Int J Adv Manuf Technol (2006) 30: 554–560
DOI 10.1007/s00170-005-0042-9

ORIGINAL ARTICLE

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Intelligent, flexible disassembly

Received: 8 August 2004 / Accepted: 22 April 2005 / Published online: 24 November 2005

Abstract Semi- or fully-automatised disassembly, especially of electr(on)ic devices, is a a hot topic today and not only because of the standardization by the European Commission (directive on waste from electrical and electronic equipment—WEEE). Usually, only toxic components are removed manually while the rest of the materials are shredded and disposed. Manual disassembly of such devices is today state of the art. Because of this EC regulation and the increasing amount of electronic scrap, manual disassembly will get more and more inefficient in the near future. Therefore, automation of the disassembly process is absolutely necessary. This paper deals with robotized, semi-automatised, flexible disassembly cells for minidisks, printed circuit boards (PCBs) and mobile phones in industrial use. Finally a new concept for modular disassembly cells based on "disassembly families", mobile robots and multi agent systems (MAS) is presented.

Keywords Assembly · Disassembly · Recycling · MAS · Intelligent control

1 Introduction

Assembly and disassembly processes are similar from the viewpoint of automation. While assembly automation is more or less a "classical" subject; disassembly automation is a quite new field.

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The average number of employees in some European countries in mechanical, automotive and electric companies is 200. Therefore they are "small or medium enterprises" (SMEs) and it can be assumed that about 20% of their employees are involved in assembly and, in the future, also in disassembly. Their products are manufactured 50% in small series, 30% in large series, 10% individual and only 10% in mass production [1]. Austria, Slovenia and other small European countries are typical examples.

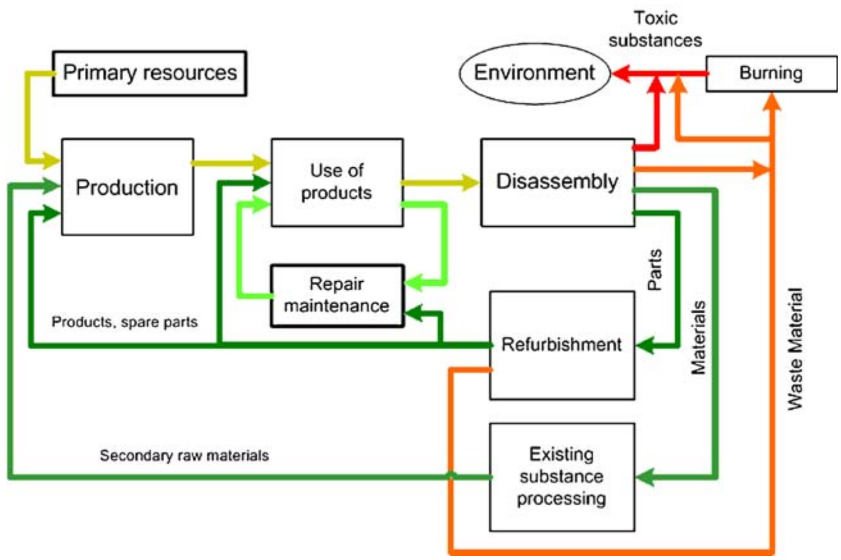
It can be assumed that only a few products are currently suitable for conventional assembly and disassembly automation. Rationalisation of both processes requires the introduction of flexible systems now and in the future. Successful assembly systems are going to be a combination of manual assembly, conventional assembly automation and robotized assembly systems and, in the future, the promising intelligent assembly systems. This is also valid for disassembly automation.

2 Disassembly

Electr(on)ic products have, like others, a life cycle starting with the production and ending with disassembly and material recycling (Fig. 1). Because of the tremendous increase in numbers of products such as computers, printers, telephones, mobile phones and other electronic consumer goods to be disassembled and recycled, a full or partial automation of the disassembly process is necessary to increase efficiency. The importance of disassembling, as the first step in the recycling process, will increase dramatically in the nearest future. Currently, disassembling is mainly carried out manually and sometimes mechanized.

