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Micro-robotic handling solutions for PCB (re-)manufacturing

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Abstract

The wide investigation of the last decades on a variety of electronic products in order to increase their performance while miniaturizing them, has raised new issues related to their manufacturing, remanufacturing and reuse at their end-of-life. This scenario introduces further challenges, related to demanding specifications, to be addressed with enhanced or new (re-) manufacturing processes, innovative systems, and advanced strategies. In this context, this paper discusses some challenging applications exploiting novel automatic solutions on different complexity levels of the process, from the component to the whole system, including devices, tools and robotized work-cells developed by the authors.

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Keywords: Micro-assembly robotics; electronics manufacturing; PCB remanufacturing; collaborative robotics; micro-handling.

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1. Introduction

In the last decades, electronic products have been widely investigated, leading to the development of enabling technologies, processes and devices in many fields, including smart manufacturing, automotive, aerospace, and biomedical. Their progressive miniaturization calls for smaller and smaller components, integrating an increasing number of functionalities. Therefore, an optimization of the PCB (Printed Circuit Board) structure and components

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layout is required. This approach is very beneficial in terms of achievable performance; however, due to the large amount of PCBs in different products, new issues related to the remanufacturing and reuse of the end-of-life (EoL) products arise [1]. Recent industrial trends strongly promote these concepts as paradigms of the so called "circular economy".

This scenario introduces further challenges, related to demanding specifications, to be addressed with enhanced or new (re-)manufacturing processes, innovative devices and tools, and advanced strategies, widely investigated with different approaches. In the (re-)manufacturing processes of PCBs, the manipulation of micro-components requires high precision, reliability and high throughput, difficult to be achieved at the micro-scale due to the adhesion forces often hindering the process, therefore limiting the overall performance of the conventional systems.

In this context, the current paper discusses some challenging applications exploiting novel automatic solutions on different complexity levels of the process, from the component to the whole system, including devices, tools and robotized work-cells. Section 2 investigates the main issues, challenges and trends related to the PCB (re)manufacturing, while in section 3 the role of robotics is discussed. The successive sections present some micro-robotic handling solutions developed in the last years by MEDIS (Micro Enabled Devices and Systems) group of the Institute of Industrial Technologies and Automation of the National Research Council of Italy (ITIA-CNR).

2. Issues and new trends in electronics (re)manufacturing

The customization trend of electronic products requires manufacturing systems which can be rapidly reconfigured and optimized for many varieties of production batches, even very small ones. Current SMT (Surface Mount Technology) manufacturing systems are weak in this capability. SMD placement machines typically represent the bottleneck of SMT assembly lines, becoming the key-issue for assembly line optimization [2]. High throughput pick-and-place 3D robotic systems for new demanding PCB are required [3].

The control parameters of the assembly equipment should be effectively adjusted in real-time. The dynamic changes of the manufacturing environment, working conditions and necessary motion accuracy are challenging to be assessed, requiring the implementation of a fine-tunable high-performance adaptive control scheme [2]. Manufacturers are developing new assembly machine architectures [3] with innovative motion control optimization techniques [4], to increase pick-and-place machine performance. Other relevant issues in BGA (Ball Grid Array) manufacturing operations are [5]: solder application, reflow, cleaning system, solder joints inspection. Quality tests are crucial, due to the long time they require. Tests results are highly variable and the cause of failures may not be traceable. In order to mitigate these issues a design for test (DfT) approach can be adopted [6].

The management of EoL products is a relevant issue in modern electronics. The re-manufacturing consists of a set of technologies, tools and knowledge-based methods to recover and upgrade PCBs and components from post-consumer products, to support a sustainable implementation of the circular economy paradigm [1]. Most of the issues are common to manufacturing, such as the precise placement and alignment of micro SMT components, solder paste application, inspection of solder joints. The remanufacturing of customized products is limited by the lack of processes, technologies and methods complying with the new requirements in terms of efficiency, flexibility and reconfigurability. Due to the rapid innovation in the field of electronic technologies, electronic systems can get outdated and redundant much earlier than expected [7,8]. The resulting several product variants on the market, with highly heterogeneous and often unknown structures and components, together with a lack of knowledge of the EoL product to rework, limit the performance of current re-manufacturing systems. Complex products are still designed with obsolete design principles, hindering their automated disassembly and re-manufacturing, that have to be therefore performed manually [8]. Remanufacturing of BGAs is more difficult with respect to other packages because solder joints are placed under the component body [2].

