to the boundary.

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, forces monitoring plays a crucial role to avoid damage 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 tactile probe are used mainly for object recognition, that is when the objects occluding contours have been already 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 surface, edges, corners), whereas the dynamic sensor provides an estimation of surface roughness by means of a gentle rubbing action, the thermal sensor contributes to determine object material by means of an appropriate sensorimotor procedure.

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

2. ACTIVE INTEGRATION OF SENSORY MODALITIES

The major problems of disassembly are associated with perceptual difficulties. In fact, fundamental difficulties have emerged in the analysis of perceptual data and artificial perception seems far from seing 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, which have focused their efforts toward the comprehension of how specific tasks (such as feature extraction) can be accomplished. This is particularly true for the case of computer vision, which is, with no doubt, the field which has received most attention in recent years. In order to overcome these limitations 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 with different sensory modalities [3]: the simultaneous use of more than a single sensory modality could result in a great simplification of perception goals. Things that are difficult to understand with one sense can be obvious with others: thus all the senses should cooperate toward the final understanding of the scene. With the term "data-fusion" we mean also the cooperative 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 specialization of processing algorithms, only a small part of the total amount of information present at the input can be efficiently processed [4]. The remaining information is not only neglected, but even acts as noise. Furthermore, these algorithms are not conceived for working in cooperation 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 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 [5] and its sensorial diversifications such as active vision [6], active touch [7], and so forth, have been recently formalized and discussed.

A very interesting consideration concerns the advantages of allowing the system to learn during its operative life. By means of learning the stored knowledge of the system can be updated and new motor actions can be found so as to adapt to changing environments and to different tasks. Adaptability is a major issue, when working in unstructured environments in the presence of uncertainty, because unexpected events can be used as a guide for future operations. The robotics community has assisted in recent years to the explosion of applications involving neural networks architectures, which are intrinsecally able to learn on the basis of experience and therefore potentially very suitable tools for achieving adaptable behavior in robots.

3. SYSTEM ARCHITECTURE

In our laboratory we have recently focused our attention on the very general problem of disassembly, i.e. disassembly without any specific *a priori* knowledge [8], [9]. The general problem of disassembly of objects should be approached by using hands to separate assembled parts. However, as a first step, we have considered the problem of extracting and recognizing 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.

Several objects are located in front of a PUMA 562 manipulator, and within the visual field of two b/w TV cameras. The cameras are located above the scene and provide 3D visual information. Tactile information is also acquired actively and integrated with the results of visual analysis. Tactile data are provided by two devices: a 6 axis F/T sensor and a multifunctional 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 [9][13], is a composite fingertip provided with multiple sensing capabilities. Basically, the probe incorporates a tactile 16x16 piezoresistive array sensor based on semiconductor polymer technology [14], 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. 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). The sensors consist of a SMD-type resistance and a thermistor located immediately above it. Typical sensor performances have been discussed in [9] and [15]. The procedure followed to explore, disassemble and recognize objects is depicted in Figure 2.

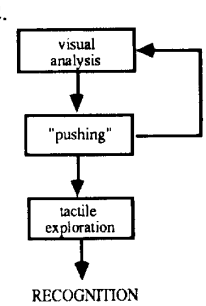

Fig.2 The procedure for disassemble and recognize objects.

and relative position, which largely depends on the specific object feature; the dynamic sensor provides edge enhancement when slided 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). Some 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 [16] [17].

4. RESULTS

As a testing example, the system has been applied to the sorting of common objects such as those which can usually be found in a shopping-bag. Due to the virtually illimitate 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 the experiments is shown in Figure 3.

	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					√					√	√				√	

Fig. 3 The objects used in the experiment and their properties.

As shown by the properties of each object, none of them can be recognized using either vision or touch alone. For example, glass and plastic bottles, which have very similar shapes, can be singled out only by detecting their different thermal properties. Also a coffee tin, a can, a barley-coffee, a tomato tin and a jam jar have similar shapes (all are cylinders) but different material properties and textures. For other objects, such as a soap bar and a sponge, material hardness (which can be estimated by means of the force/torque sensor located at the wrist of the PUMA manipulator) can play a major role [9]. Several procedures for differentiating the objects of the scene are shown in Figure 4.

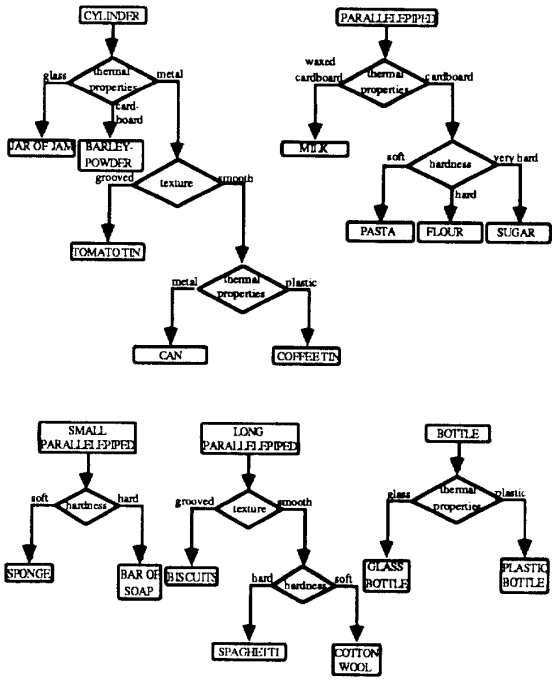

Fig.4 Integration of visual and tactile information for object recognition.