For economic reasons, disassembly cells have to be highly flexible, accurate, sensor equipped and low-cost. Until now a very high standard in the field of automation and robotics has been reached, but the focus was only on assembly. Therefore, the degree of automation in disassembly is currently very low—only some pilot or demonstration projects have been realized, mainly in research institutes.

Fig. 1 Product life cycle [2]



Existing automation concepts are very inflexible and only developed for a special task or product. "Stiff" automatised disassembly in single purpose cells—only for one product (e.g. one type of PC)—cannot be economically feasible today.

The number of devices or parts to be collected and concentrated on at the disassembly cell is usually too low for a two shift operation of the cell. For example, in the case of computer keyboards of a distinct type, all keyboards from entire Europe per year could be disassembled in three months by one semi-automatised cell.

Economic disassembly is only possible today by *modularity of the robotized cells*. The main innovative features of such cells will be: ability to disassemble different products with only few soft- and hardware modifications of the system, low investment costs, step-by-step investments because of the modularity, and that the predominant working conditions (toxic vapours, etc.) could be changed efficiently by the system. Because of the modularity it is easily possible to build up disassembly cells for different product groups.

The number of devices to be collected and concentrated on at the disassembly cell is usually too low for a two-shift working cycle of the cells. Therefore, a new approach is forming for relevant product groups—so called *disassembly families "*[2]. These are groups of different products with nearly the same size that require nearly the same disassembly operations.

2.1 Realized disassembly cells

In the following, some realized examples of semi-automatised disassembly cells are presented.

2.2 Disassembling of Mini Discs

Sony DADC Austria is one of the largest producers of optical storage units with Mini Discs as their main product some years ago. Some of the produced Mini Discs did not satisfy the quality standards. Due to the rising waste disposal costs and the high costs of human work, an automatic recycling of Mini Discs was the key aspect of this research project. There were two different types of Mini Discs: a playback-only and a recordable.

An assembled playback-only Mini Disc consists of the following parts: upper cartridge, label, disk, clamping plate, shutter lock, shutter and lower cartridge. The recordable Mini Disc has two shutters, one on each side. The clamping plate is made of a special type of magnetic steel and the label is made of paper. The upper and lower cartridge and the disc consist of Polycarbonat, while the shutter lock and the shutter are of Ployoxymethylen.

The designed disassembly cell (Fig. 2) consists of two main components: a feeding system and the disassembly system itself. Furthermore, there is the cell control unit, a transportation unit between the two components and sensors to control all operations.

The feeding system takes the Mini Discs from a container. A recognition or inspection of the Mini Discs is not necessary, because every disk is equal. The transportation system is equipped with sensors to orient and align the Mini Discs.

Afterwards, the Mini Disc is taken into the disassembly system. It is fixed and cracked with wedges from the side. Now the upper and lower cartridge is separated. A vacuum gripper picks the upper cartridge and puts it into the special container. This process is controlled by an optoelectronic sensor. At the next stations, the clamping plate, the shutter lock and finally the shutter are removed with special tools. The parts are stored in different containers for further use.

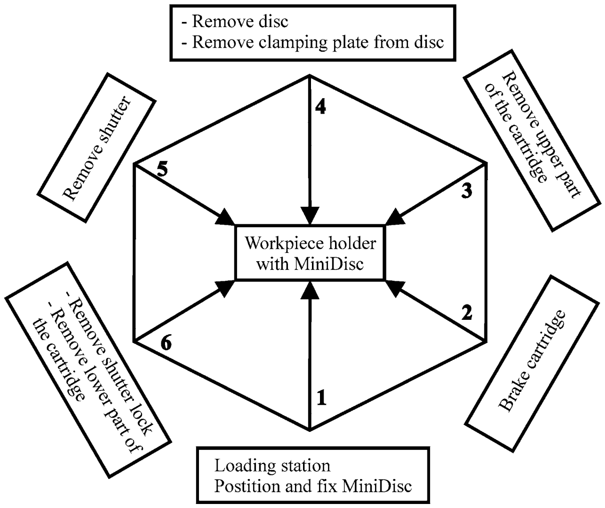


Fig. 2 Layout of the disassembly cell for Mini Discs

This cell operated very well for 10 years and then Mini Discs were replaced by other storage media.

