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Robotic Technologies for Proton Exchange Membrane Fuel Cell Assembly

Vladimir Gurau, Devin Fowler and Daniel Cox

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<http://dx.doi.org/10.5772/intechopen.71470>

Abstract

Proton exchange membrane fuel cell (PEMFC) stacks and their components are currently being manufactured using laboratory fabrication methods. While in recent years these methods have been scaled up in size, they do not incorporate high-volume manufacturing methods. In this context, manufacturing R&D is necessary to prepare advanced manufacturing and assembly technologies that are required for low-cost, high-volume fuel cell power plant production. U.S. Department of Energy (DOE) has identified high-priority manufacturing R&D needs for PEMFCs. Along with efforts to develop technologies for high-speed manufacturing of fuel cell components, DOE identified the need for demonstrating automated assembly processes for fuel cell stacks. The scope of this chapter is to review current manufacturing R&D efforts in the area of automated processes for assembling PEMFC stacks, to present the current state of development, successful demonstrations, related technological challenges and the technical solutions used to overcome them. An emphasis of this review is on the design of tools used for robotic grasping, handling and inserting fuel cell components in the stack and on the use of design for manufacture and assembly (DFMA) strategies that enable the automated assembly process.

Keywords: proton exchange membrane fuel cell (PEMFC), automated fuel cell assembly, robotic assembly, end-effector, design for manufacture and assembly (DFMA)

1. Introduction

Fuel cells have been advocated as clean, energy-efficient alternatives to internal combustion engines in vehicles and as power sources in stationary and portable power applications. For transportation applications, current focus is on direct hydrogen fuel cells such as proton exchange membrane fuel cells (PEMFCs), in which on-board storage of hydrogen is supplied

by a hydrogen generation, delivery and fueling infrastructure. In addition to the transportation fuel cell application, there is current support for distributed generation fuel cell applications with a near-term focus on fuel cell systems running on natural gas or liquid petroleum gas, as well as stationary, portable and auxiliary power applications where earlier market entry would assist in the development of a fuel cell manufacturing base [1].

Compared to other types of fuel cells, the PEMFC offers the advantages of delivering higher gravimetric and volumetric power density and for operating at lower temperatures, which result in a quick start up time and less wear on systems components. For these reasons, PEMFCs find today extensive applications in transportation and stationary uses. When compared to other types of fuel cells, PEMFCs dominated the market in recent years in both number of units and in total power shipped, accounting for over 65% of global shipments in 2015. PEMFCs generated a revenue over USD 2 billion in 2015 [2] and are expected to generate USD 12 billion in 2025 [3].

The PEMFC power plant consists of four main subsystems: (1) the fuel cell stack; (2) the balance-of-plant subsystem, which includes the water and thermal management modules, the air delivery module and the hydrogen generation/storage module; (3) the power conditioning subsystem and (4) system controls. The fuel cell stack and its components are currently manufactured using laboratory fabrication methods that have been scaled up in size but do not incorporate high-volume manufacturing methods. The entire fuel cell power plant is usually constructed by integrating its subsystems, but each subsystem is assembled separately by a labor-intensive process. In this context, manufacturing research and development is needed to prepare advanced manufacturing and assembly technologies that are necessary for low-cost, high-volume fuel cell power plant production. U.S. Department of Energy (DOE) has identified high-priority manufacturing R&D needs for PEMFCs. A summary of these needs include [4]: (1) to identify relationships between physical and manufacturing properties of fuel cell components, (2) to develop technologies for high-speed manufacturing of fuel cell components, (3) to identify the cost of PEMFC at several levels of manufacturing, (4) to develop agile, flexible manufacturing and assembly processes, (5) to develop automated processes for assembling fuel cell stacks, (6) to establish flexible automated manufacturing technology facility and (7) to develop production hardware for rapid fuel cell stack postassembly testing, including leak detection.

This chapter reviews the current manufacturing R&D efforts in the area of automated processes for assembling proton exchange membrane fuel cell (PEMFC) stacks and presents the current state of development, successful demonstrations, related technological challenges and the technical solutions used to overcome them. An emphasis of this review is on the design of tools used for robotic grasping, handling and inserting fuel cell components in the stack and on the use of design for manufacture and assembly (DFMA) strategies that enable the automated assembly process. Even though there have been demonstrated automated or semiautomated processes for manufacturing of some fuel cell components, this work is not intended to cover them. While the authors are not aware of any published or demonstrated automated technologies that integrate the automated manufacturing of fuel cell components with the automated assembly of fuel cell stacks, they will provide strategies for achieving this goal.