Improvements in design and manufacturing technologies to enhance integration and performance enable the development of devices with embedded components into the inner layer of a rigid PCB (embedded PCB) [9], of flexible PCBs, or of solder-free PCBs. Moreover, thanks to thermosets and thermoplastics molding technologies, PCBs can be designed with 3D complex shapes as 3D Molded Interconnect Device (3D-MID), to respond to new demanding applications (biomedical implants, ergonomics in automotive, etc.) [10]. The necessity of many varieties and small batch productions of electronic devices leaded to novel manufacturing technologies, such as 3D printing and hybrid additive manufacturing technologies for PCB prototyping and small scale productions [11].

In re-manufacturing, the increasing awareness of the need to manage the electronic products at their EoL has stimulated the development of new approaches towards efficient and flexible technologies to enable PCBs recovery and to collect re-usable components. From the analysis of the EoL product significant improvements in products design can be brought, e.g. applying the concepts of the design for disassembly and remanufacturing [7,8]. Linking the electronic product characteristics (i.e. components, reflow parameters, fixturing, etc.), and disassembly and remanufacturing plans, is a new trend to enable an automated and adaptable re-manufacturing process. Moreover, the development of flexible and reconfigurable tools, consisting of standardized modules and minimum application-specific elements, is a key-approach to support and improve the adaptability to different automated processes, while saving setup costs [12]. The inspection based on visual sensing, such as X-rays, hyper-spectral and 3D vision systems, is widening and more commonly adopted to assess the effectiveness of the re-manufacturing process [13].

3. The role of robotics in PCB (re-)manufacturing.

In the (re-)manufacturing processes of PCBs, the automated manipulation and assembly of micro-components (such as resistors, capacitors) with sub-millimetric size and different properties (e.g. shape, material, color) requires high precision, reliability, flexibility, throughput, and low cost, that can be achieved by automated work-cells integrating high-performance robots, gripping tools, sensing systems, and control strategies.

In general, the new issues related to PCB (re-)manufacturing impose new challenges in the design, development and control of both hardware and software equipment. System automation requires the use of one or more sensors providing specific information about the robot end-effector or the object to manipulate, as well as the working environment. Due to the reduced dimensions of the components, the use of precise positioning equipment and fixturing is extremely difficult, therefore vision systems play an essential role in the field of automated micro-manipulation, due to the variety of issues they can address, e.g. inspection, quality control, supervision or vision-based robot control [14]. The vision-based control and robot guidance increase work-cell flexibility and autonomy exploiting the visual information, to implement e.g. the look-and-move or visual servoing strategies.

Convenient micro-grippers and release strategies are fundamental for the successful execution of the manipulation operations, since the performance of the conventional gripping tools is limited by the influence of adhesion forces at the micro-scale (e.g. electrostatic, van der Waals and capillary forces). Indeed, as the component size decreases, their effects prevail over that of the gravitational force and can adversely affect the pick, the handling and the release of a micro-component [15]. For example, the undesired grip can occur due to a sudden electrostatic jump, or the release can be inhibited by the sticking of the component on the gripping tool due to the presence of a capillary bridge between them.

Moreover, the interaction between the manipulator and the micro-part can be monitored in order to guarantee the correct manipulation with the desired force and avoid damage of fragile micro-components: force sensing methods, for example, can be useful for robot control, implementing hybrid position-force or impedance control strategies. In addition, instrumenting the gripper with a force sensor can provide a contact feedback to implement a tactile control during the task [16].

Furthermore, symbiotic human-robot collaboration is one of the key-research trends about the evolution of robot control stimulated by Industry 4.0 [17], since the combination of human flexibility and the accuracy of the robot can enable innovative and effective (de-)production strategies. The trend of collaborative robotics, with relative safety requirements recently specified by [18], differs from the conventional robotics characterized by heavy and strong machines, operating in cages inaccessible to operators: mostly lightweight, their intrinsic safety highly enhance their flexibility. The flexibility introduced with collaborative robots can play an important role in (re-)manufacturing processes, requiring rapid and customized changes in the tasks.