2.3 Disassembly cell for printed circuit boards [2, 3]

The task was to develop a modular disassembly cell for removing re-useable electronic components from old as well as new PCBs. This disassembly process can be divided in several steps. At the beginning, the PCBs are dismantled from collected electrical and electronic equipment manually. Today automation of this process is not very efficient because of the complexity. But in the future we have to think during the design process about automatised assembly and disassembly—assembly and disassembly oriented design.

The layout of the cell is shown in Fig. 3. The basis of this disassembly cell is a very stiff frame construction developed from commercially available profiles. In a manual feeding station, the PCBs with a maximum size of 300×220 mm are attached on special workpiece holders [4].

The PCB disassembly cell consists of a transportation system, a vision system, a de-soldering station, a station for removing socketed parts and a heating de-soldering station. The parts to be disassembled are usually in the same position attached to the printed circuit boards. Therefore feeding of the cell is done manually. In the first station, the "vision system", the components on the PCBs are identified and by means of the host computer classified into valuable, environmental relevant and remaining components. To determine the position coordinates and other component data, a high resolution image detecting system is especially necessary and is realized in the module "vision system". The re-useable components to be disassembled are localized and identified on the printed circuit board. This information is transmitted to the control computer (CC) and to the next stations, e.g. the de-soldering and the robot system. The vision system must be able to detect a position with an accuracy of +/–0.1 mm (coordinates, etc.) and determine the characters (number and letters) on the parts (optical character recognition OCR) with an average probability of 95%. This information about the parts will be stored in the CC database. The de-soldering system is able to detect the electronic components (position, geometry, dimensions of the part, etc.) from the CC, which are directly fixed on the printed circuit board. The robot system has several tasks: to remove socketed components, to pick up de-soldered parts and put them into appropriate storage devices (magazines).

The de-soldering process is carried out by laser technology. The diode lasers are moved by a cross table. The desoldered parts are put on a buffer store outside the laser. An