The PEMFC stack consists of several single (unit) cells connected in series (**Figure 1**) and clamped together between two end plates, usually using threaded components. A single cell

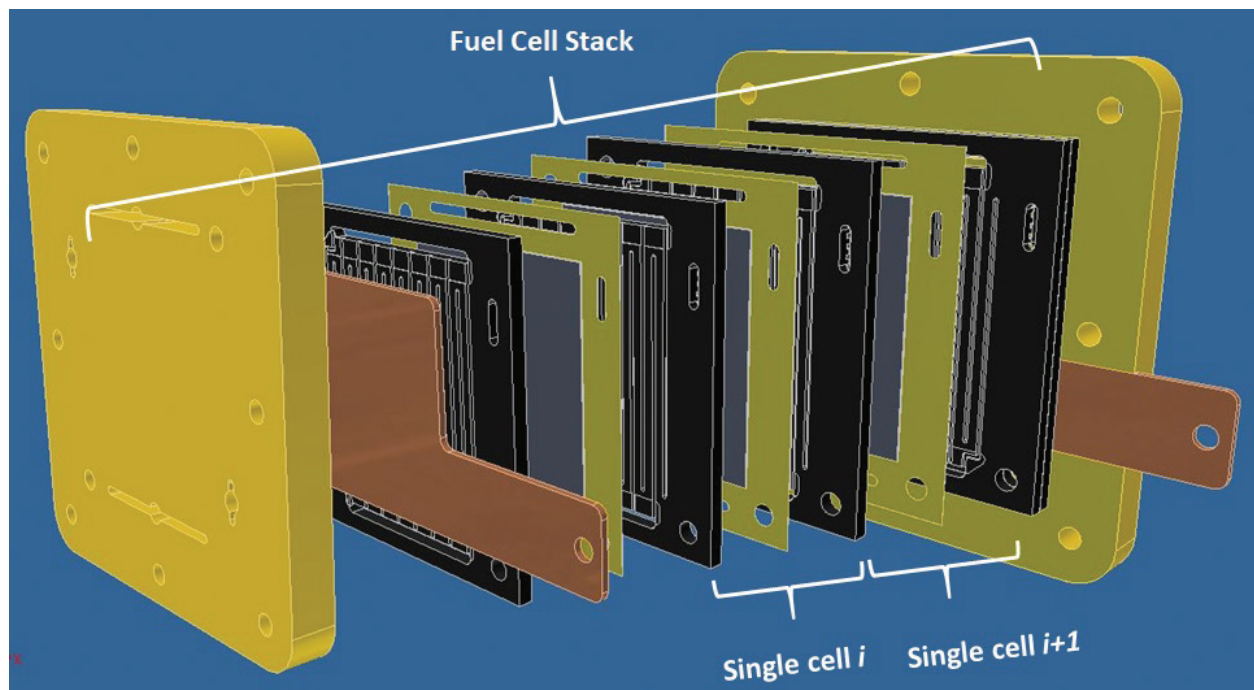


Figure 1. Exploded view of a PEM fuel cell stack consisting of multiple single (unit) cells.

consists of a membrane electrode assembly (MEA) placed between two electrically conductive collector plates that have a network of channels (flow fields) fabricated into the planar surfaces (**Figure 2**). The MEA consists of five components: a proton conductive membrane bounded by two catalyst layers, one on each side of the membrane, and two porous gas diffusion layers (GDLs) bonded each on the other side of the catalyst layers. In a fuel cell stack, the

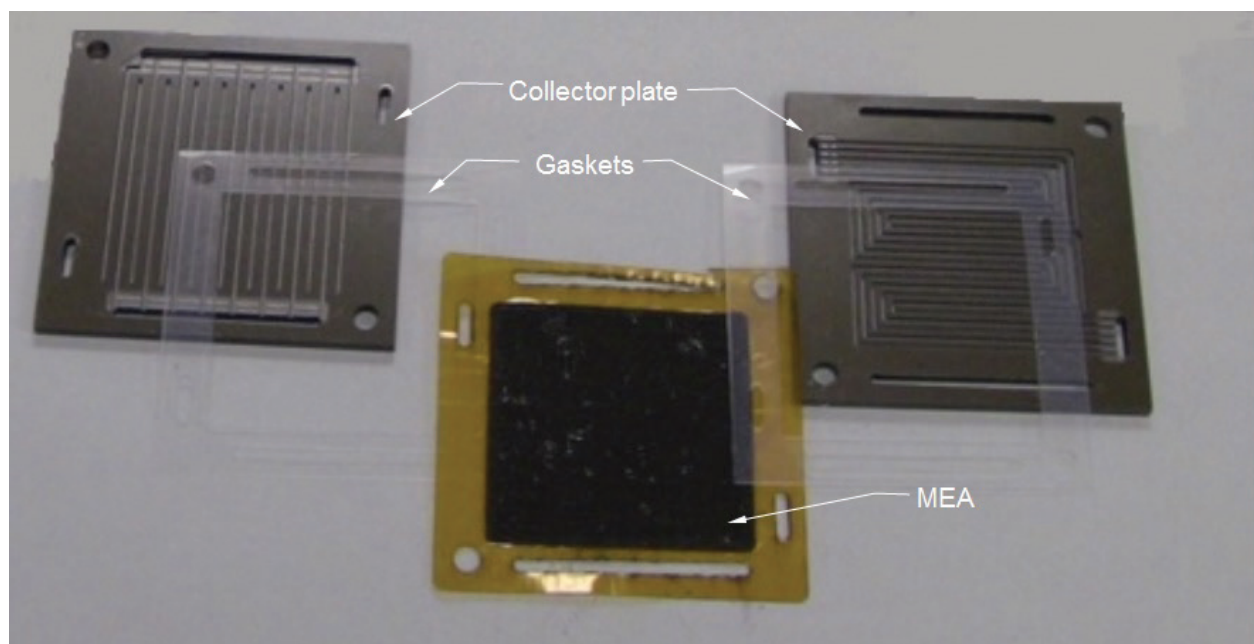


Figure 2. Components of a single (unit) cell.

