Flexible disassembly systems—layouts and modules for processing obsolete products

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Abstract: Currently, a significant amount of worldwide research is dedicated to manual or automated disassembly. This field of application has progressed remarkably over the past few years because industry has been forced to consider new technologies for processing electronic waste. This is due to changing environmental legislation, increasing amounts of obsolete appliances, decreasing landfill space and a growing public awareness of environmental problems. These considerations lead to growing research, development and implementation of manual and automated disassembly systems which are able to process a wide range of obsolete electronic appliances.

The present paper investigates different prototypes of manual and automated disassembly cells at disassembly companies and research institutes. The approach, technology and architecture of these systems are described. Typical hardware components of flexible disassembly systems are then identified and explained. Furthermore, suggestions are made for modularization and standardization of these components, even if only at a very cursory level.

Keywords: flexible disassembly systems, recycling, modularization, environmental legislation

1 INTRODUCTION

Environmental aspects have gained increasing attention in the last decade. This is due to the fact that natural resources are becoming scarce and waste dump capacity in many industrial countries is already limited by legislation. In Germany and the Netherlands, for example, the opening of new waste dumps is no longer allowed. The existing ones are predicted to be filled by 2005 [**1**].

Different market studies illustrate that within the next few years the estimated amount of obsolete products returning to the manufacturers will increase exponentially. Mass processing technologies such as dumping, shredding or burning currently prove to be economic solutions for many kinds of simple household waste and small consumer electronics. Complex technical products, however, require different strategies, as they are often remanufactured, used for the recovery of exchange parts or contain toxic components, demanding their removal before recycling. Here, disassembly has to be applied. Regarding the disassembly technology, most disassembly systems are manual or mechanized, as many steps cannot yet be performed by robots owing to the uncertainty of the products. The products typically processed on disassembly systems are large and medium-sized electrical products such as TV sets, computers, home electronics and copy machines. As their disassembly is very expensive, great effort has been made over the last few years by way of research and development towards automation. The expectation on automated disassembly, however, has not yet been fulfilled owing to the severe constraints on disassembly technology. Disassembly systems have to deal with missing product information, varying products, different product conditions and unpredictable material behaviour and product states. Common layouts of disassembly systems are the disassembly line, the flexible cell and the single workstation [**2**]. Systems having flexible transport systems, and to some extent automated or mechanized workstations, promise productivity by maintaining high flexibility. They are therefore seen as suitable for processing great numbers of large and medium-sized electrical appliances. Disassembly systems can be fully automated, hybrid, mechanized or manual.

Disassembly cells are applied to sort materials, to remove hazardous materials and to recover exchange parts. For the first application, destructive methods are applied, but for the other two applications, non-destructive disassembly is favoured [**3**]. At the Fraunhofer Institute for Manufacturing Engineering and Automation in

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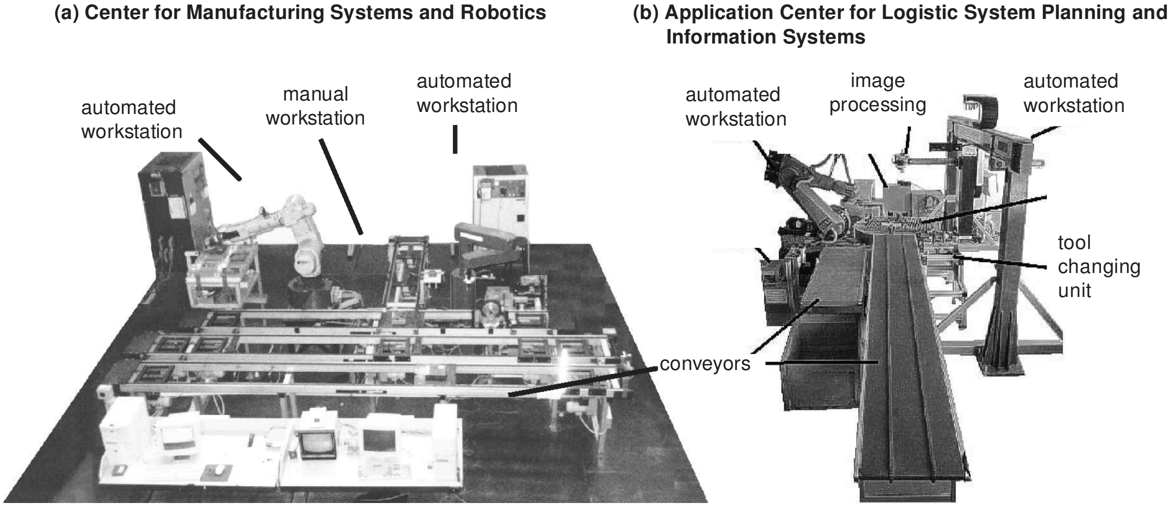