Fig. 3 Layout of the disassembly cell for PCBs

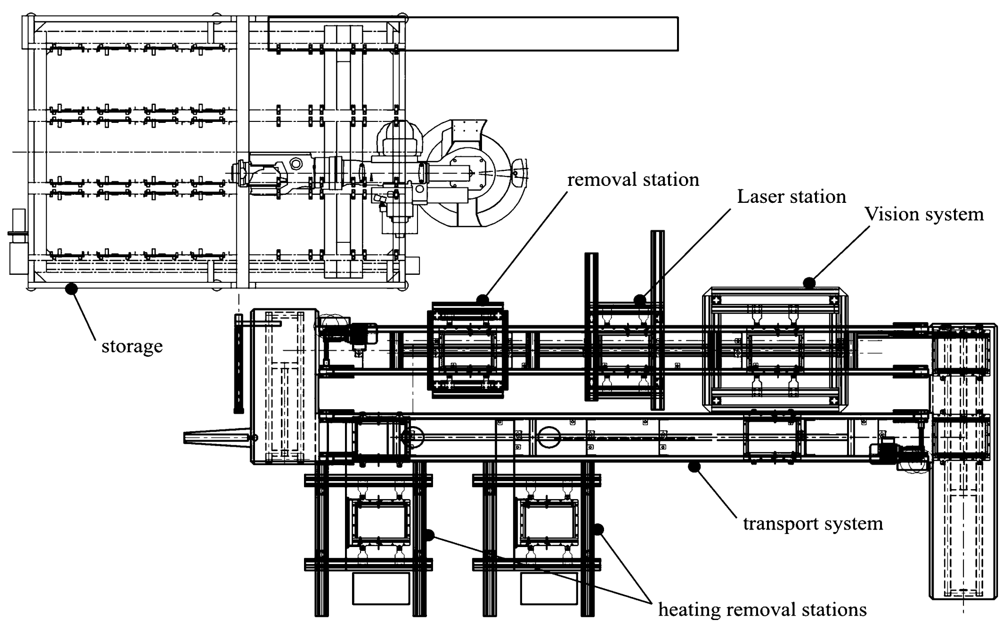


Fig. 4 Industrial disassembly cell

industrial robot picks up these parts and puts it into the appropriate magazines.

The third station is the removal station for socketed parts. The same industrial robot equipped with special grippers as well as external sensors removes these parts and store them in magazines.

For large, discrete and inexpensive parts like transistors, condensers, and inductors the heating-removal station was developed. Such parts are de-soldered with temperatures between 110 and 380 degrees and should not be overheated because of their functionality. These parts are usually distributed over the whole PCB. The kernel of this station is a temperature controlled heating device with 3 kW of power. The control of this station gets information from the vision system and the host computer. In addition to the other stations it also receives the temperature limits of each part. According to this information a suction gripper or a gripper mounted on a cross-table picks up the parts during the heating process. The parts are then removed and stored in magazines. After one shift (8 hr) the magazines will be changed.

We chose a robot with a reasonable accuracy ±0.2 mm, a reasonable payload (15 kg) and a relatively innovative controller based on the operating system Windows NT. This robot also offers the possibility to work with signals from simple low-cost sensors (e.g. micro switches). A multi-purpose gripper equipped with simple sensors as a weighted compromise between flexibility, costs and time was developed. As the demand for real time could be branched out to lower level controllers, it was possible to implement the control system using Microsoft Visual C++ under Microsoft Windows. Hence the user interface is intuitive and easy to use. The CC displays the actual state of all modules within the cell and has all components for network connection. So a remote access maintenance system using an Internet connection can be used. One industrial disassembly cell (Fig. 4) is in use since the beginning of 2001 and works very efficiently.

An Internet connection between several cell robots allows the transfer of data for statistics as well as new programs, program upgrades, and program parameters. This could be a first step in the direction of so called “e-robots”.

2.4 A semi-automatised disassembly cell for mobile phones [5]

Fortunately, new mobile phones (2–3 years old) have more and more a standardized construction. Unfortunately, the size of the mobile phones will be smaller and smaller in the future, determined only by the size of the human fingers to operate the keyboard. Usually in mobile phones there are a lot of re-useable parts, e.g. some PCB’s from the printed circuit boards, some contacts and the microphones. Furthermore, the housing of the phones is usually a very expensive material.

Problems arising during the development of the cell include:

1. There is only uncertain information available to recognize from the barcode the exact type of the phone.
2. The mobile phones have different dimensions and different forms.
3. The producer of the mobile phones usually uses very different screws with different heads but fortunately with nearly the same diameter (1.25 mm).
4. The materials are quite different-therefore it is very difficult to obtain the optimum milling and drilling speed.

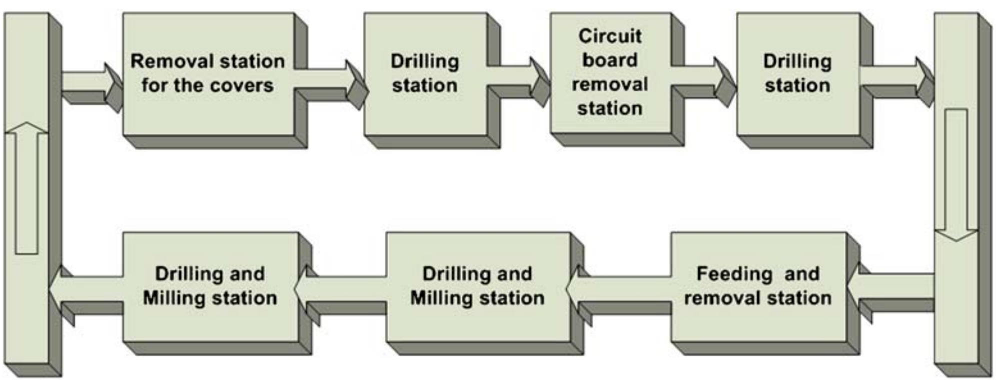


Fig. 5 Layout of the disassembly cell [5]