collector plates have flow fields on both planar sides. One side serves as anode flow field for one single cell and the other side serves as cathode flow field for the adjacent single cell. In this case, the collector plates are called bipolar plates and have the additional role of connecting the single cells electrically in series. Each single cell is equipped with two gaskets placed on the peripheral area of each flow field, which are intended to prevent overboard reactant gas leaks or leaks between anode and cathode.

2. Justification for automated assembly of PEMFC stacks

Today, fuel cell stacks are assembled mostly manually in a lengthy process involving a repetitive work cycle in which human errors are common. A recent study of PEMFC system cost [5] based on application of standard DFMA analysis methods, including the *Boothroyd-Dewhurst DFMA*® software [6] estimated the time necessary to manually assemble PEMFCs to be between 0.64 and 0.83 minutes per cell. This result may support the conclusion that cost savings incurred by introduction of an automated stack assembly process are small compared to the overall PEMFC system cost. In the early stages of fuel cell prototype development, fuel cell stacks may be assembled manually, but the introduction of automated assembly processes becomes economically justifiable once the production quantity increases. Today, there are no fuel cell companies having the manufacturing capacity to produce more than a few hundred fuel cell systems per year. Three-to-four orders of magnitude increase in production rate will be needed for the transition to a hydrogen-based fuel cell transportation system [4].

Apart from an economic justification, there are other reasons for adopting automated processes for assembling PEMFC stacks. Fuel cell manufacturers must increase the production volume to continually reduce costs while improving quality, reliability, performance and safety. A justification reason for adopting automated assembly technology is related to the objective and subjective effects on the worker and on the product quality associated to the monotony of repetitive work cycles characteristic to assembly of fuel cell stacks consisting of large number of cells. A recent study [7] showed that a manual assembly process of a 20-cell PEMFC stack lasted on average 50% longer than the robotic assembly process. The delays in the manual operations, as compared to the operations performed by the robot, were in part due to periodic breaks necessary for the human operator performing a repetitive work cycle. These delays are expected to increase significantly as the size of the fuel cell stack increases. Automated fuel cell assembly processes are further justified when integrated into larger automation lines in which the fuel cell components are produced as well using automatic technologies.

3. Technological challenges

One of the most significant technological challenges represents the difficulty to align accurately the fuel cell components in the stack when the assembly process is executed by a robot

that has limited accuracy and repeatability and no joint flexibility (lack of compliance) [7, 8]. Assembly of fuel cell stacks requires perfect indexing and aligning of bipolar plates, MEAs and gaskets. Misalignment of components generates overboard leaks or leaks between anode and cathode of the reactant gasses during fuel cell operation. GDLs must fit within the central, open area of the peripheral gaskets without overlapping them. A minimum clearance between GDLs and gaskets must allow them to expand in-plane during the application of the compression load. In order to avoid component misalignment during a manual fuel cell assembly process, it is a common practice to use steel alignment pins mounted in one end plate along with positioning holes in the fuel cell components that are used to guide them along the pins.

Nevertheless, when the fuel cell components are inserted along rigid alignment pins that have a certain tolerance to position, straightness and parallelism by a robot arm with limited accuracy and repeatability and no joint flexibility (no compliance), this method alone will result in jamming and breaking the fuel cell components during their insertion process. The challenge of precisely aligning the fuel cell components in the stack increases with stack length, which is determined by its number of cells. Earlier research on robotic assembly of PEMFC stacks [9, 10] attributed these failures to a low bearing ratio (positioning hole diameter to component thickness ratio) characteristic to thin fuel cell components and to warping of flexible MEAs and gaskets. Later successful demonstrations of fuel cell robotic assembly processes [7, 8] were made possible by a careful selection of a combination of allowances between the alignment pins and positioning holes and between the GDLs and the peripheral gaskets, by using flexible alignment pins and end-effectors possessing passive compliance.

In an automated assembly process, a second significant challenge represents the diversity of fuel cell components that need to be grasped and handled by robot end-effectors. These components include graphite bipolar plates, thin, flexible rubber gaskets and membrane electrode assemblies (MEAs). Initial demonstrations of robotic assembly processes [9, 10] were based on expensive workcells using multiple robots, each equipped with a different type of end-effector for grasping and handling specific fuel cell components.

4. Design for manufacture and assembly of fuel cell components

A deterrent to successfully demonstrate automated assembly technologies for fuel cells has been an insufficient use of DFMA principles in designing components. There have been attempts to demonstrate robotic assembly processes using off-the-shelf fuel cell components that were not designed for an automated assembly [9, 10].