Fig. 1 Examples of hybrid disassembly cells

Stuttgart, a research system for the disassembly of cars has been installed. In this system, car roofs are removed with the aid of two robots and a vision system [**4**]. At the Bremen Institute of Industrial Technology and Applied Work Science, an autonomous robot cell for the disassembly of car parts has been installed. The system is provided with a robot, a handling system and a vision system as well as disassembly tools [**5**]. Two other exemplary disassembly cells with a high degree of automation are depicted in Fig. 1, where (a) shows a disassembly system at the Technion in Haifa, Israel, and (b) shows the disassembly system at the BTU in Cottbus, Germany. These and other systems presented in this paper are mainly prototypes, developed at research facilities and companies. Their layout and degree of automation as well as their typical elements are the point of this paper. Furthermore, different modules (of which they consist) are discussed, leading to the proposal of modular and application-specific disassembly systems. The software to control such systems is equally important as the hardware, but this topic is not covered in the present paper (see, instead, references [**2**] and [**6**] to [**8**].

2 DIFFERENT SOLUTIONS FOR DISASSEMBLY CELLS

In the last few years, a remarkable number of semi-automated and automated disassembly systems have been developed. Most of them were planned and built at research institutes and research departments in companies in order to gain experience with a technology that will become a crucial cost factor in the future. As they all have different approaches, it is of great interest to compare these solutions in order to find the common approaches for different and specific problems. An overview of the systems considered in this paper is depicted in Fig. 2.

2.1 Application Centre for Logistic System Planning and Information Systems

The disassembly system at the Fraunhofer Application Centre for Logistic System Planning and Information Systems [**9**, **10**] presents an approach for the automated disassembly of TV sets (Fig. 2a). It consists of an industrial robot system with knowledge-oriented software and an image processing system. The system is exclusively designed to process obsolete TV sets and monitors with a disassembly time of 5–7 min for a TV set (over 200 devices per day). The basic element of the cell is a flexible, programmable disassembly station which reacts to different product types and to variations in the product caused by different treatments during use. It consists of a disassembly robot [a four-degree-of-freedom (4 DOF) portal robot], using disassembly tools to loosen connections with or without connecting elements, a robot with different grippers for the handling of components (6 DOF Kuka robot), a tool changing unit, fixtures such as clamps and a centre tool, a conveyor system, programmable robot controllers, safety sensing devices and an image processing system. For each appliance, a dispatcher accesses the database containing the disassembly programs for the robots. This database is permanently expanding, leading to a learning system. With the increasing gathered data, the number of products that can be disassembled in the cell increases. After starting the product-specific programs for the robots, the appliance is channelled into the disassembly system. Firstly, the back cover of the TV set is removed, followed by the PCBs, electronic components and the picture tube. The disassembled components, as well as the rest of the cover, are then channelled out of the cell by a conveyor.