4. The proposed novel robotic solutions

Challenging applications in the PCB (re)manufacturing include the re-balling of BGA packages, the precise positioning of SMT components in PCB structures such as conventional rigid planar PCB (2D packaging technology) or innovative embedded PCB (3D packaging technology), inspection and quality control. In the following, novel automatic solutions are proposed and discussed on different complexity levels (see Fig. 1).

The paper discusses the precise manipulation of different electronic components, such as micro SMD and solder balls. To handle these types of components, two methods and related devices are presented: a vacuum micro-gripper integrating an innovative release system, and a store-and-place device, able to single-sort micro-spheres with high throughput. Both tools have been prototyped and tested.

At a work-cell level, two systems are discussed: the former represents a vision-based robotized micro-manipulation and assembly work-cell; the latter includes a collaborative dual arm robot able to safely interact with the human operator and other robots for components handling and inspection. Finally, at a factory level, these two work-cells have been integrated to set up a pilot plant to support different PCB remanufacturing phases.

5. Manipulation devices and tools

5.1. Innovative vacuum gripper with integrated release system

Among the micro-gripping solutions, vacuum micro-grippers are being commonly used in electronics, mainly because of their simple working principle, reliability, structure, and actuation, and of the possibility to manipulate fragile components. A vacuum micro-gripper integrating an innovative system to support the release at the micro-scale was conceived and patented [19]. The release system is movable between two configurations so that it does not interfere during the picking phase but acts once the release is required. In the embodiment shown in Fig. 1, the gripper body consists of a main hollow part and a cannula with internal diameter *d*. The release system consists of a retractile thin needle with diameter $d_n < d$ and an in-built mass (disk), inserted into the gripper body. When the vacuum is applied, the release system lifts, and the micro-component can be sucked. When the release is required,