5. Some of the mobile phones are assembly-oriented constructed-e.g. some damping material is glowed on the plastic parts of the mobile phones.
6. It is very difficult to remove some spare parts like microphones, contacts, antennas, LCD displays from the mobile phones.

After a detailed analysis of used mobile phones concerning the parts, as well as the assembly technology and tests for disassembly with the most common mobile phones, the following concept for the disassembly cell was created (Figs. 5, 6, 7).

The cell consists of five automated stations: a feeding and removal station, a drilling and milling station, a removal station for the covers, a drilling station, and a circuit board removal station. There is also an additional drilling station, plus a manual feeding and removal station.

Before a mobile phone is fixed on a workpiece holder, the power supply will be removed and the type of the phone will be manually recognized by a barcode reader. Then, the control computer knows exactly the type of the phone. The main dimensions of the phone are stored in a database of the host computer.

For an exact positioning of the mobile phones on the workpiece holders a special construction with positioning pins is used. The transportation system is a very simple commercially available construction consisting of aluminium profiles with two lateral movements. According to the necessary disassembly operations, the workpiece holders with the mobile phones are stopped, lifted and fixed in a distinct station.

The drilling and milling station consist of a frame of aluminium profiles with pneumatic cylinders for the workpiece holders. For milling, two semi-automatised, commercially available milling devices are used. These are controlled via a serial interface from the host computer as well as from the PLC. The positioning is carried out by a simple Cartesian robot with 3 DOFs.

In the drilling and milling station the upper part of the phone will be cut off from the lower part and the screws, usually between 4 and 17, are removed by a simple drilling mechanism. The dust content is removed by air from the workpiece holder.

Fig. 6 Industrial disassembly cell for mobile phones

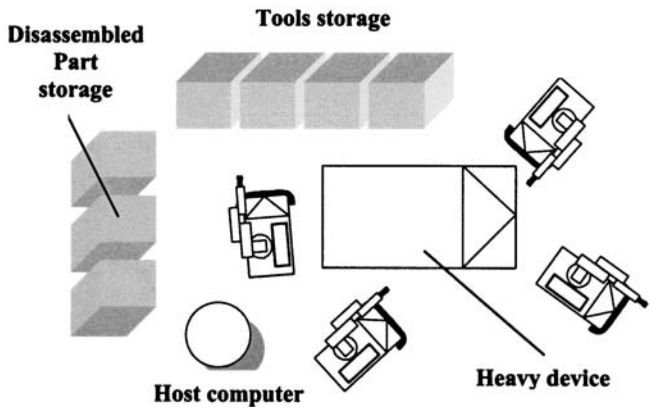


Fig. 7 Disassembly multi agent system (DMAS)

In the third station, the cover removal station, the cover as well as the keyboard are removed by pneumatic sucks. These two parts are separated in a storage device. In the next station, the drilling station; the screws are removed which connect the printed circuit board on the lower part of the housing. In the printed circuit removal station various other parts will be removed from the phone and put in special storage devices. Because some mobile phones have additional parts connected with the power part of the housing, the remaining screws will be removed in the last drilling station. Finally, the lower part of the phone will be removed in the fixing and removal station.

For development of this semi-automated disassembly cell for used mobile phones, some previous tests were necessary. In the drilling and milling station it was necessary to make tests with grinding wheels, different saws and with milling devices. Finally, a milling device was chosen as the right tool for this task.