To reduce the manufacturing cost and shorten the product development time, DFMA principles must be considered in the earliest design stages of fuel cell components [11]. The fuel cell components must include design features that allow an accurate engagement and component alignment during pickup and release operations, as well as compensate for the robot limited accuracy, repeatability and lack of compliance [7, 8, 12, 13]. The *Boothroyd-Dewhurst*

DFMA analysis method [6] provides systematic procedures for evaluating and improving the product design for ease of assembly and quantifies the time and cost of the assembly process based on component design features.

Before analyzing DFMA recommendations and design solutions that address them, one must consider design restrictions specific to fuel cell components. The most important are: (i) PEMFC components are flat, thin parts. Their planar area may range from 1 cm² to a few hundred cm² while their thickness ranges from submillimeter-scale (gaskets and MEAs) to a few millimeters (bipolar plates). (ii) Most PEMFC components have no symmetry. The anode and cathode sides of MEAs have different catalyst loadings (mgPt/cm²) and often have different catalyst types. The anode and cathode flow fields of bipolar plates are not identical, their design depending on the required mass flow rate of gas and on special requirements for removing liquid water from the flow field. The orientation of the PEMFC components in the stack is important. (iii) Some fuel cell components (gaskets and MEAs) are flexible, having the tendency to bend or warp during their handling and insertion operations.

We will discuss next DFMA recommendations for robot assembly [6] that are specific to fuel cell components and will present design solutions that address these recommendations:

- i. Reduce part count. This is a major strategy for reducing assembly and manufacture cost. Often, MEA manufacturers readily integrate GDLs in the MEA assembly, but GDLs may be assembled separately in the stack. GDLs are thin, porous layers that are difficult to be handled by end-effectors equipped with vacuum cups. *KUKA Robot Group* demonstrated a robot assembly [14] of PEMFC stacks in which GDLs were picked and inserted in the stack as separate components. Peripheral gaskets are usually assembled as separate components, but they can be integrated with the bipolar plates. This solution reduces the gasket material waste. *ZSW (Center for Hydrogen and Solar Technology* in Ulm, Germany and *Zentrum für Brennstoffzellentechnik* in Duisburg, Germany) demonstrated automated PEMFC assembly lines in which liquid rubber was applied directly on the peripheral areas of bipolar plates and MEAs using a syringe [15] or screen printing technique [16] and then the rubber was allowed to cure before final assembly.
- ii. Include features such as leads, lips and chamfers that make parts self-aligning in the assembly. Due to limited accuracy and repeatability of robots, this is a vitally important method to ensure fault-free part insertion in the stack. Designs [17] of self-aligning bipolar plates using protrusions and recesses have been proposed (**Figure 3**). Due to MEA and gaskets tendency to warp, this technical solution may require holding down the components and securing them using special purpose fixturing that must be activated by the robot controller. This solution may add the assembly cost significantly. A successful solution for aligning and securing the components in the stack after insertion is the use of alignment pins mounted on the base end plate (**Figure 4**) and positioning holes in the fuel cell components. The clearance between the alignment pins and positioning holes must be equal or less than the clearance between the gaskets and the GDLs. This prevents the gaskets from overlapping the MEAs after insertion. As described earlier, since the alignment pins have a certain tolerance to



Figure 3. Design features used for self-aligning bipolar plates [17]. Source: United States Patent and Trademark Office, www.uspto.gov.

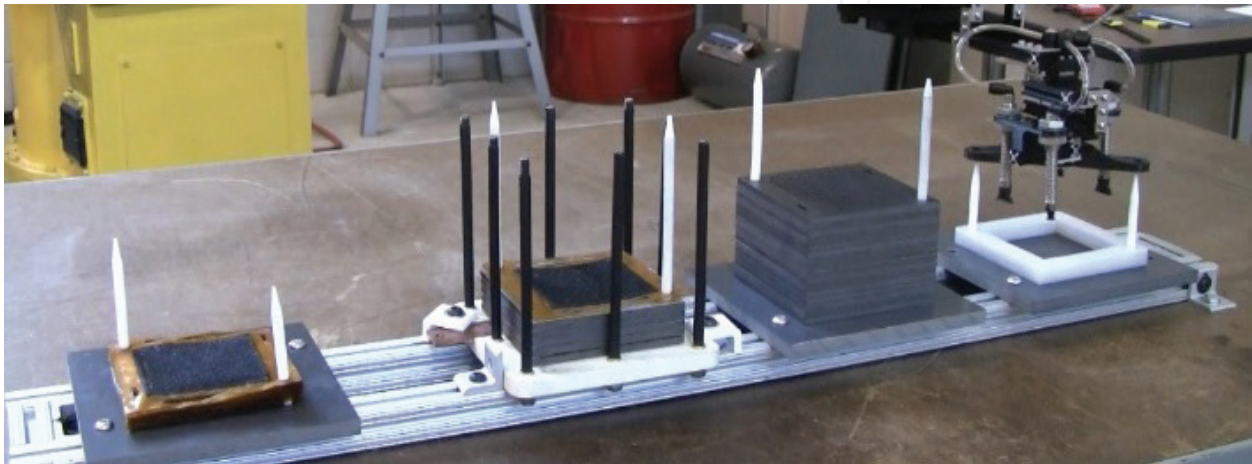


Figure 4. Component presenters and PEMFC stack (second from left) equipped with flexible alignment pins made of poly(tetra)fluoroethylene and used for locating component during pickup and release operations; reproduced from [7].

