HYDRO2 bot

User Manual

HydroBot Rev. 2.0
22.08.2025

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1. Introduction

HydroBot is a demonstrator platform for fuel cell electric vehicles. It is a remote-controlled robot that is primarily powered by a 12.8 V LiFePO4 battery. Additionally, it is equipped with a 60 W fuel cell stack and can carry up to 8 g of hydrogen in eight metal-hydride cartridges. The fuel cell is used to charge the battery while the robot is operating, which shows the power system of a fuel cell electric vehicle: An electric motor is powered from a fuel cell with a buffer battery. Depending on the load conditions, the fuel cell directly powers the motors and charges the battery (idle/low load), or the motors are powered by the fuel cell as well as the battery (high load).

This robotic platform uses Mecanum wheels as a drive system. Mecanum wheels allow a vehicle to drive in any direction without requiring a classical steering assembly. The wheels consist of freely spinning rollers acting as wheel treads that are oriented at 45° relative to the axis. They work by selectively adjusting the rotation speed and direction for all four wheels, and therefore, require independent motors and drive trains for each wheel.

2. Hazards and safety precautions

HydroBot is not a commercial product. It is not for sale. The developer team shall not be held responsible for any accidents and damage that occur from operating the robot, in particular if not adhering to this manual and its appendix.

Caution:

- Read this manual carefully before operating the robot. Do not operate the robot unattended. Do not disassemble the robot. Maintenance must only be performed by the developer team. Contact the developer team if you encounter any malfunctions.

- Hydrogen is an odorless, flammable, and explosive gas. The hydrogen storage cartridges must be removed from the robot whenever they are not used. They must only be connected to the robot directly before use. Only Hydrostik Pro cartridges from Horizon Educational must be used for the robot. Only use the robot in well-ventilated areas, avoid direct sunlight, and avoid possible ignition sources. Do not touch the fuel cell components during and directly after operation, as they can become hot.

- The battery can provide large currents, and short circuits may heat up components and cause fire. Make sure never to exceed 14.6 V battery voltage while charging. Only the built-in charge port shall be used to stay within safe voltage limits for the battery. The charge port is compatible with DC power supplies between 10 and 32 V DC. Do not exceed this voltage range. Make sure to use a power supply with a rating of at least 60 W. Only plug in a power supply when the robot is switched on. Do not switch off the robot while charging. Do not discharge the battery below 10.0 V. The battery voltage should be checked and charged every 1-2 months to maintain its state of charge.

- The robot is controlled wirelessly. Take care when handling the device and drive it cautiously. Ensure to stay in line of sight of the robot and not exceed 10 m between the remote control and the robot. The built-in distance sensors do not guarantee the robot from stopping before hitting any obstacle, as they do not cover every angle. Minors must not operate the robot without supervision. The robot must be switched off immediately in case of unexpected behavior due to signal interference.

3. Specifications

Footprint:	580x594x296 mm (LxBxH)
Weight:	17.8 kg (including battery and hydrogen cartridges)
Battery:	pbq LiFePO4; 12.8 V, 7.2 Ah (LF 7.2-12) Voltage window: 14.4 V (100 % SOC) – 10.0 V (0 % SOC) Max. continuous discharge current: 20 A. Max. charge current: 7.5 A
Charge port:	10-32 V DC; 2.1/5.5 mm power jack Charging profile: constant current (3 A) Battery disconnect voltage: 14 V Battery reconnect voltage: 13.4 V Internally operated by a TDK Lambda I7C4W008A120V-P03-R (14 V, 3 A)
Mainboard:	Custom PCB for power distribution and control logic, 20 A fused Main control: ESP32 (sensors, motor control, FC control, LED, and LCD control) Voltage and current (ACS712) sensing of battery and fuel cell via ADS1115 ADCs Auxiliary control: Arduino Nano (distance sensors) FC controller interface: signal relay FC load connection: power relay and diode for reverse current protection
Motor driver:	2x Cytron MDD20A dual-channel brushed DC driver 6-30 V, up to 20 A continuous current per channel
Motor:	4x Servocity brushed DC motor with planetary gearbox 12 V, 0.52 A idle current, 20 A stall current 27:1 gear reduction, 313 rpm no-load speed
Drive system:	4x Mecanum wheel with 2.6:1 gear reduction (planetary gearbox) Speed, transversal direction, and rotation are computed from three joystick inputs Maximum speed: 3 km/h 4x HC-SR04 ultrasonic sensors (motor off distance: 25 cm)
Fuel cell:	Horizon Educational H-60 PEM Fuel Cell Proton exchange membrane fuel cell stack with 60 W peak power output Voltage window: ~18.5 V (open circuit) – 12.0 V (peak power) Undervoltage protection: <10 V Overcurrent protection: >6 A Overtemperature protection: 65 °C FC controller powered by a TDK Lambda I7C4W008A120V-P03-R (13 V) Hydrogen supply: 8x Hydrostik Pro hydrogen storage cartridges Custom connector block machined from aluminum Pressure sensor: WIKA A-10-6-BG310-NHZZ-GA-AKB-ZW (PE 81.60) Pressure range: 0...1 bar, 0...5 V
Control:	Wireless at 2.4 GHz (ESP-NOW)