Further extensive tests were carried out for the removal of the screws. From the literature there are very highly sophisticated, complicated and therefore very expensive and heavy devices known to exist, but we found a very simple and very cheap method for removal of the screws.

The next two drilling stations are identically constructed and are used for removal of the screws from the upper and lower side of the mobile phones. Both stations consist mainly of one electrical screw driver positioned by a Cartesian robot.

The printed circuit board removal station consists of a pneumatic suck as well as a control level electric driven parallel gripper. The movement in the x and y axes is carried out by an electric position axes, the movement in z direction is carried out by pneumatic cylinder.

This semi-automatised modular partially intelligent disassembly cell for mobile phones was developed based on considerable experience with similar cells for assembly as well as disassembly. Therefore, it was not necessary to use industrial robots. Because of economical reasons—costs of the cell—only simple Cartesian robots operated by controlled x, y and z axes are used. One cell is currently in the test phase and a while a second is being improved upon in construction.

2.5 Summary

As previously outlined for assembly and disassembly, only stationary, mostly unintelligent robots are currently used. Existing disassembling plants are only “single purpose plants”. Most electric and electronic products can be classified into product groups and disassembled either semi or fully automatically. A modular system for creating flexible, intelligent, “low cost” disassembly cells was developed. It consists of fully compatible hardware (robots, tools, grippers, changing systems for tools and grippers, transportation devices, image processing systems, etc.) and software modules (cell planning, simulation, control, image processing, knowledge based systems, etc.), partially adapting commercially available modules, and some additional developments. The capabilities of the system will be shown by demonstrators for different types of video recorders from the consumer products group, various types of PCs including peripheral equipment from the office and information devices group and different types of mobile phones from the communication facilities group.

Therefore, the main innovative features of the proposed system are:

1. The ability to disassemble different products of a product group with few software modifications of the system
2. Low investment costs
3. Step-by-step investments because of the modularity
4. The predominant working conditions (toxic vaporous, hard work) could be changed efficiently by the proposed system
5. The work security and job quality will be increased
6. Because of the modularity it is easily possible to build up disassembly cells for different product groups

2.6 Perspectives in disassembly

Mobile robots offer new possibilities, e.g. for flexible disassembly of huge and heavy devices.

In terms of the mechanical construction, electronics, control and software architecture, the complete vehicle is based on a modular, component based design concept. The purpose of this modular approach is to facilitate easy maintenance, system modification and improvement, combined with faster customization.

In addition to stationary robots, mobile robots for disassembly should be (a) intelligent in the sense of path planning and able to communicate with other robots, (b) cooperative with other (stationary or mobile) robots, and (c) able to form a disassembly multi agent system DMAS, which is one of the future possibilities for reducing disassembly costs [6, 7]. Derived from multi-agent-systems (MAS), such systems are one of the key technologies for constructing decentralized, adaptive, intelligent and complex systems. A DMAS consists of several “agents” (soft- and hardware) working together towards a common goal, having different features for specific subtasks. Therefore, only the definition of a global task is necessary for a DMAS. The software of the system divides this global task into a number of subtasks. The “agents” try to fulfil these subtasks in a cooperative way.