position, straightness and parallelism and since robots have limited accuracy, repeatability and no flexibility, components tend to jam and break during the automated insertion process. A demonstrated solution to this problem [7, 8, 12, 13] is the use of flexible alignment pins instead of rigid pins made of steel. When they are made of a polymer, the pins do not need to be extracted from the stack at the end of the assembly process, reducing thus the assembly cost. For ease of component insertion, pins can be designed with large chamfers. Alignment pins made from polymers are easier to cut to size and chamfer than steel pins. In addition to this solution, the end-effector may be designed with passive or active compliance.

- iii. Design features such that components do not require to be secured after insertion. The alignment pins discussed above locate the components after insertion even when MEAs and gaskets have the tendency to warp.

Other DFMA recommendations for robot assembly [6], such as designing products that can be assembled in a layer fashion directly from above, or avoiding the need for reorientation of the partial assembly, are generally satisfied by the PEMFC configuration and do not require special design.

5. End-effectors for manipulation of PEMFC components

The design of robot end-effectors must be integrated with the design of fuel cell components. They must be able to compensate for the robot's limitations in accuracy, repeatability and lack of compliance. To minimize the number of robots needed for assembly, to reduce the assembly cost and to enable designs of flexible robot workcells, it is preferable to design end-effectors capable of grasping and handling most types of fuel cell components. In addition, it is preferable to design end-effectors capable of assembling fuel cell stacks of any size (number of cells).

Initial demonstrations [9, 10] of robot workcells for automated assembly of PEMFC stacks used robots with different types of end-effectors, including double-acting finger grippers for clamping bipolar plates from their lateral surfaces and pneumatic end-effectors for manipulating gaskets and MEAs. Due to the thin configuration of fuel cell components, finger grippers designed for clamping them laterally and grasping from presenters require additional equipment such as feeders or feedback vision systems to determine their location at submillimeter scale and their speed appropriate for indexing during pickup and release operations.

Designs of inexpensive, more flexible end-effectors capable of manipulating all fuel cell component types have been demonstrated [7, 8, 12, 14]. They are equipped with vacuum cups and are designed to grasp the components from their top planar surface. Suspension mechanisms used to provide a soft touch and to reduce the machine need for indexing when picking up and releasing fuel cell components can be provided. The suspension mechanisms reduce the need for accuracy when approaching the component presenters or the stack and eliminate the need for expensive feedback visual systems (**Figure 5**).

To compensate for a general robot's limited accuracy, repeatability and lack of joint flexibility, end-effectors with passive compliance have been demonstrated [7, 8, 12].

The end-effector shown in **Figure 6** consists of three subassemblies connected to each other by two miniature linear blocks and rails oriented at 90° relative to each other. They allow the lower subassembly that grasps the fuel cell components and the top subassembly that attaches the end-effector to the robot wrist assembly to have a relative motion along the X and Y axes between them. Stoppers delimit each block's travel to about 3 mm along the rail. These linear blocks and rail system offer the end-effector a reliable passive compliance capability that compensates for the robot's limitations in accuracy, repeatability and lack of joint flexibility.

In addition to this, the linear blocks and rail system allow the end-effector to slide the positioning holes on the fuel cell components along the alignment pins when the latter have a certain tolerance to position, parallelism and straightness. This compliance system along with the conical tip of the alignment pins (**Figure 4**) may compensate for misalignments as large as a few millimeters, which are much larger than the usual limitations in a robot's accuracy and repeatability. The lower subassembly of the end-effector (**Figure 6**) has the role to pick up and release the fuel cell components and to align them along the alignment pins on one fuel cell end plate. Four level compensators equipped with suspension mechanisms and vacuum

