

Sustainable by Design: Advancing Hydrogen Fuel Cell Production through Automation

Carmelo Mineo^{1*}, *Ignazio Infantino*¹, *Orazio Barbera*², *Giosuè Giacoppo*², and *Nicola Montinaro*³

¹Institute for High-Performance Computing and Networking (ICAR), National Research Council (CNR), 90146 Palermo, Italy

²Institute for Advanced Energy Technologies "Nicola Giordano" (ITAE), National Research Council (CNR), 98126 Messina, Italy

³Department of Engineering, University of Palermo, 90128 Palermo, Italy

Abstract. The "Integrated Hydrogen Technologies" project is an extensive and comprehensive initiative funded by the Italian government to advance hydrogen fuel cell technologies for sustainable energy systems. The project outlines several research avenues to enhance fuel cell technology further and promote its integration into the global energy landscape, contributing to the acceleration of a clean, efficient, and sustainable energy transition. The project addresses critical challenges in fuel cell production, including material sustainability, production efficiency, and scalability. This article reports on the project activities targeted at the diffusion of fuel cell units. These activities have been motivated by the expected extensive use of hydrogen as an energy carrier in the transport and stationary sectors. They comprise the development of innovative processes for producing bipolar stack plates based on additive manufacturing and sustainability-by-design criteria. Furthermore, automated assembly of fuel stacks is being developed to enable high production capacities.

1 Introduction

The advent of robotics and autonomous systems has ushered in a new era of advanced manufacturing, where precision, efficiency, and sustainability are at the forefront of industrial innovation. Among the myriad applications of these technologies, the production of hydrogen fuel cells stands out as a critical area for development, especially in the context of global efforts towards sustainable energy solutions. Hydrogen fuel cells, known for their high energy efficiency and zero-emission operation, are pivotal in transitioning from fossil fuels to renewable energy sources. However, the manufacturing processes for these systems pose significant challenges, primarily due to the sensitive nature of the materials involved and the intricate assembly required. The US Department of Energy (DOE) has identified high-priority research and manufacturing development needs for proton exchange membrane fuel cells (PEMFCs) [1]. Recent successful demonstrations for the assembly of PEMFCs have

* Corresponding author: carmelo.mineo@icar.cnr.it

used general-purpose robotic work cells [2-7] and automation lines [8, 9]. In these applications, robots pick fuel cell components such as gaskets, Membrane Electrode Assemblies (MEAs) and bipolar plates from stacks placed in predefined positions and place them into the fuel cell stack in a predefined order. The fuel cell components must be manually inserted in the same orientation into the predefined stacks before the robotic assembly begins. However, in most cases, fuel cell components are asymmetrical. That means it may happen that some components must be rotated around the insertion axis and around a perpendicular axis to adjust their orientation and match the correct stacking orientation. It is crucial that during manual insertion into the predefined stack locations, all components are oriented correctly for the subsequent robotic assembly process to lead to functional PEMFC stacks. Fuel cell seals and MEAs are typically only slightly asymmetrical, making human errors in orientation very likely. Furthermore, seals and MEAs are flexible, flat, thin parts that are difficult to handle. For fuel cell stacks producing a few kilowatts of electrical power, the seals and MEAs can have a planar area between one hundred and a few hundred cm^2 , while their thickness is on the sub-millimetre scale, leading to a time-consuming sorting and handling process. The combined effect of the dimensional characteristics of the fuel cell components and their high total angle of symmetry (high asymmetry) makes the process of manipulation, orientation examination and reorientation a repetitive work cycle that can cause mental stress and fatigue to human operators. Manual manipulation, human examination of orientation, and manual reorientation of fuel cell components can ultimately negate the benefits of automated manufacturing processes for fuel cell components or the robotic assembly process.

2 Additive manufacturing of bipolar plates

Bipolar plates are commonly manufactured through subtractive techniques, producing high wasted material rates. The present work focused on designing a power stack between 2.5 and 5 kW, based on bipolar plates produced by enabling innovative production through metal deposition additive manufacturing. This objective has required significant redesigning of the bipolar plate geometry and internal fluid/gas channels. Following the excessive residual stress and deformations of the vertically 3D printed plates of the early attempts, the main effort has been related to the elimination of any geometric overhand in internal and external channels to allow laying the plate flat and horizontally on the printing bed of the additive manufacturing machine (see Fig. 1).