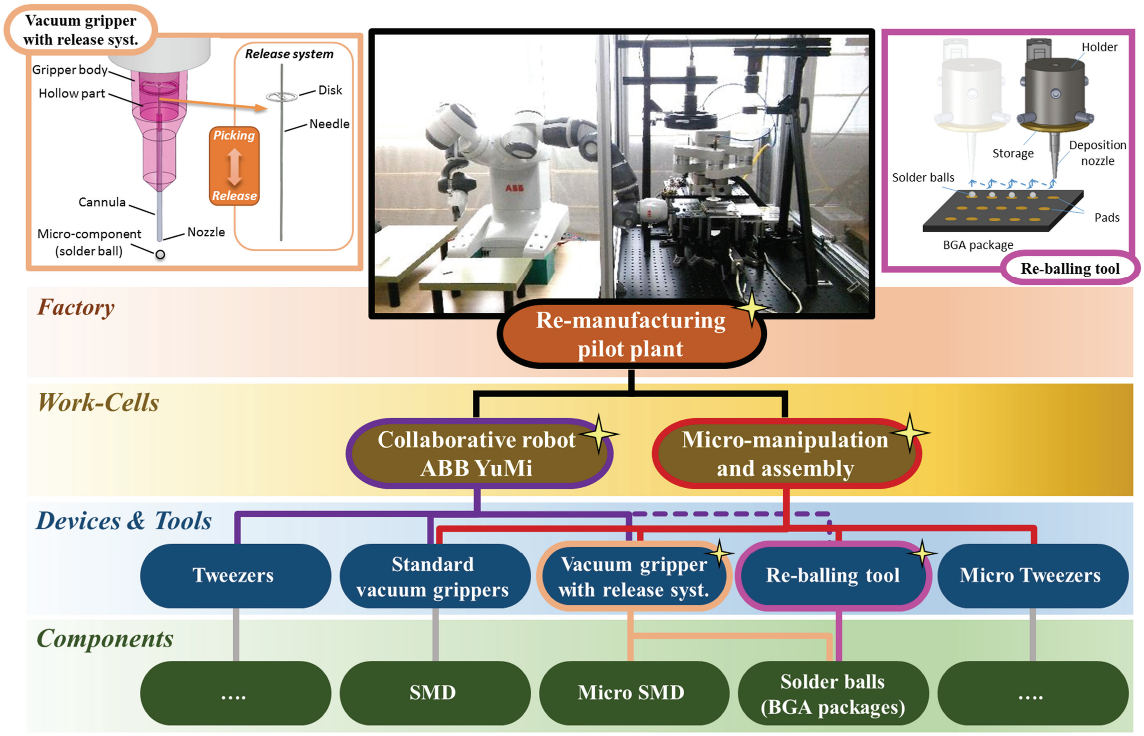

Fig. 1. Novel robotic solutions on different complexity levels.

the elimination of the pressure difference between inside and outside the gripper leads the needle to project externally from the nozzle, impacting the component then forcing its detachment. An interesting feature of this innovative device is the use of only one actuator (a vacuum ejector), for both picking the components and moving the release system, keeping the overall device simple and lightweight. Moreover, the micro-gripper has been designed to be easily mounted on a robotic system. Indeed, the prototype has been effectively integrated in the work-cell described in section 6.1 and tested in manipulating components of different shape, size and mass. In particular, solder balls with diameter of 0.5 mm and SMT resistors with size 1.5 x 0.8 x 0.45 mm have been used to assess its releasing performance. Both grasping and releasing tests were performed and the results demonstrated the ability of this gripper to manipulate micro-components better than a conventional vacuum microgripper, assuring a reliable release [20]. Solder balls with diameter of 0.6 mm have been manipulated for the "Pick-and-Place Re-balling" (P&PR) of a BGA package consisting of a 11x11 matrix with a pad diameter of 1 mm and a pitch of 2.5 mm. The task was executed with a degree of success of 100%, however the complete process was time-consuming [21]. Moreover, preliminary experiments on the picking and placement of SMT capacitors with size of 0.4x0.2x0.2 mm for the manufacturing of embedded circuits have been performed.

5.2. Re-balling tool

An innovative method for the re-balling of a BGA package was designed. This method, called "Store and Place Re-balling" (S&PR), is similar to the "Pick and Place Re-balling" procedure [21], but the task throughput is increased by the elimination of the picking phase of the solder spheres. A new tool was developed within the activities of the "FIDEAS" project to implement the S&PR, complying with the reconfigurability requirement of the de-manufacturing approach. The innovative tool allows to carry a specific quantity of identical solder micro-spheres in an integrated storage, singularize on site a single sphere, and finally position the singularized sphere with the desired precision.

The conceived tool is based on an innovative singularization mechanism that allows the sorting of a single solder micro-sphere from an unordered stock contained inside a storage, in order to isolate it from the others and deposit it in a specific position (i.e. in the case of the re-balling task, on the pad of the BGA substrate).

This device was designed to process a specific sphere dimension, therefore it is necessary to provide as many storages as the number of required sphere formats. For this reason, the tool was designed to be modular in order that the storages are easily interchanged on the tool holder by means of a removable connection. The device was designed to singularize and depose solder micro-spheres with a diameter ranging from 0.2 mm to 1 mm, however it can be extended to a wider range. In order to place the singularized sphere at a specific position with high precision, the device storages integrate deposition nozzles, designed according to the sphere diameters. Through the holder, the device can be mounted on the end-effector of a robot with suitable performance installed in all the automated stations for the rework of PCBs and the change of the storage can be executed automatically exploiting the robot movements and a storage holder.

The prototype of the mechanism was realized to experimentally validate its effectiveness and to assess its performance. Indeed, since the device handles sub-millimeter objects, it is affected by various issues related to the adhesive forces, that are not precisely estimable and that influence the multi-physic modeling and the related simulation results. The tool was then mounted in the micro-assembly work-cell (Section 6.1) for the re-balling of two different BGA packages with solder balls with diameter of 0.6 mm and 0.3 mm [21] respectively. The experiments have been performed moving the robot at 10% of its maximum velocity. The throughput was about 2 seconds per ball with a degree of success of 100% for both the BGA re-balling experiments.