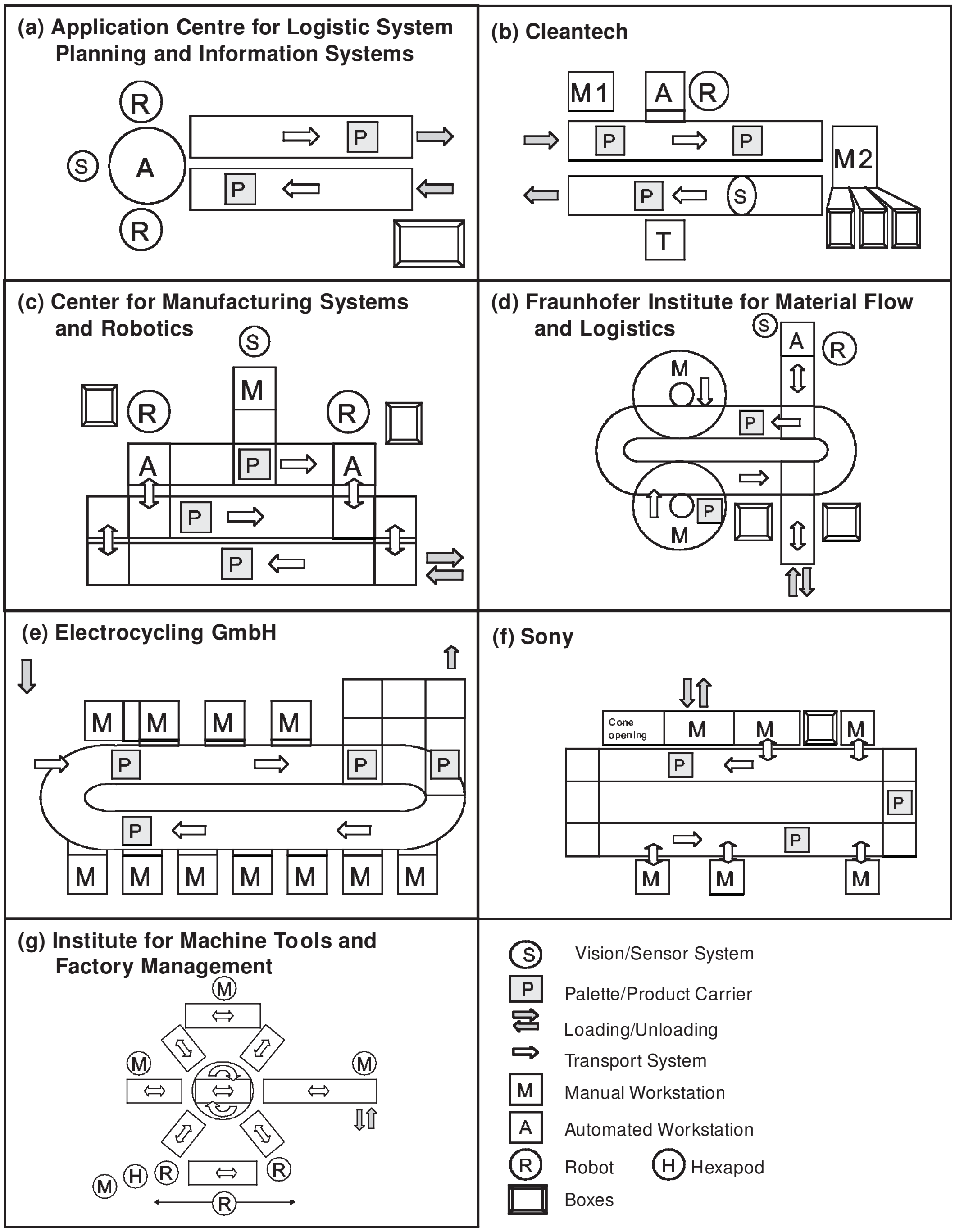

Fig. 2 Layouts of existing disassembly cells

2.2 Cleantech

Within the scope of a research project, a disassembly cell for the processing of electrical planing machines and high pressure cleaning machines has been established in Bochum, Germany [**11**]. It consists of three workstations connected to each other by two linear conveyors. One of the workstations is automatic, two are manual. They are modular in design. The automated working system primarily performs the unscrewing operations. The actual removal of the small components and their separation is then carried out manually. At the second manual workstation, cleaning with an air stream for dust, wet cleaning for oil and dirt as well as testing are carried out. Specific emphasis in the design of this system has been put on ergonomical aspects of the manual workstations (Fig. 2b).