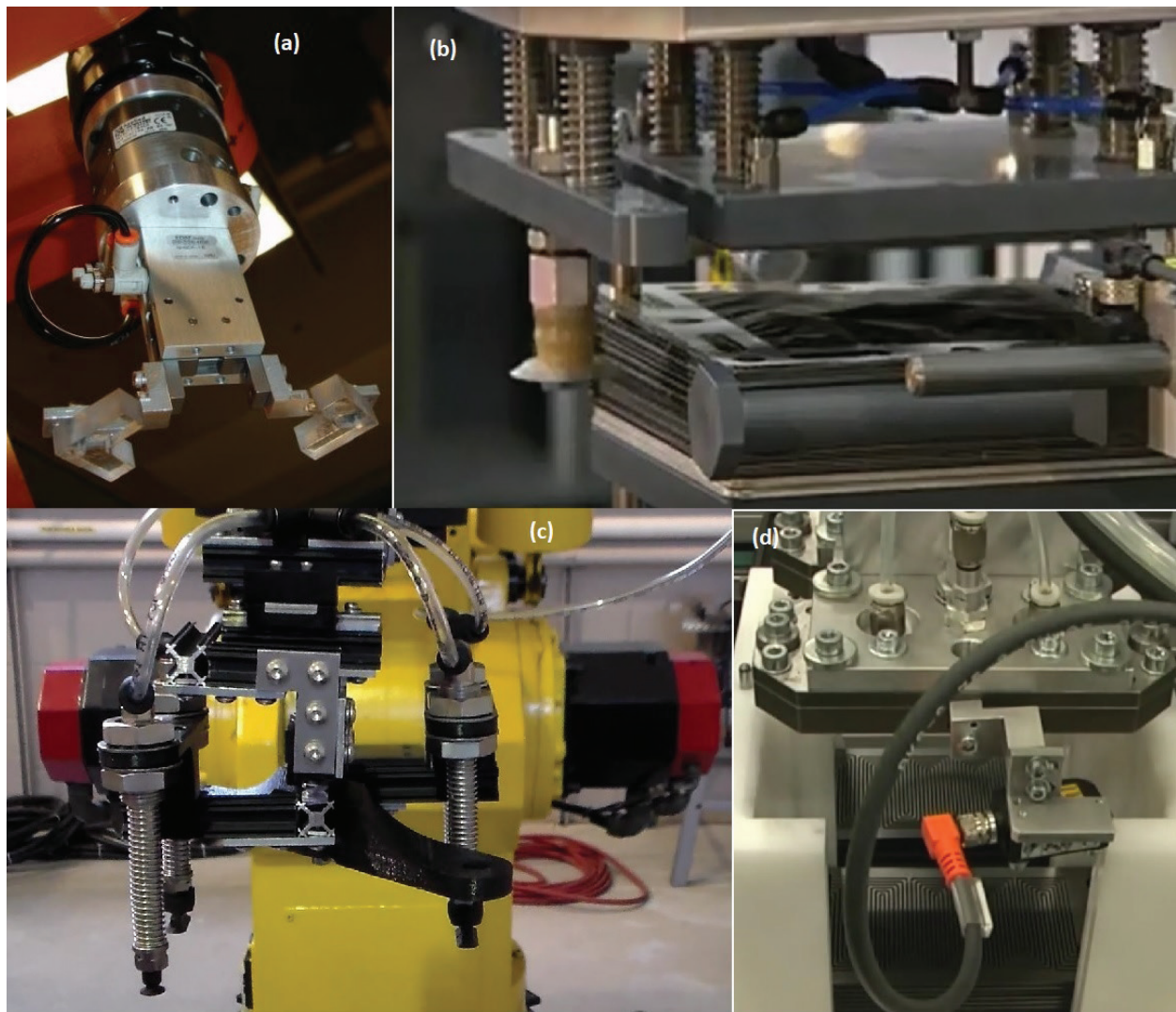


Figure 5. End-effectors used for PEMFC components manipulation: (a) double-acting finger gripper; reproduced with permission from [9]; (b) pneumatic end-effector with suspension mechanism; reproduced from [14]; (c) end-effector with vacuum cups and suspension mechanism used in [7]; (d) pneumatic end-effector; reproduced from [16].

cups are mounted on the lower subassembly to provide a soft touch and to reduce the need for machine indexing when the fuel cell components are picked up and released in the stack. The four vacuum cups are pneumatically connected through tubing and fittings mounted on the level compensators to a miniature vacuum pump controlled by the robot. The lower subassembly is also equipped with a winglet with two positioning holes that align with the positioning holes on the fuel cell components during pickup and release operations. The top subassembly connects the end-effector to the robot wrist-assembly. The intermediate subassembly has the only role of interconnecting the lower and the top subassemblies through the miniature linear blocks and rails and to provide passive compliance to the end-effector. To enable robotic assembly of fuel cell stacks consisting of any large number of cells, the interface component of this end-effector that attaches to the robot wrist-assembly is off-centered relative to the suspension mechanisms and vacuum cups, preventing the fuel cell stack from interfering with the robot wrist-assembly during pickup and release operations.

