

## DESIGNING A NOVEL HYDROGEN POWER SYSTEM FOR SERVICE ROBOTS

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### Abstract

Service robots require long operational autonomy and high-power capabilities to perform complex tasks effectively. However, conventional power sources, such as Li-Ion batteries, often fall short in providing extended runtimes, while hydrogen fuel cells, despite their high energy density, exhibit slow dynamic responses. This paper presents a novel hybrid power system that combines a hydrogen fuel cell with a Li-Ion battery pack to power service robots. We introduce a system architecture that dynamically allocates power flow between the fuel cell and the battery, utilizing the battery to meet peak power demands and transient loads, and the fuel cell as the primary energy source for continuous operation. The proposed architecture provides a stable power output under various load conditions, thereby enhancing the capabilities of service robots in diverse operating environments.

**Key words:** service robots, hydrogen fuel cells, power systems

**Introduction.** With hydrogen fuel available, the service robots themselves must convert that fuel into usable power. This is accomplished via an onboard hydrogen fuel cell power system. A hydrogen fuel cell is an electrochemical generator that combines hydrogen gas with oxygen from the air to produce electricity, with water vapour as its exhaust. The most common type of mobile application is the

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PEM fuel cell, which operates at relatively low temperatures ( $\sim 60\text{--}80^\circ\text{C}$ ) and can rapidly adjust its output to match the load. In a PEM fuel cell stack, each cell consists of a membrane electrode assembly where hydrogen enters on the anode side and air on the cathode side. Through a catalyst (platinum-based), hydrogen molecules split into protons and electrons. The PEM membrane allows only protons to pass through to the cathode; the electrons must travel through an external circuit, thus providing an electric current to drive motors or electronics. At the cathode, the protons reunite with electrons and oxygen to form water ( $\text{H}_2\text{O}$ ) and release heat [1]. Multiple cells are stacked in series to provide the desired voltage and power output for the robot. Small fuel cell systems for robots might produce anywhere from tens of watts to a few kilowatts of power, depending on the robot's requirements.

The fuel cells provide continuous power as long as hydrogen is supplied, unlike batteries, which store a fixed amount of energy. This means a robot with a fuel cell can operate significantly longer on a given weight of fuel compared to one with a battery. For example, Doosan's 2.6 kW portable fuel cell pack (designed for drones) achieves about 400–500 Wh/kg, which is 4–5 times the energy density of a lithium battery [2]. This allowed their drone to fly for two hours, over four times longer than an equivalent drone with the same battery. In-ground robots exhibit similar improvements in endurance – a fuel cell robot can run for many hours or even a full day on a tank of hydrogen, whereas a battery robot might exhaust its charge in 1–2 hours and require a lengthy recharge. Refuelling with hydrogen is also much faster than charging a battery: it may take just a few minutes to swap or refill hydrogen (comparable to pumping gasoline), whereas recharging a large battery could take hours. The quick refuelling capability significantly reduces downtime for service robots, enabling higher utilization, particularly in time-sensitive operations (e.g., search-and-rescue, continuous monitoring).

From a system integration perspective, a fuel-cell-powered robot typically includes [3]:

- An onboard hydrogen tank or metal hydride canister to store the fuel. This tank may store hydrogen at high pressure (e.g., 10–30 bar in a metal hydride, or up to 300 bar if using a composite cylinder for higher capacity).
- The fuel cell stack, along with its control electronics, regulates the reaction, humidification, and cooling. The stack generates DC electricity.
- A power conditioning unit (DC/DC converter) to adjust the fuel cell's output voltage and supply stable power to the robot's motors and computers. Often, fuel cells output a range of voltages (e.g.,  $\sim 20\text{--}30\text{ V}$  for a small stack), and a DC/DC converter steps this up or down to the required voltage (e.g., 24 V or 48 V bus) for the robot.
- A battery or ultracapacitor buffer is often used in tandem with the fuel cell on the robot. This small battery (different from the main battery-only design) can smooth out the power supply, provide peak currents for sudden loads (since

fuel cells have a finite ramp rate), and store recaptured energy from regenerative braking. It essentially hybridizes the system for better performance and longevity (fuel cells last longer if not stressed with rapid transients).

- An auxiliary power source (typically 12 V) for supplying the fuel cell controller. That can be an additional DC/DC converter or a small battery.
- Thermal and water management: The fuel cell cooling system (radiator or fans) to remove waste heat, and water management to handle the product water (usually it just evaporates as vapour if the exhaust is warm; in cold conditions, it must be prevented from freezing).

A fuel cell power system is a suitable alternative for powering mobile service robots. When these robots need to refuel, they either receive hydrogen from a charging station or replace their onboard canister with a full one. Aside from occasional refuelling, the robot is effectively independent – the fuel cell continuously supplies power, and any excess power (during idling) can be used to charge a small battery buffer. Notably, the only emission from this process is water, making it highly environmentally friendly and safe to use indoors or in sensitive environments, such as farms or hospitals. Hydrogen-powered robots produce zero toxic emissions and minimal noise, an advantage for both environmental and operator considerations [4].