2.3 Centre for Manufacturing Systems and Robotics

The flexible disassembly cell at the Technion's Centre for Manufacturing Systems and Robotics [**12**] in Israel consists of two robots (a 6 DOF Mantec and a 4 DOF

GM Fanuc) and a loop-like automated conveying system. The conveyor is continuously running and has stoppers and elevators. Besides the two automated stations a third station for manual work has been installed. This station is equipped with a vision system, identifying the current state of the product and the process (Fig. 2c). It is currently used as a prototype to disassemble car radios. The products are carried and fixed on to pallets. The system is designed to run multiple pallets simultaneously. The pallets can be identified by an electronic non-contact badge/detector. The access of pallets to the system is carried out by having separate in- and out-segments. The general and more complicated layout of the transport system allows for individual orders of operations for each pallet, leading to high flexibility. The conveyors in front of the workstations allow pallets to be stored in order to get high utilization. A computer vision and inspection station is under construction. The process plan is automatically generated and adapted at the running process using Petri nets. While the process is running, a genetic algorithm for scheduling optimizes the order of operations and defines the order of release of products.

2.4 Fraunhofer Institute for Material Flow and Logistics

The disassembly cell at the Fraunhofer Institute for Material Flow and Logistics in Dortmund, Germany, consists of two manual workstations and an automated workstation with a 6 DOF Stäubli robot. At the automated station, the screws and the cover are removed. A three-dimensional vision system supervises the automated process. An extension for the automated removal of cables and components is planned. An additional station is used for loading and unloading products. The transport system has a circular structure with branches out to the workstations. This allows for arbitrary material flow as well as repeating operations. Circular transport systems lead to the manual workstations, allowing buffer pallets in front of each workplace (Fig. 2d). The system is capable of processing products of up to 40 kg weight and to 600 mm × 480 mm size. The disassembled products are various types of microwave. Sensors and a vision system support the automated workstation and the handling of different types of product [**13**].

Obsolete products are manually loaded on to pallets which fix and carry them through the system. They are additionally equipped with a mobile information carrier. This information carrier is loaded with process information for the specific product, allowing much to be downloaded to the workstations giving necessary information to the disassembly worker and to the robot. With this, only the general information about a product type has to be taken from the central database. Five fractions are disassembled: metal, plastics, copper, cable and complete parts for reuse. Disassembly-specific tools applied in the process include a tool for cutting cables and one for unscrewing.

2.5 Electrocycling

The disassembly plant in Goslar, Germany, is set up for approximately 21 000 t of electronic scrap a year [**14**]. The disassembly is mainly conducted manually by conventional tools such as chisels, tongs or screwdrivers. Electrocycling has different disassembly lines: a line for telephones, a line for light appliances up to 5 kg, a line for medium-sized appliances, TV sets and monitors up to 50 kg, a line for heavy appliances up to 200 kg (which is equipped with adjustable tables and special lifting devices) and a special line for screen tube processing. After being dismantled, the separated components are conveyed to the subsequent process steps or are collected in special containers.

The disassembly line depicted in Fig. 2e is used for processing products weighing 5–70 kg such as CD players, TV sets, computers and microwaves. Parts to be separated are batteries, capacitors, LCDs, glass tubes, copper coils and circuit boards. A circular transportation system carries pallets with the products to the workstations. With a switch that can be operated by foot, the worker stops a product at the conveyor ring and leads it across a line to his/her workplace. The plastic pallets have a metal frame for stability but do not fix the product. Besides the 11 manual stations, two loading systems with a lift are part of the system. After the disassembly process, the fractions are shredded. Specific tools used are air-pressured unscrewing tools and scissors.