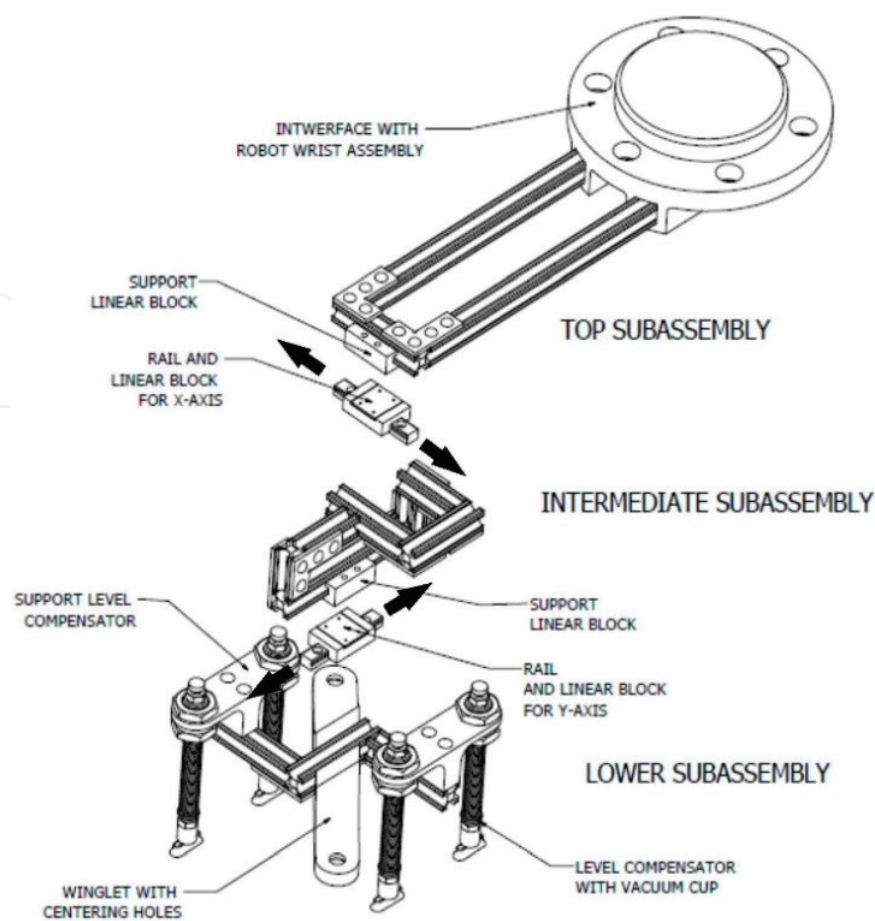


Figure 6. Partially exploded view of an end-effector with passive compliance; reproduced from [7].

6. Workcell design for automated assembly of PEMFC stacks

There have been successful demonstrations of automated assembly technologies for PEMFC stacks using special-purpose automation lines [15, 16], workcells consisting of multiple general-purpose robots [9, 10] and workcells consisting of a single robot [7, 8, 14]. There are two strategies to accomplish the automated assembly process: (i) assemble first single (unit) cells, fasten them, test them and then assemble the single cells in the final stack and (ii) assemble the entire stack directly by repeatedly adding bipolar plates, gaskets and MEAs.

The first strategy enables testing and servicing single cells, without disassembling the entire stack, but has additional manufacturing operations. It was demonstrated by ZSW [15] and ZBT [16] both in Germany. The workcells consist of special-purpose automation lines comprising multiple stations for assembling single cells, including stations for application of liquid rubber as sealant, for curing the rubber, for application of the MEA, for fastening the cell and testing it for gas leaks. The single cells are transported between stations by conveyors. ZSW assembly line [15] uses a KUKA robot for assembling the single cells in the stack.

The second strategy was demonstrated using general-purpose robot workcells. The Center for Automation Technologies and Systems (CATS) at Rensselaer Polytechnic Institute [9, 10] demonstrated a workcell consisting of three KUKA robots surrounding a moving shuttle cart and dedicated part bins (**Figure 7a**). Each robot is dedicated to a single stack component and assembly is accomplished on the shuttle cart that moves between robots. Other components to this workcell include a control center, a vision system and subsystems consisting of a shuttle cart with decrementing Z parts feeders and robotic end-effectors.

KUKA Robot Group [14] (**Figure 7b**) and Kent State University [7, 8, 12, 13] (**Figure 7c**) demonstrated flexible, inexpensive workcells consisting of a single general-purpose robot equipped with universal end-effectors capable of manipulating all fuel cell components. In both workcells, fuel cell components are stacked in presenters from which the robot picks components and inserts them in the stack. These workcell arrangements eliminate the need for conveyors,