**Example implementations of hydrogen-powered service robots.** To illustrate the practical application of a hydrogen power system, this report examines two different mobile service robots. The selected examples, a compact general-purpose mobile robot with a manipulator and an indoor service robot, demonstrate the diverse potential applications for a solar-hydrogen energy system.

**Athena 2.0 mobile robot.** The Athena 2.0 is a general-purpose wheeled robot platform (developed by Slamtec) known for its compact size and agility [5]. The base Athena 2 robot has a footprint of approximately 0.4 m by 0.4 m and a height of around 0.6 m, weighing between 22 and 30 kg, including its batteries. It supports autonomous navigation via LiDAR and can carry payloads of about 40–60 kg on flat surfaces. The robot can be equipped with an arm manipulator for pick-and-place operations. Currently, Athena 2 (like most mobile robots) is powered by a rechargeable lithium-ion battery (a LiFePO battery, 22.4 V/20 Ah). This battery provides several hours of operation on a single charge, offering eight hours of run time with a full load of 40 kg. By integrating a hydrogen fuel cell power system, Athena 2 could extend its operating time and work truly off-grid. The concept would be to replace the battery with a small fuel cell (300 W PEM fuel cell) and a hydrogen storage canister. The fuel cell supplies continuous power to the base's drive motors and the arm, while a small buffer battery handles peak currents when the arm lifts or the robot accelerates. This battery also provides power for the fuel cell start-up. The main components include a 300 W PEM fuel cell with a nominal output of 36 V [6], a DC/DC converter that provides 24 V

for robot power, a small Li-Ion buffer battery (24 V/5 Ah), and a metal hydride tank (800 Nl, usable 600 Nl of H<sub>2</sub> [7]). The stored hydrogen in the tank is roughly equivalent to 1 kWh of energy, considering the efficiency of the fuel stack, and that increases the robot's run time by a factor of 2.5 to 20 hours. Additional components include a controller for the fuel and a small DC/DC converter for its power. A block diagram of the power system is shown in Fig. 1.

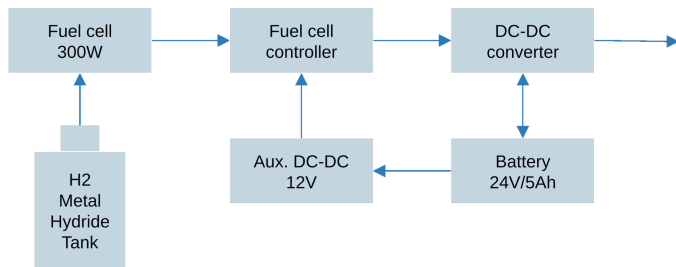


Fig. 1. Block diagram of the hydrogen power system for Athena 2.0 service robot

When the robot runs low on hydrogen, it navigates to the hydrogen charging station for a tank swap with a fresh one, then resumes its duties without a long delay.

**AnRI-2 service robot with fuel cell power system.** The AnRI-2 (Anthropomorphic Intelligent Robot, model 2) is a service robot developed at the Institute of Robotics – BAS. It is an informational service robot equipped with a large display on top, designed to interact with people (for example, as a receptionist, hospital assistant, or lecturer). Unlike Athena 2, which is focused on manipulation and transport, AnRI-2's main feature is its ability to communicate and provide information via its screen and speech – essentially a robot kiosk with mobility. It has a roughly person-height frame on wheels, with the screen positioned at about head height for an adult. It can navigate autonomously in indoor environments, such as hospital corridors or lobbies. One of the intended use cases of AnRI-2 is assisting in medical facilities, where it can deliver messages, guide patients, or provide telepresence. A hydrogen fuel cell power system offers an attractive solution for long-duration service. In our previous research [8], we examined the use of a hydrogen fuel cell to power such a collaborative service robot, highlighting the ecological operation (with no emissions in a hospital) and extended runtime as key advantages. By outfitting AnRI-2 with a compact fuel cell to power its electronics, wheels, and screen, as well as a hydrogen supply, the robot can operate for an entire day (or multiple shifts) without needing to be plugged in.

The power system of AnRI-2 is shown in Fig. 2, which is similar to that used in the Anthena 2.0 robot. It utilizes the same tank for hydrogen storage, but the fuel cell has a lower power output (200 W at 24 V). The electric power output

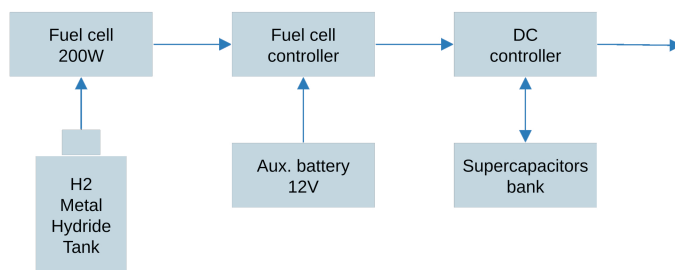


Fig. 2. Block diagram of the hybrid power system for the AnRI-2 service robot

also differs, and to stabilize the output power, we are using a supercapacitor bank. As the power consumption of AnRI-2 is relatively constant, the capacitor bank is sufficient for stable operation, providing simple power management. There is an additional small LTO (lithium-titanium-oxide) battery (12 V/10 Ah) that powers the fuel cell controller and other electronics during start-up and stand-by mode. This type of battery has a high cycle life and excellent safety [9]. At a moderate power draw (say 40–60 W on average while cruising slowly and running its computer and display), the amount of hydrogen in the tank could provide about 16–25 hours of continuous operation. In practice, the robot may not even need to run continuously, allowing it to operate for several days on a single charge. This increased reliability is noted as a benefit in hydrogen-powered service robots. The initial prototype of AnRI-2 with hydrogen power will incorporate safety features, such as hydrogen leak detectors (since it is used indoors) and a well-ventilated storage area for the hydride canister.