2.6 Sony

In the disassembly cell at Sony in Stuttgart, Germany, TV sets are disassembled. The average disassembly time for one product is 10 min. Fifteen different fractions are separated (e.g. plastic, circuit boards, glass tube). The design of the system is completely modular, enabling changes in its architecture such as enlarging it to increase the capacity of the cell. The system modularity enables the worker's position to be changed with small effort.

The system consists of an automated transport system, which links together four disassembly cells with a test station and a loading/unloading workstation. The structure of the cell is circular and numerically controlled. One station is used for loading, testing, disassembly of the product back-cover and the ventilation of the tube. Three other stations are used for the remaining disassembly operations. Additionally, a test station is implemented. The pallets have a rough surface, which makes a special fixture obsolete. The pallets move on to the circular transport system and are lifted to the workplaces (Fig. 2f). An information carrier on the pallet records the binary status of the process (the product is disassembled or not). The pallet rotates until the information carrier indicates a finished process. The structure allows different processing times at the different manual workstations. The pallets are fixed at the workstations with bolts and are directly used as the work table. No automation of the actual process has been implemented [**15**].

2.7 Institute for Machine Tools and Factory Management

The disassembly cell at the Institute for Machine Tools and Factory Management in Berlin processes washing machines. This is associated with high demands on handling big loads, as washing machines are both heavy and robust. The approach of the cell (compare Fig. 2g) is to have an area where automated processes are conducted and to have another area where manual disassembly can take place [**16**, **17**]. This is to protect the worker from movements of the robots, but also to avoid negative impacts of emissions, e.g. from the plasma cutting. The transport system has a high degree of complexity. All elements of the transport system are bidirectional, and one element is even able to rotate. Transportation is done across the centre of the system, but it is also possible to bypass the centre between the two manual workstations and between the two automated workstations. The system is equipped with three robots, one of which is mobile and can be moved to either of the other robots. On the left-hand side, the robot is additionally supported by a hexapod system, which cooperates with the robot and can also hand out the products to a worker for manual operations. A special technology applied in the system is plasma cutting of the metal covering. Manual work is applied when automated processes fail or when processes are too complicated to be automated.

3 COMPARISON AND EVALUATION OF COMPONENTS OF THE SYSTEM

In the previous section, different architectures and approaches for flexible disassembly systems have been described. Although they appear to be different, they are mostly designed modularly and contain similar components. However, despite promising high flexibility, they all concentrate on a small bandwidth of products.

In addition to the more or less automated transport, a strong focus lies on mechanizing or automating processes. However, most manual processes are not avoidable, leading therefore to hybrid systems which combine manual skills with partly automated processes [**6**]. The hardware of disassembly systems consists of the actual disassembly workstation, a transport system, sensors, disassembly tools and containers for the separated components. The commonly followed strategy in designing a disassembly system is therefore to combine different modules being offered on the market. This approach is described by Wiendahl *et al.* [**6**]. An overview of the systems and their components is given in Table 1. In the following, different functions performed in a disassembly system are described, leading to general recommendations.

3.1 Workstations

The workstations are the places where actual disassembly is carried out. Workstations can be either automated, manual or hybrid. Hybrid stations are manual stations with special tool facilitating operations within the disassembly process. Only a few companies offer special workstations for manual disassembly [**18**]. At the investigated disassembly systems, the workstations are mainly designed to carry out specialized tasks such as identification, handling and separation. In addition, the fixtures and sensors are mostly adapted to these tasks. As a result, the flexibility of individual workstations usually appears to be low. To increase the flexibility of such a disassembly system, two or more workstations are linked together. The main tools in automated disassembly workplaces are robots with a high degree of freedom.