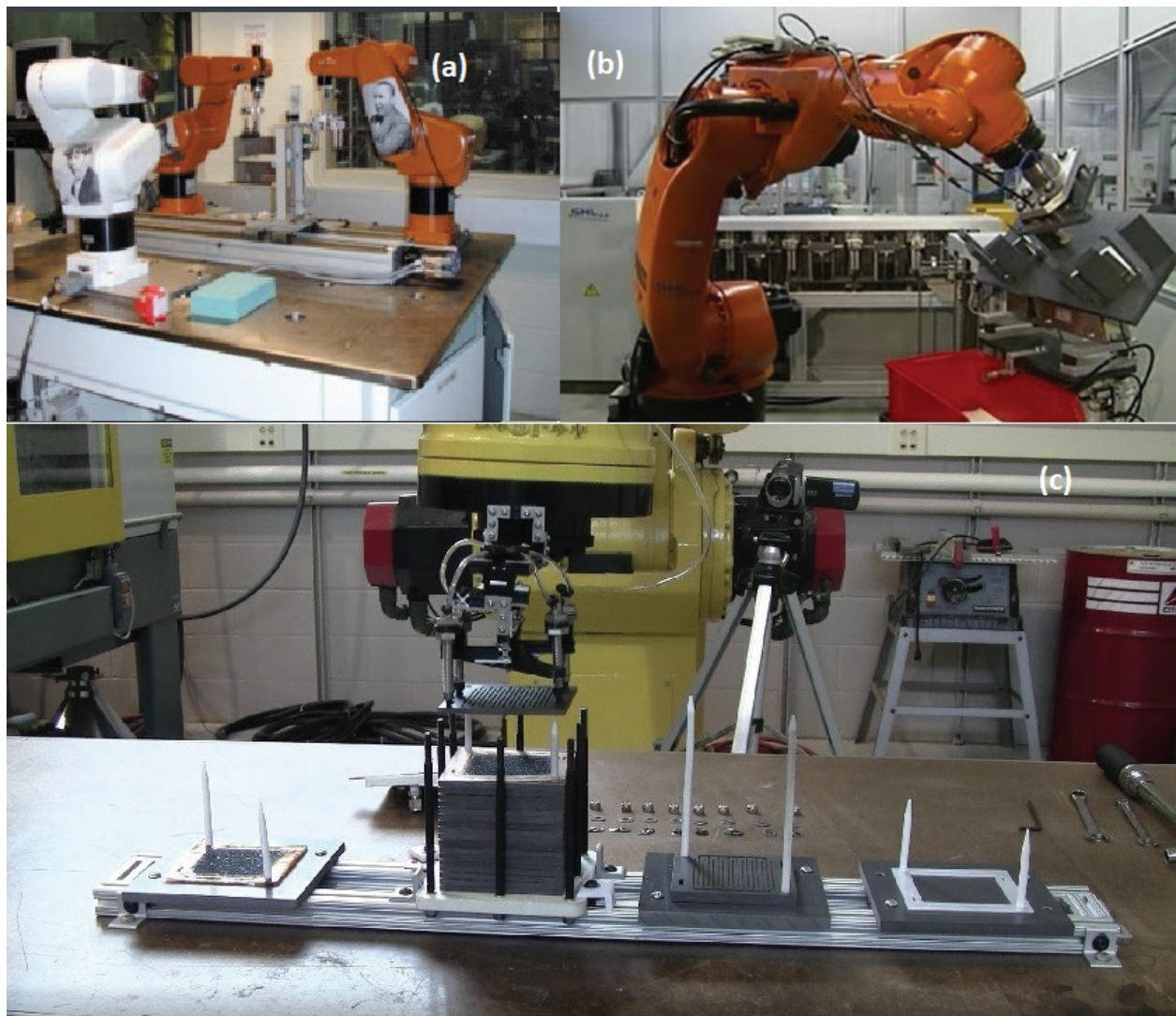


Figure 7. General purpose robot workcells for assembly of PEMFC stacks: (a) workcell consisting of 3 KUKA robots with 6 DOF (degrees of freedom); reproduced with permission from [9]; (b) workcell consisting of a single KUKA robot with 6 DOF; reproduced from [14]; (c) workcell consisting of a single Fanuc robot with 6 DOF used in [7].

indexing mobile shuttle carts on which the fuel cell stack is built, component feeders or feedback visual systems. The workcell demonstrated at Kent State University consists of a Fanuc S 420F robot, three presenters containing bipolar plates, gaskets and MEAs and the end plate with alignment pins on which the fuel cell stack is built (**Figure 7c**). The presenters where the fuel cell components are picked from consist of support plates with two poly(tetra)fluoroethylene (PTFE) alignment pins each similar to the alignment pins on the fuel cell end plate. The presenters and the fuel cell end plate are mounted on an aluminum extrusion framing attached to the workbench. The presenters are permanently mounted to the frame. Every time a new stack is assembled, a fuel cell end plate is attached to the frame using locators and clamps (see also **Figure 4**). The locators allow the new end plate to be mounted every time in the same position.

7. Future work

All automated assembly processes presented here use special-purpose automation lines or general-purpose robots that pick fuel cell components from presenters and insert them in the stack. The fuel cell components in presenters are all oriented in the same position, for example, the bipolar plates with the anode flow field, and the MEAs with the cathode oriented upward. To integrate an automated assembly process into a larger line in which the fuel cell components are also produced using automatic technologies, intermediate stations are required, where the position of components is analyzed and the components are reoriented and then stacked in presenters all with the same orientation. These complex tasks require in addition to automated quality control operations, collaborative robot activities and image analysis. These complex tasks remain to be demonstrated.

Acknowledgements

Preparation of this chapter was made possible with funds from Georgia Southern University.

Author details

Vladimir Gurau*, Devin Fowler and Daniel Cox

*Address all correspondence to: vgurau@georgiasouthern.edu

Georgia Southern University, Department of Manufacturing Engineering, Statesboro, GA, USA

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