The sequence shown in Fig.5 illustrates a typical system operation.

Objects are moved until the bottle on the right is isolated and then removed.

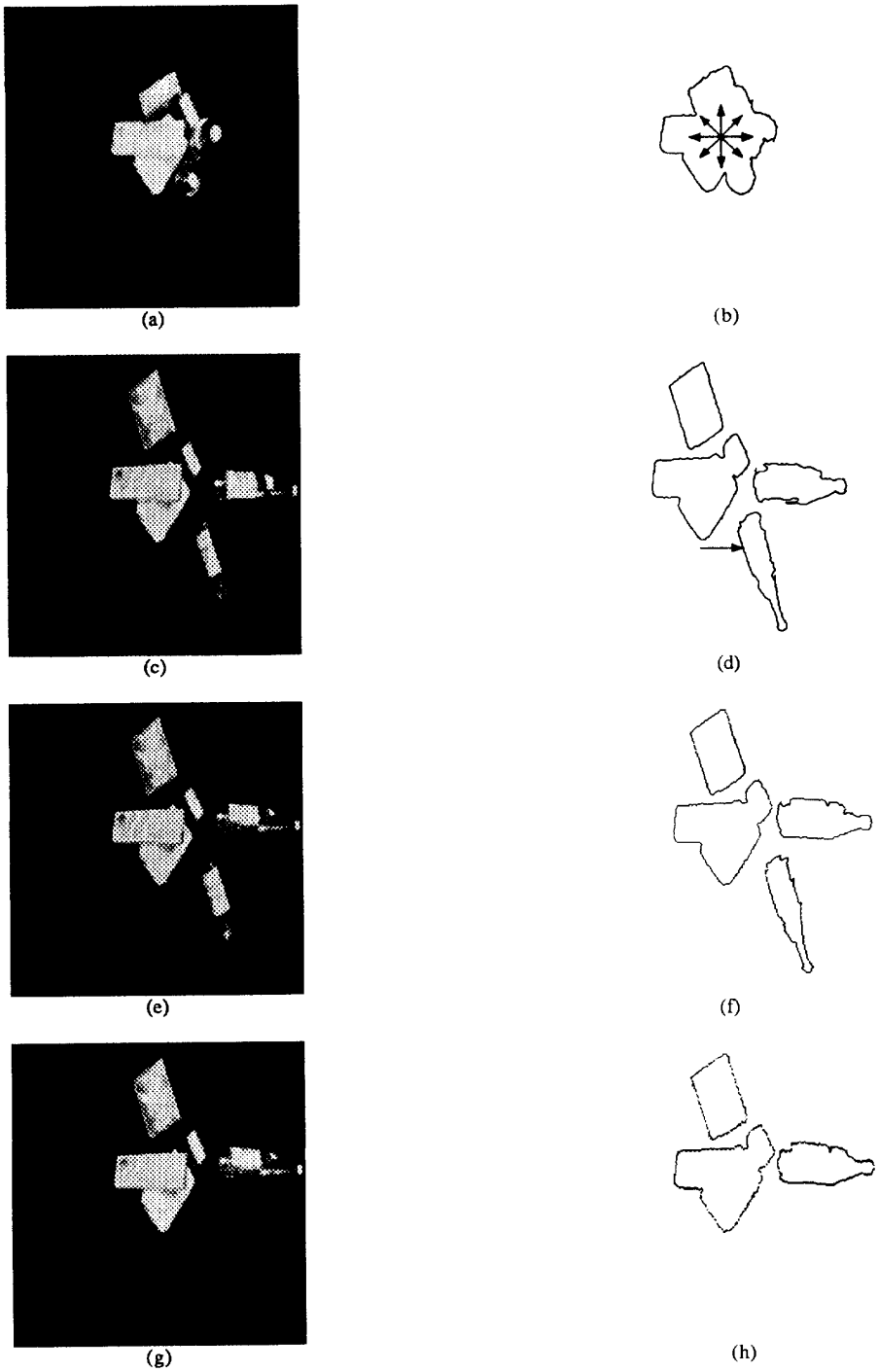

Fig.5 A cluster of objects to be disassembled. (a): Initial status; (b): boundary after visual analysis and pushing directions. (c): Image after pushing; (d) boundary with pushing direction; (e) image after pushing; (f) boundary after pushing; (g) the object recognized by shape (a bottle) has been removed; the procedure continues by visual analysis (h).

5. CONCLUSIONS

In this paper we have proposed a general robotic system for investigating disassembly problems. We have also pointed out that many factors contribute to make disassembly an extremely promising field for robotics research, 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 followed approach 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. In this paper, the integration of tactile and visual data with active exploration ("pushing") procedures has been examined and the application of the robotic system 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: on one hand we are investigating the processing of different visual features such as regions and motion; on the other hand we are extending the capabilities of the 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.

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