3.2 Fixtures

Fixing the product to the workplace is a requirement for automated disassembly but also useful in manual disassembly. Its task is to put a product into a defined position and to prevent it from changing this position during the process and during transport. The fixing technology can be destructive or non-destructive. As in disassembly the core of a product is often not reused, destructive fixing is applicable. The degree of automation of a fixture depends on its ability automatically to clamp and orient a product. In disassembly it is sometimes necessary to have an automatic orientation of the product that corresponds to the requirements of the different workstations. Generally, a fixture can be mobile (e.g. on a palette) or stationary on a workplace (see Section 3.6). Fixtures on pallets of a transport system are characterized by higher flexibility with regard to product-specific set-ups. However, a special fixture device at the workstation strongly depends on the logistics of the system. If the system consists of only one workstation and is designed for specific product types, the fixture device can also be installed at the workstation. If more workstations are applied, a palette-based fixture device should be preferred because of the higher flexibility and the reduction in set-up times for different product types.

Table 1 Overview of system components

Location	Processed products	Workstations	Transport systems	Sensors	Tools	Fixtures
Application Centre for Logistic System Planning and Information Systems	TV sets, monitors	Automated workstation with a 4 DOF robot for disassembly operations and 1× 6 DOF robot for handling operations	Two linear conveyors	Vision system with two cameras mounted on the 4 DOF robot, mechanical sensors, magnetic sensors	Different screwdrivers, saws, chisels, grippers	Special fixture table for TV sets and monitors
Centre for Manufacturing Systems and Robotics	Various electronic products (car radios)	Workstation with 4 DOF robot and workstation with 6 DOF robot	Loop-like conveyor system with special pallets, stoppers and elevators	Vision system with one camera mounted on the conveyor system	Special screwdrivers with screw sucking device, pneumatic chisels, grippers	Special fixtures mounted on the pallets
Fraunhofer Institute for Material Flow and Logistics	Various electronic products up to 40 kg and 600 × 480 mm (microwaves)	2 manual workstations and 1 automated workstation	Circular conveyor system with pallets	3D vision system mounted on the conveyor system, light sensors	Tools for unscrewing and cutting	
Institute for Machine Tools and Factory Management	Washing machines	2 stationary robots, 1 mobile robot, 1 hexapod, 2 manual workstations	Flexible bidirectional conveyor system and a modular workpiece carrier	Vision system, light sensors for the vision system	Tools for cutting and unscrewing as well as plasma cutting technology, hydraulic scissors	Products can be fixed by the hexapod
Electrocycling	Various electronic products (telephones, TV sets, monitors, light and heavy products)	Four manual or mechanized workstations	Separate conveyor system for every workstation to channel the products or components in or out		Conventional tools (screwdriver, tongs, chisels)	Special mechanical fixtures for heavy products
Cleantech	Electrical planing machines, high-pressure cleaning machines	1 automated workstation for unscrewing, a manual workstation for removal and separation operations, a manual workstation for cleaning and test	Automated conveyor system in ring structure	Light sensors for the conveyor system		
Sony	TV sets	Four manual disassembly cells	Circular conveyor system with pallets and lifts	Sensors only for the conveyor system		

Another criterion of fixing systems is the DOF and its capability of orienting a product. A simple fixture to keep the product clamped to a palette or a box on which the product is transported has no DOF. Some developed fixing systems, such as the disassembly system for car radios in Haifa, consist of a special gadget for holding and turning the product on one axis. New concepts based on hexapod technologies even offer 6 DOF [**19**]. Whether or not DOF are needed depends on the product type and its design.