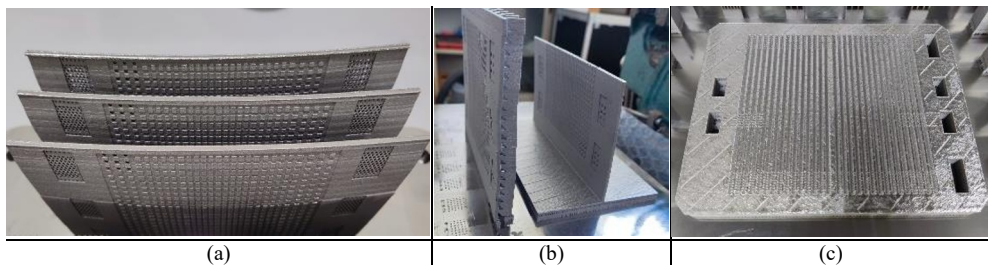


Fig. 1. Metal additive manufacturing of PEMFC bipolar plate. In the first attempt, the printing failed due to excessive deformation caused by residual tensions during cooling (a). The second attempt showed marginal improvements (b). The plate was printed horizontally in the third attempt (c).

3 Conceptual design of novel assembly system

A conceptual design of a novel system and framework targeted to assemble the components of PEMFC stacks, overcoming the limitation of current automated systems, was developed. The system uses a collaborative robotic arm equipped with force and torque

sensors. This work investigated viable solutions for manipulating stack components, identifying the most promising solution for the implementation. A vision system, consisting of a camera and image processing algorithms, will be integrated into the robotic system to detect the orientation and measure the position of the components. During pick and place operations, the vision system will be crucial in instructing the robot's manipulation for orientation and position correction.

3.1 System components

The robot used in this work is a *KUKA iiwa 7 R800* manipulator [10], designed to work collaboratively with humans in shared production and work environments. The reason for choosing such a robot is twofold. Besides allowing the implementation of human-robot collaboration features and human intervention to overcome potential assembly process issues, the robot force-torque sensors' high resolution allows sensor-driven accurate picking and placing of the PEMFC stack parts. While waiting for the additive-manufactured PEFC stack plates, the robotic assembly system's conceptualisation used two sets of existing models for all stack parts. The first PEFC digital part model set had a bipolar plate of 303mm x 134mm. The second set of physical sample parts had a bipolar plate of 158mm x 121mm. This work used these two sets of sample models/parts to generate a virtual simulation of the intended workflow (see Fig. 2) and test different part-picking and transport tooling strategies.

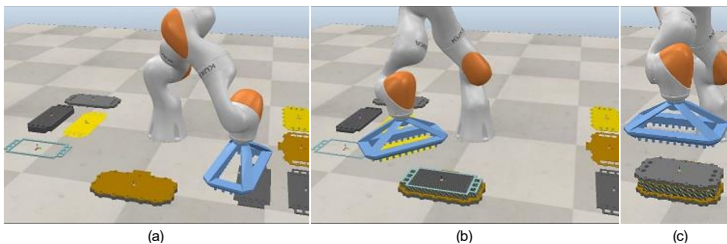


Fig. 2. Virtual environment showing the KUKA iiwa 7 R800 arm, a conceptual model of the grasping tool and the parts of the PEFC stack (with a bipolar plate of 303mm x 134mm). Phases of the simulated assembly process: start (a), middle (b) and end of the process (c).

Since all the parts of a PEFC stack are plates of small thicknesses (compared to the other dimensions), it was deemed appropriate to restrict the search for the best grasping system to the field of vacuum grippers. Therefore, vacuum grippers with foam and suction cups were tested and compared. Regarding vacuum gripping systems with foam, the surface vacuum gripping systems by SCHMALZ, belonging to the FQE product series [11], were considered. These surface vacuum gripping systems are used in numerous automatic handling processes (e.g. palletisation, packaging and automatic selection of goods). They do not have an on-board vacuum generator and require a compressed air supply. Regarding grippers with suction cups, the OnRobot VG10 gripper [12] was deemed worth the testing. The VG10 gripper does not require any external air supply. It is equipped with adjustable arms mounted on a central unit. Each arm supports three suction cups. Four other suction cups are mounted on the central body of the gripper. Adjusting the angle of each of the VG10's four arms allows for handling various objects of different sizes. The tests revealed that the foam-based vacuum grasping system is unsuitable for picking and moving the sample parts of the stack since the thin parts formed creases during grasping (see Fig. 3a and Fig. 3b) rather than remaining flat in contact with the foam. There is concern that the crease deformations could damage or even break the more fragile components. Furthermore, excessive deformation makes it very difficult to ensure the release and placement of the parts in the exact staking location.