6. Robotized work-cells

6.1. Micro-manipulation and assembly work-cell

A reconfigurable robotized work-cell was conceived and prototyped for manipulating and assembling micro-components for applications in different industrial fields [22]. The hereafter called "micro-assembly work-cell", installed at ITIA Micro-robotics Lab, integrates many devices that cooperate to execute the desired task. A Mitsubishi RP-1AH robot with 4 degrees of freedom and a good repeatability (e.g. ± 5 µm in the *x-y* plane) can access three working areas, whose planarity and compliance can be adjusted, that cover its working space and support the components to manipulate and assemble. These areas are monitored by three corresponding fixed 2D vision systems and a mobile one attached to the robot end-effector. Spatial resolution under 10 µm can be set according to the set up configuration. The robot can mount four different types of standard vacuum micro-grippers, the innovative gripper described in section 5.1, and pneumatically driven micro-tweezers, exchangeable by a tool change system. Moreover, the re-balling tool (section 5.2) can be mounted on the robot end-effector. The micro-components are usually available on the central area (Area 1), whose bottom view is provided by a camera installed horizontally and a mirror inclined at 45°. They are firstly randomly placed on the area, therefore identified by the vision system that sends to the controller their planar pose to allow the picking. The release components or substrates are fixed on the side areas (Areas 2 and 3) supervised by the corresponding vision system, that identifies the release sites before the placement and checks the success of the operation.

A software architecture developed according to the plug and produce paradigm was implemented for the control and the supervision of the task execution, including a user-friendly and intuitive HMI. Suitable machine vision algorithms and special calibration procedures are also available to enable the look-and-move strategy. In particular, three searching and matching algorithms have been implemented, that is pattern matching, geometric matching, and particle analysis. A method called "virtual grid calibration" was conceived and successfully implemented to simultaneously and automatically calibrate the cameras and register them with respect to the robot [23].

This work-cell, initially developed within the activities of the "REMS" project, represents an useful experimental setup for research activities on [14]:

- micro-gripper performance (tests on the gripping and releasing of micro-spheres and parallelepipeds to assess the vacuum gripper accuracy, repeatability, and reliability);
- release issues (investigating and comparing different strategies);
- unconventional calibration strategies (robot-camera, gripper);
- tests on the execution of challenging tasks in an assembly sequence;
- conception of innovative manipulation and assembly methods;

It currently represents a test bench for the placement of SMT components in planar and embedding PCB structures, and rework of high-value SMT packages.

6.2. Collaborative work-cell

As per the dissertations reported in the previous sections, a collaborative robotics work-cell was reputed appropriate for a pilot electronics assembly plant. The core system of the work-cell is the ABB IRB14000 YuMi®, a dual arm collaborative robot with 7 degrees of freedom per arm and a repeatability of ±0.02 mm. The robot can operate in conjunction with the operator or other robots sharing a certain workspace. Each end-effector equips a vacuum gripper, mechanical tweezers and an integrated vision system (camera, lens, LED) to inspect components and guide robot movements.

The layout of the work-cell was designed to efficiently exploit the two quasi-spherical working volumes of the robot and to enable the presence of the operator. As shown in Fig. 2, the work-cell was equipped with dedicated working areas; in the stand-alone configuration three working areas, reachable from both the robot and the operator, can be placed. The side areas represent the charge and discharge zones of the components, while the central area is used to assembly or inspect them. The position of the operator, in front of the robot, was chosen to easily access the central area and co-work with it. The collaborative work-cell is intended to perform mostly: the check of electronic components, thanks to its dexterously floating cameras, and the assembly of small products, even integrating electronic components. As an example of electronic components' check, the robot was taught to analyze different types of re-balled BGA packages, in order to detect missing solder balls. A potential application is related to the assembly of small mechatronic products for biomedical applications, such as ear prostheses, typically composed of a plastic case and miniaturized on-board electronics.