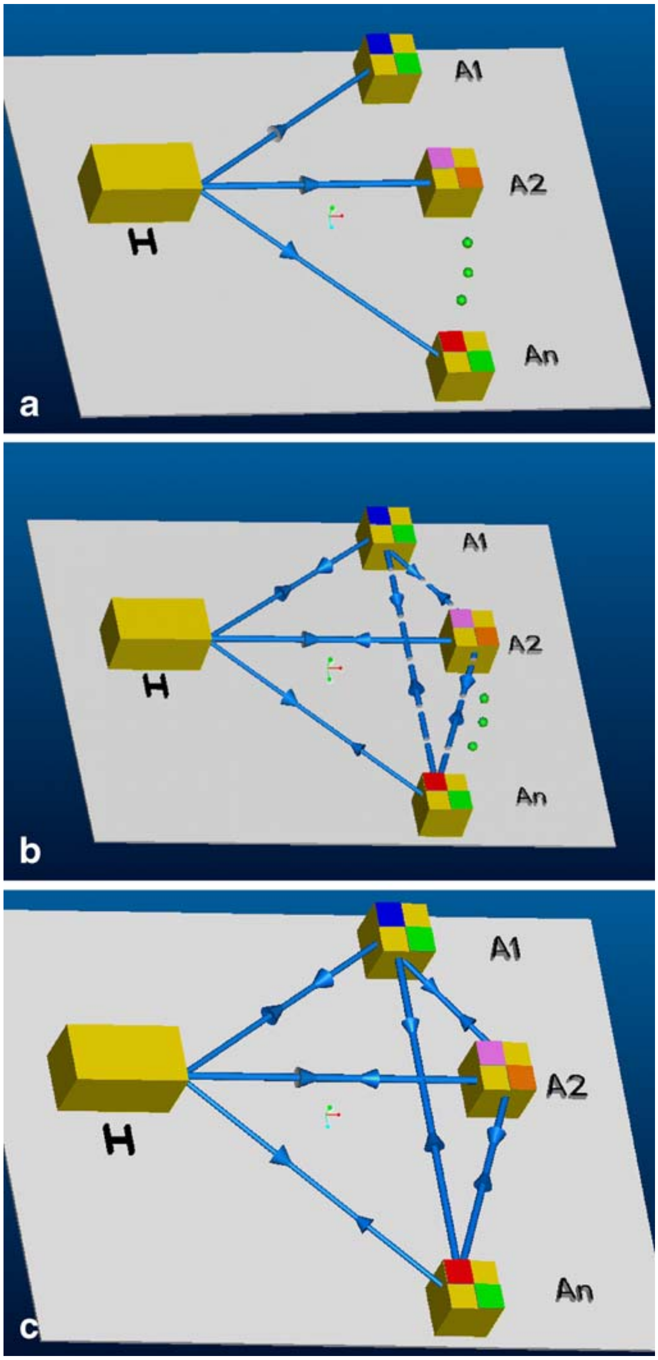


Fig. 8 **a** Hierarchical communication between host and the agents **b** Bi-directional communication between host and the agents and partial communication between the agents **c** Full communication between host and the agents and among agents

The features of a “technical” agent are:

1. The ability to optimize one or more processes simultaneously

2. Autonomy, i.e. an agent can make its own decisions to stabilize the current state and to improve this state to reach an optimum for the whole system
3. Communication and interaction, i.e. to reach this optimum each agent must interact with the other agents in the MAS
4. Especially for intelligent mobile robots (agents)—forming a DMAS—cooperating in CIM or ims systems, some additional features of these are necessary based on:

   a. Modularization of hard- and software
   b. Realization of distributed information systems
   c. Formal description of interactions
   d. Distributed control architecture
   e. Distributed and decentralized planning
   f. Cooperative game and optimization theory

For heterogeneous robots it is difficult to implement the communication because each robot has its own kinematic structure and programming language, etc. Furthermore, the range of frequencies used for communication and the capability of RF modules is limited. It is necessary to develop standardized communication protocols and methods, which should be one area of study in future years.

Fig. 8a shows the present situation of the unidirectional communication between the host (H) and the agents (A 1, A2, .., An). Solid lines indicate full communication while dotted lines depict restricted (partial) communication. In the future, the agents should also communicate with the host and with the other agents, as shown in Fig. 8b and c [7].

3 Summary

In this paper an overview on the development of assembly and disassembly is given from a practical as well as theoretical viewpoint. Realized industrial projects by the authors were described and shortly discussed. Finally an outline is given for future developments of disassembly systems, such a multi agent assembly and disassembly systems.

Acknowledgement Parts of these projects were supported by the Austrian Ministry for Science and Technology.

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