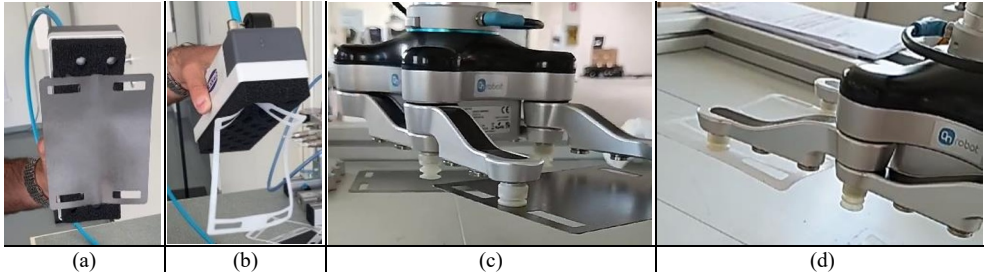


Fig. 3. Photos of the grip tests of the gas diffusion electrode and Teflon gasket of the PEFC stack with a 158mm x 121mm bipolar plate through the SCHMALZ FQE system (a, b) and the OnRobot VG10 system (c, d).

Thus, the OnRobot VG10 system was the best grasping system of the two tested systems since it could lift, move, and release all the sample parts without deforming them. Eventually, it was decided to employ the OnRobot VGC10 system [13] rather than the tested VG10 system. The VGC10 system has the same vacuum generation unit as the VG10, but it is smaller and lighter than the VG10, without compromising the payload (up to 15kg). It is designed to allow customisation since the user can attach a personalised frame to support suction cups. Fig. 4 illustrates the VGC10 system and the bespoke design of the grasping tool, comprising 14 suction cups (four circular and ten oval cups) mounted on anti-rotation spring rods supported by a custom frame.

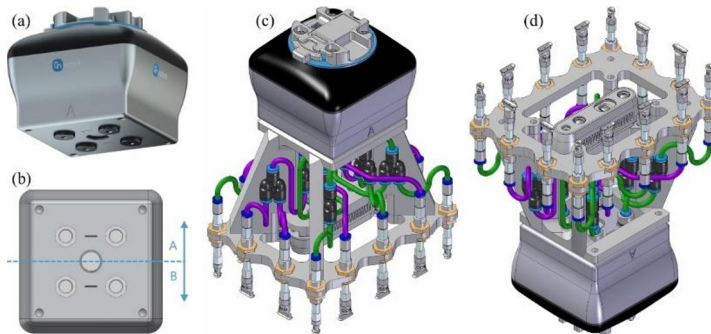


Fig. 4. Photo of the OnRobot VGC10 system [13] (a) and view of the surface with the output suction holes (b), where the dashed line and arrows indicate the separation of the holes belonging to Channel A and Channel B. Illustration of the designed grasping tool with six suction cups connected to Channel A and eight suction cups connected to Channel B (c, d), comprising a dual-lens stereoscopic camera.

The designed grasping tool also supports a 3D vision camera (see Fig. 4d). That is an Intel RealSense Depth Camera D435i [14], a dual-lens stereoscopic camera that can capture colour images and detect depth in real-time.

3.2 System framework, vision and human-machine interface

Even if the components of PEFC stacks are highly standardised and the present project aims to minimise assembly times, the possibility that humans may have to intervene during the assembly process to apply corrective actions cannot be excluded. This consideration is in line with the current research trend in industrial robotics. While the main problem of the fourth industrial revolution (Industry 4.0) concerns the introduction of systems with autonomous behaviour, the fifth industrial revolution (Industry 5.0) presupposes the synergy between people and autonomous machines [15]. The assembly of a PEFC stack is similar to all assembly activities, which are widespread in industrial production. This work has

conceptualised a flexible framework suitable to support both the traditional automation of all phases of the assembly process and human-robot collaboration. Fundamentally, this framework is based on a digital representation of the real-world system (a digital twin), which paves the way to implementing multiple Industry 5.0 paradigms. The framework is illustrated in Fig. 5. A computer runs a tailor-made modular software package that includes the module for communication and real-time control of the cobot, the module for controlling the robotic gripper, the processing of data from the sensors, artificial intelligence algorithms and graphical user interface (GUI).

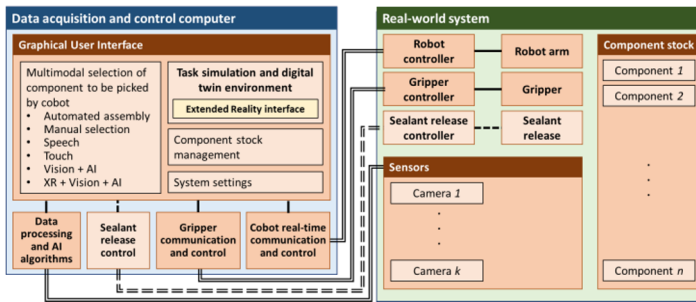


Fig. 5. System framework.