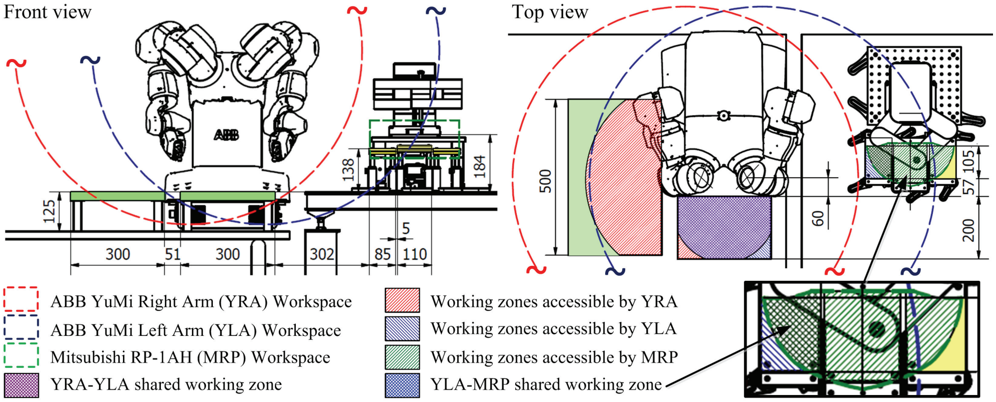

Fig. 2. Proposed pilot plant for the Remanufacturing pilot plant and interaction of the two work-cells.

7. Factory: Remanufacturing pilot plant

Starting from stand-alone work-cells, modularity design principles and standardization of interfaces (mechanical, electrical, etc.) enable the development of reconfigurable and scalable plants for (re-)manufacturing applications.

The work-cells can be combined to respond to new customized and demanding applications, changing their configuration and adding other modules to increase the plant capacity. The integration of the work-cells into a plant is achieved through specific technologies such as control systems, smart and distributed sensors, real-time communications, standardized information modeling, connectivity technologies, etc.

The work-cells described in the previous sections have been combined to realize a micro-assembly/(re-) manufacturing pilot plant for PCBs and electronic devices, developed within the “EDOC@WORK3.0” research project. The pilot plant exploits capabilities and performance of the component work-cells: high-accuracy micro-assembly and collaborative robotics. In the specific layout of Fig. 2, the left arm of YuMi (YLA) is intended to work in conjunction with both the right arm (YRA) and the micro-assembly work-cell, being able to access one of its side working areas (shared area). The resulting pilot plant is intended to be a sub-system of more complex plants for electronics industry. To explain this capability, a few feasible application cases are briefly described.

The first application case is a smart assembly of components (SMTs, THTs, mechanical parts) on PCBs for customized small batch production. The plant could generate several variants of products exploiting its flexibility and works in conjunction with a reflow station. YuMi provides the PCBs to the area shared with the micro-assembly work-cell (Area 2); several SMT components are recognized on the Area 1 through the vision system and accurately placed on the PCB pads. When the PCB is completely assembled, YuMi can perform an additional inspection and finally transfer it to the SMT reflow station. When the SMT reflow is completed, YuMi can transfer the PCB to its area shared with the operator that, with its cooperation, mounts the THT components and mechanical parts (heat sinks, connectors, etc.). Finally, YuMi executes a sampled quality control of the solder joints.

As a further application case, the plant can be exploited for the rework of electronic assembled parts such as PCBs, and other devices, and product quality control.

8. Conclusions

The paper presented some novel tools, devices and robotized work-cells for PCB (re-)manufacturing developed by the MEDIS group of ITIA-CNR. In particular, the work focused on the precise positioning of SMT components in conventional rigid planar PCB and embedded PCB, the re-balling of BGA packages for the remanufacturing process, the inspection and control of the task success.

A vacuum micro-gripper integrating an innovative system to support the release of the component, and a store-and-place device, able to single-sort solder micro-balls with high throughput, were presented. Both the tools were integrated in an automated work-cell demonstrating their potentialities. Indeed, at a higher level, a vision-based robotized micro-manipulation and assembly work-cell was developed pursuing modularity, reconfigurability, and user-friendliness. A further work-cell was also presented, that includes a collaborative robot for the handling, processing and inspection of components. The effective cooperation of these two work-cells was also demonstrated at a factory level setting-up a pilot plant for micro (dis-)assembly.

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