3.3 Sensors

In flexible disassembly systems, sensors are needed to grasp information about the current progress of disassembly, about environmental influences and about product-specific parameters to transport the products in the system and to plan and control the disassembly process. Because of the complexity of technical products and the uncertainties in information about the use phase of a product, sensor integration is necessary for the automation of the disassembly process. Main tasks for sensors are object parameter recognition, positioning, monitoring and collision detection. Generally, visual and tactile sensors can differ in intelligence and complexity. In addition, the types of sensor are based on different physical working principles, such as mechanical, magnetic, electrical and optical principles, each having advantages and disadvantages. In considering the disassembly systems investigated, it can be concluded that highly sophisticated sensor systems are only demanded in automated disassembly workstations. Manual workstations only require easy sensors to increase the material and product flow.

Very common in automation is the use of vision sensors based on two dimensions (e.g. a camera) for object and parameter recognition and process monitoring. Two-dimensional image processing systems are used to find out the position of an object and to identify the component. A colour image processing system can be applied to receive additional information. If the application needs depth information, two separate cameras can be used. In more advanced systems, three-dimensional laser scanners are applied to obtain a three-dimensional image of the object.

Generally, in disassembly it is very difficult to identify objects, to recognize object conditions and to monitor the disassembly process. Sophisticated sensors applied to existing disassembly systems have often specific solutions for problems. Here, a big challenge for further research towards standardization and modularization could be identified. A main goal, besides the modularization of the hardware, is the development of compact program modules for general sensor tasks during disassembly.

For tactile sensors, reliable approaches exist for automated control of complex tasks. Most common in industry is the application of six-axis force/torque sensors mounted between the robot arm and the end-effector. Usually, one such sensor is sufficient to fulfil the tasks, but for a precise control more sensors are needed to integrate into the end-effector.

Other areas of sensor integration concern the control of the workflow within the disassembly system. Here, easy sensors such as light barrier or magnetic sensors are applied to control lifts, conveyors or the loading of workstations. For this, standardized and modular solutions have been developed by the industry and can be found in manual as well as in automated workstations.

3.4 Robots

The robots in automated workstations carry out both simple and complex motion tasks. Robots are usually mounted at a fixed position to support handling, separation and identification operations within a certain working space. Most common is the use of 4 DOF and 6 DOF robots in workstations. Sophisticated disassembly workstations are designed to use two robots simultaneously: one for handling tasks and the other for separation tasks. This is due to the decrease in expenditures for tool changing operations. Additionally, many separation operations demand additional handling of effected components to support the separation process. Such workstations are therefore characterized by an increased flexibility regarding product variants or separation processes. If the workstation is designed with only one robot, it is often necessary to support complex separation operations by means of flexible fixture devices (see Section 3.2) which can undertake the necessary object handling.

3.5 Tools

Flexible disassembly systems require special tools to carry out handling and separation tasks. Generally, tools can be divided into handling tools and separation tools. In addition, multifunctional tools are currently in development by various research groups. These tools are used particularly for processes with permanently changing demands on the end-effectors, such as automated disassembly. The advantage is increased processing times due to reduced tool changes.

Standard handling tools are two-finger parallel grippers, three-finger centric grippers, two-finger angle grippers, multipin grippers, vacuum grippers and magnetic stick grippers. Separation tools that are often used are chisels, tongs, screwdrivers for various kinds of screw, cutters and drilling or milling units. To save on disassembly times and to increase the reliability of separation operations, highly specialized tools have been developed for automated disassembly, such as screwdrivers with a sucking device, special unscrewing tools

[20], left-turning drilling tools [21], flexible disassembly grippers [22], special disassembly tools for destructive disassembly [23] and a hydraulic hammer for the fast disassembly of point-formed and point-welded connections [24]. An example for multifunctional tools is the order-dependent adaptable tool with gripper, unscrewing and camera module as developed by Tritsch [25].