In summary, the AnRI-2 robot demonstrates how hydrogen could empower service robots to perform round-the-clock duties in sensitive environments. The success of such an implementation would pave the way for similar robots (e.g., security patrol robots, delivery robots in airports or malls) to use on-site hydrogen generation for power.

**Comparison of implemented power systems.** Table 1 presents the main technical specifications of the described power systems. The hydrogen power system achieves a theoretical energy density closer to that of the  $\text{LiFePO}_4$  battery.

T a b l e 1

Main specifications of the robot’s power systems

| Robot      | Type                          | Stored energy | Weight | Energy density | Output power | Typical run time |
|------------|-------------------------------|---------------|--------|----------------|--------------|------------------|
| Athena 2.0 | Battery $\text{LiFePO}_4$     | 440 Wh        | 2.9 kg | 150 Wh/kg      | 600 W        | 8 h              |
| Athena 2.0 | H <sub>2</sub> tank fuel cell | 1025 Wh       | 7.3 kg | 140 Wh/kg      | 300 W        | 20 h             |
| AnRI-2     | H <sub>2</sub> tank fuel cell | 1025 Wh       | 7.3 kg | 140 Wh/kg      | 200 W        | 22 h             |

The practical value is lower, considering the usable storage of the hydride canister tank and the weight of the fuel cell. We can expect values of around 800 Wh for stored energy and an energy density of around 90 Wh/kg. A solution for improving energy density is the use of high-pressure (350 bar) storage tanks for hydrogen [10]. This technology enables achieving an energy density of over 1000 Wh/kg, which is several times better than that of Li-Ion batteries.

**Discussion.** Adopting green hydrogen power systems for service mobile robots offers several compelling benefits:

- **Extended operating time:** Hydrogen fuel cells can supply power for significantly longer periods than batteries. This is especially advantageous for missions where robots need to cover large areas or be on standby for extended periods (e.g., surveillance, agriculture). Longer runtimes increase productivity and reduce the number of robots required to complete a task.

- **Refuelling time:** Using hydrogen enables quick refuelling, either by swapping the fuel tank or utilizing a high-pressure storage system. Both options facilitate rapid refuelling in order of minutes.

- **Zero emissions and clean operation:** Hydrogen fuel cells produce only water and heat as byproducts, with no exhaust pollutants. This is crucial for indoor or sensitive environments (hospitals, food production, wildlife areas).

- **Scalability and modularity:** A hydrogen-based power system can be scaled by adjusting tank size and fuel cell capacity independently.

Despite the advantages, several challenges and downsides exist when applying green hydrogen in service robotics. It is important to recognize these factors to assess where the technology is viable and what areas need improvement:

- **Energy efficiency:** When converting stored hydrogen into electricity, the fuel cell loses approximately 40–50% of the fuel's energy, primarily as waste heat. This conversion inefficiency is compounded by the energy previously used to compress and store the hydrogen on board, further reducing the net power available.

- **Complexity of the system:** A hydrogen-based power solution involves numerous components, including storage tanks, fuel cells, regulators, and batteries, which make the system more complex than a simple battery and charger.

- **Weight and volume of storage:** Although hydrogen has an excellent gravimetric energy density, its advantages are diminished when stored in practical containers. The weight of the fuel cell and auxiliaries (such as a cooler) also partially offsets the weight savings of carrying hydrogen compared to batteries. Essentially, hydrogen's benefits are primarily evident in medium to larger robots, where a slight increase in fuel tank volume is acceptable and the mission duration exceeds battery limits.

- **Economics and cost:** Fuel cell technology and equipment are still relatively expensive, especially at small scales. A small fuel cell stack (200–500 W) costs a few thousand euros. Metal hydride canisters and specialized components add to the cost.

- **Safety:** Hydrogen's flammability requires careful safety management. For small robots, metal hydride storage offers a significant safety advantage by keeping the gas in a stable, low-pressure, non-gaseous form. Despite the small volumes and advanced storage, all hydrogen handling must strictly follow established safety protocols.

**Conclusion.** For service robots that require continuous operation over long periods, hydrogen fuel cells offer a clean and powerful energy solution. They provide the extended runtime and fast refuelling necessary for modern automation, lowering long-term operational costs, and enabling more advanced capabilities. However, these benefits come at the expense of increased system complexity and lower efficiency. That makes hydrogen most advantageous for specific applications where continuous performance is critical, provided its challenges in management, safety, and reliability are met.

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