The GUI will be composed of multiple modules. The settings module will allow managing the system settings (e.g. the parameters to connect to the cobot and the gripping system, the preferred speed and acceleration of the manipulator, the gripping power and the robot's safety distances for approach and retraction movements). Another GUI module will be dedicated to defining the initial composition of the component stock (identifying numbers and quantities of parts). It is planned to develop a GUI module to support offline simulations, which also functions as a digital twin of the actual system. Such a digital environment will enable an Extended Reality (XR) control mode in human-robot interaction. The digital environment will initially be populated with user-defined components on the component stock page, and the variables describing the stock will be updated during the execution of an assembly task to reflect the actual state of the physical stock. Finally, the GUI will enable a multimodal approach to select the component that the cobot must pick from the stock. In addition to the fully automated execution of the assembly, human intervention will be enabled. The GUI will incorporate tailored features to set up speech-based control, touch control of the robotic arm, and control via vision sensors, AI algorithms, and XR interaction capabilities.

4 Conclusions

This study demonstrates the significant advancements in hydrogen fuel cell production by additive manufacturing and assembly automation. Substantial redesigning of the bipolar plate geometry and internal fluid/gas channels has enabled additive manufacturing. A collaborative robotic system equipped with high-resolution force and torque sensors, bespoke grasping tooling and vision capabilities has been integrated to effectively handle the delicate and asymmetrical components of PEMFC stacks, reducing the reliance on manual labour and minimising human error. Looking ahead, further research is needed to optimise these technological integrations to enhance production efficiency and reduce operational costs. It is essential to explore the scalability of these automated systems for large-scale manufacturing and to evaluate their environmental impacts.

Acknowledgement

This work has been funded by the "Progetto Integrato Tecnologie dell'Idrogeno" (CUPB53C22008610001) of the Three-Year Implementation Plan 2022-2024 of the Italian National Electricity System Research (Research Topic 1.3).

References

1. "Roadmap on Manufacturing R&D for the Hydrogen Economy," in "DOE Hydrogen Program," 2005. [Online]. Available: https://www.energy.gov/sites/prod/files/2014/03/fl2/roadmap_manufacturing_hydrogen_economy.pdf
2. M. Williams, K. Tignor, L. Sigler, C. Rajagopal, and V. Gurau, "Robotic arm for automated assembly of proton exchange membrane fuel cell stacks," *Journal of Fuel Cell Science and Technology*, vol. 11, no. 5, p. 054501, 2014,
3. V. Gurau, D. Fowler, and D. Cox, "Robotic technologies for proton exchange membrane fuel cell assembly," *Proton Exchange Membrane Fuel Cells*, pp. 21-34, 2018,
4. V. Gurau and T. Armstrong-Koch, "Further improvements of an end-effector for robotic assembly of polymer electrolyte membrane fuel cells," *Energies*, vol. 8, no. 9, pp. 9452-9463, 2015,
5. C. M. Laskowski, *Design-for-manufacture guidelines for automated assembly of Proton Exchange Membrane (PEM) fuel cell stacks*. Rensselaer Polytechnic Institute, 2011
6. C. Laskowski and S. Derby, "Fuel cell ASAP: Two iterations of an automated stack assembly process and ramifications for fuel cell design-for-manufacture considerations," 2011,
7. KUKARobotGroup. The Production of Proton Exchange Membrane Fuel Cells with a KUKA Robot. <https://www.youtube.com/watch?v=E-vcRR4mC6w> (accessed on 30 January 2023).
8. P. Konold, A. Muminovic, and M. Wehrheim, "Assembly of fuel cells and stacks with robots," in *International Conference on Research and Education in Robotics*, 2008: Springer, pp. 168-179,
9. Z. für BrennstoffzellenTechnik, "Fuel Cell Manufacturing Plant/Automatisierte Brennstoffzellenmontage am ZBT," ed,
10. KUKA LBR iiwa 7 R800. <https://www.kuka.com/event/media?itemId=94F543E1211840BE8C9776066C07047A>.
11. SCHMALZ - Sistemi di presa ad area FQE. <https://www.schmalz.com/it-it/tecnica-del-vuoto-per-la-automazione/componenti-per-il-vuoto/sistemi-di-presa-ad-area-e-sistemi-di-presa/sistemi-di-presa-ad-area-fqe/>.
12. OnRobot VG10. <https://onrobot.com/it/prodotti/pinza-a-vuoto-elettrica-vg10>.
13. OnRobot VGC10. <https://onrobot.com/it/prodotti/vgc10>.
14. Intel RealSense - Depth Camera D435i. <https://www.intelrealsense.com/depth-camera-d435i/>.
15. S. Nahavandi, "Industry 5.0—A human-centric solution," *Sustainability*, vol. 11, no. 16, p. 4371, 2019.