Manual and automated workstations have different demands on the available types of handling and separation tool. Manual workstations usually require standard tools, such as screwdrivers, hammers and chisels, as human workers are flexible enough to carry out complex tasks with simple tools. The control of automated disassembly processes by means of standard tools is known to be very difficult because complex tasks have to be implemented in the robot controller. This is another reason why special tools adapted to automated disassembly have to be designed for at least the most common handling and separation tasks. For example, the most common joining technique used in technical products is the screw connection. The development of such specialized tools for unscrewing operations is profitable because they cause a perceptible increase in system performance. Therefore, for the automation of standard processes, it is suggested that specialized tools leading to better controllability, performance, reliability and economy be developed and used. Currently, research is being carried out to support these ideas.

3.6 Transport system

Besides the workstations, the transport system is the most important component of a disassembly system. It enables a reduction in the non-value-adding work in the process. Transport systems carry out simple linear or rotational motions. Transport systems always have input and output points, where the transportation of discarded products to the stations, as well as the removal of the processed products and the removal of boxes with collected parts and components, will be carried out.

The logical structure of the transport systems can be presented in loops, lines or combined layouts. A linear layout is mostly used if only one workstation is needed. The ring and combined layouts are used for flexible connection of various specialized workstations.

Two main types of transport system can be identified:

1. Transport systems with pallets, which are simultaneously used as product or workpiece carrier and fixture. The pallets are moved on belts and stoppers and are used to keep the position in a workstation. In some applications the pallets are also used as information carriers, where, for example, bar codes are attached for identification.
2. The transport system simply consists of the conveyor belt, or rolls, and the products are fixed by special devices at the workstation, for example the fixture device used to fix TVs and monitors at BTU-Cottbus.

Also, a difference in the drives (electrically driven or not electrically driven) can be identified. Currently, the development of modular transport systems and their automation has reached a high level, and they are used in a wide range of applications, such as manual disassembly lines, e.g. for the disassembly of motor blocks in the car industry.

3.7 Boxes

Boxes are used for the collection and handling of separated materials. The size and type of boxes are selected according to the type of material, the fraction size and the amount. Usually, plastic, metal and electronic fractions are to be separated, besides special fractions such as picture tubes. Large grid boxes are typically applied for plastic fractions and circuit boards. Toxic materials such as capacitors are usually collected in small containers at the workplace and are then placed in closed barrels. Small boxes with foamed materials are used for the collection of reusable components such as memory chips. A means of facilitating the separation into larger boxes for more than one workplace is the use of slides into boxes in the lower levels of the building, as applied at the electrocycling disassembly system.

4 CONCLUSIONS

Disassembly is gaining much attention in both research and industry. In particular, flexible, partially automated disassembly cells have been seen as the most promising architecture for the disassembly of complex electrical appliances. However, up to now many expectations have not been fulfilled.

When investigating and comparing existing flexible disassembly systems, a number of technological problems appear, making their application in industry still questionable. This is partly due to the fact that most solutions are very individual and do not utilize existing standardized components. Therefore, the knowledge gained by the systems is rarely transferred to other disassembly problems.

In this paper, different layouts have been discussed and analysed in order to identify general components. For this, the systems have been resolved to different single modules, which are discussed independently. First approaches for the modular disassembly workstations and transport systems are being researched [18, 26]. At manual workstations this is more advanced than at automated workstations, as they require less technology. Specific disassembly tools and sensor systems developed for some disassembly systems offer a broad spectrum for transfer, which should be utilized.

Future disassembly systems should be designed modularly, applying standardized components. For different elements, promising approaches already exist or are currently in development. Such a modular design not only offers cheaper and more reliable processes but also guarantees their reuse when the system is modified. To enable modular disassembly systems, not only do suitable components have to be developed but also clear interfaces have to be defined. Such modular disassembly systems can then be easily adapted to specific product types. Their components can also be reused for other systems when the primary system is not required any more.

However, expectations of flexible systems being able to process different kinds of product simultaneously have not yet been fulfilled. All disassembly cells presented in this paper specialize on specific products. This, however, is a realistic approach, as a specific manufacturer taking back its products requires an effective system that processes large amounts of similar products (e.g. car starters, car motors or copy machines).

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