Operating and storage conditions:

- Temperature: 5-30 °C
- Humidity: non-condensing
- Only operate in well-ventilated areas
- Avoid exposure to direct sunlight

Safety features:

- E-Stop: Kills the robot's power supply to the motors and the fuel cell stack
- Auto-stop on connection loss: The robot stops driving when it loses connection to its remote control
- Auto-power off on connection loss: The robot shuts itself down 30 s after losing connection to its remote control
- Low battery indicators: The robot and the remote control monitor their battery voltages and indicate when the battery voltage levels are critically low
- Low-pressure triggered shutdown of the fuel cell: Hydrogen supply pressure is monitored during operation, and the fuel cell is automatically shut down when running out of hydrogen
- Distance sensors: The robot is equipped with ultrasonic distance sensors that prevent the robot from hitting obstacles (auto-stopping the motors when attempting to drive into an obstacle)

4. Overview of robot and remote control

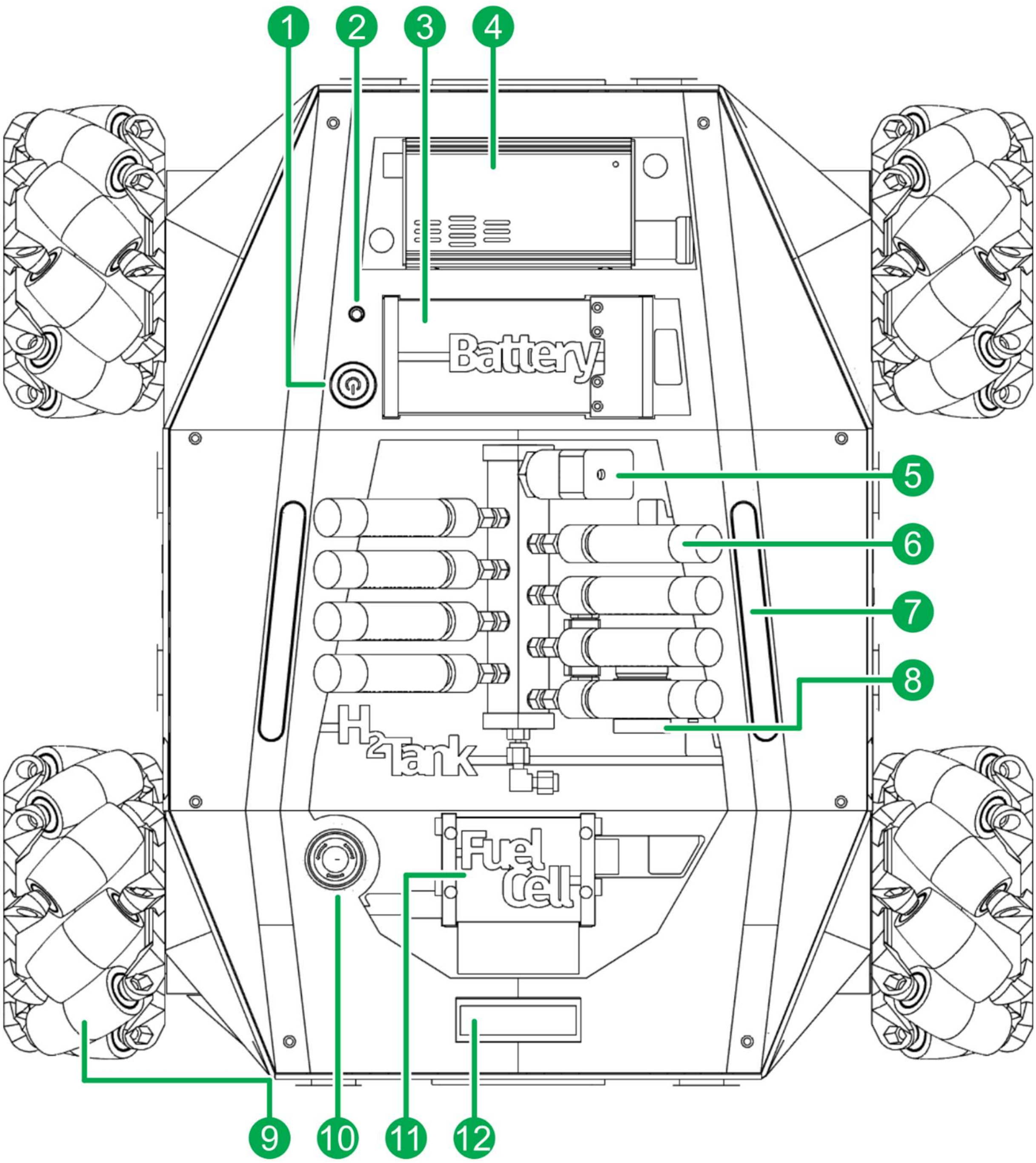

Figure 1: HydroBot, top view

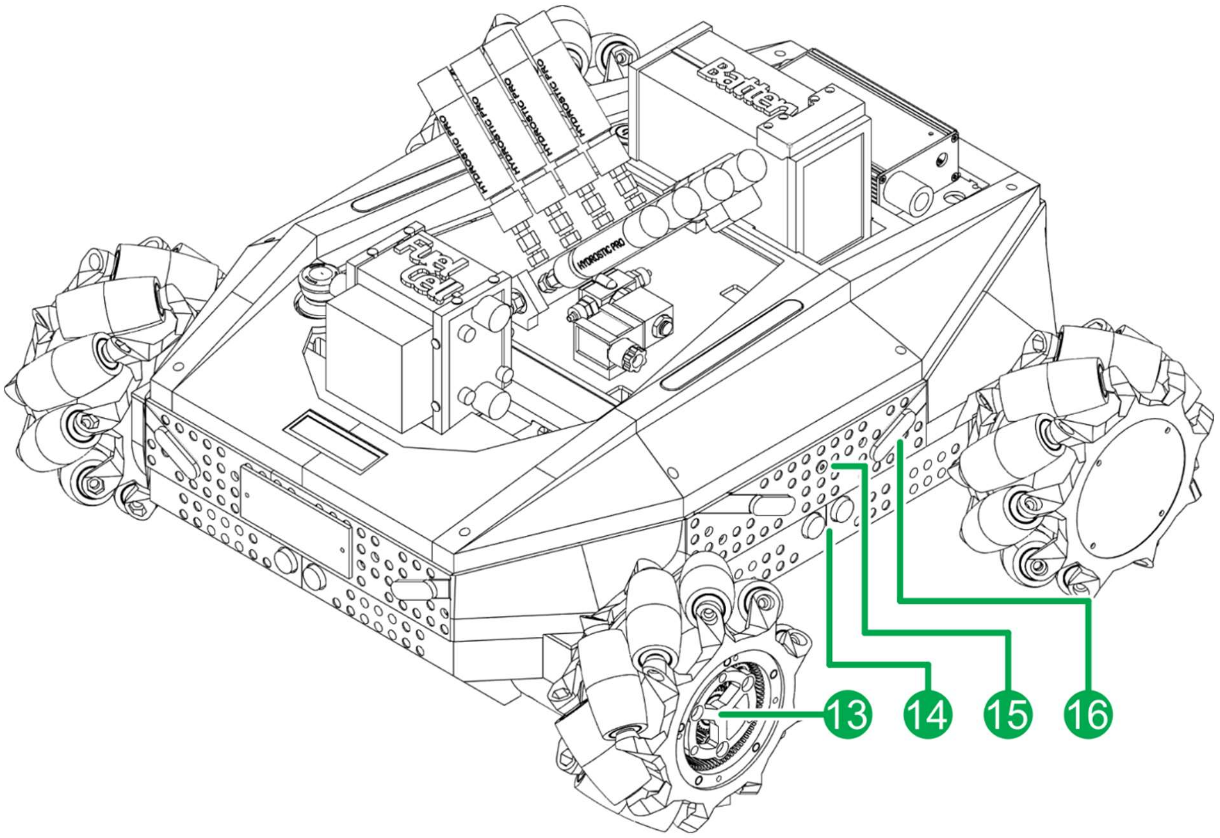

Figure 2: HydroBot, side view

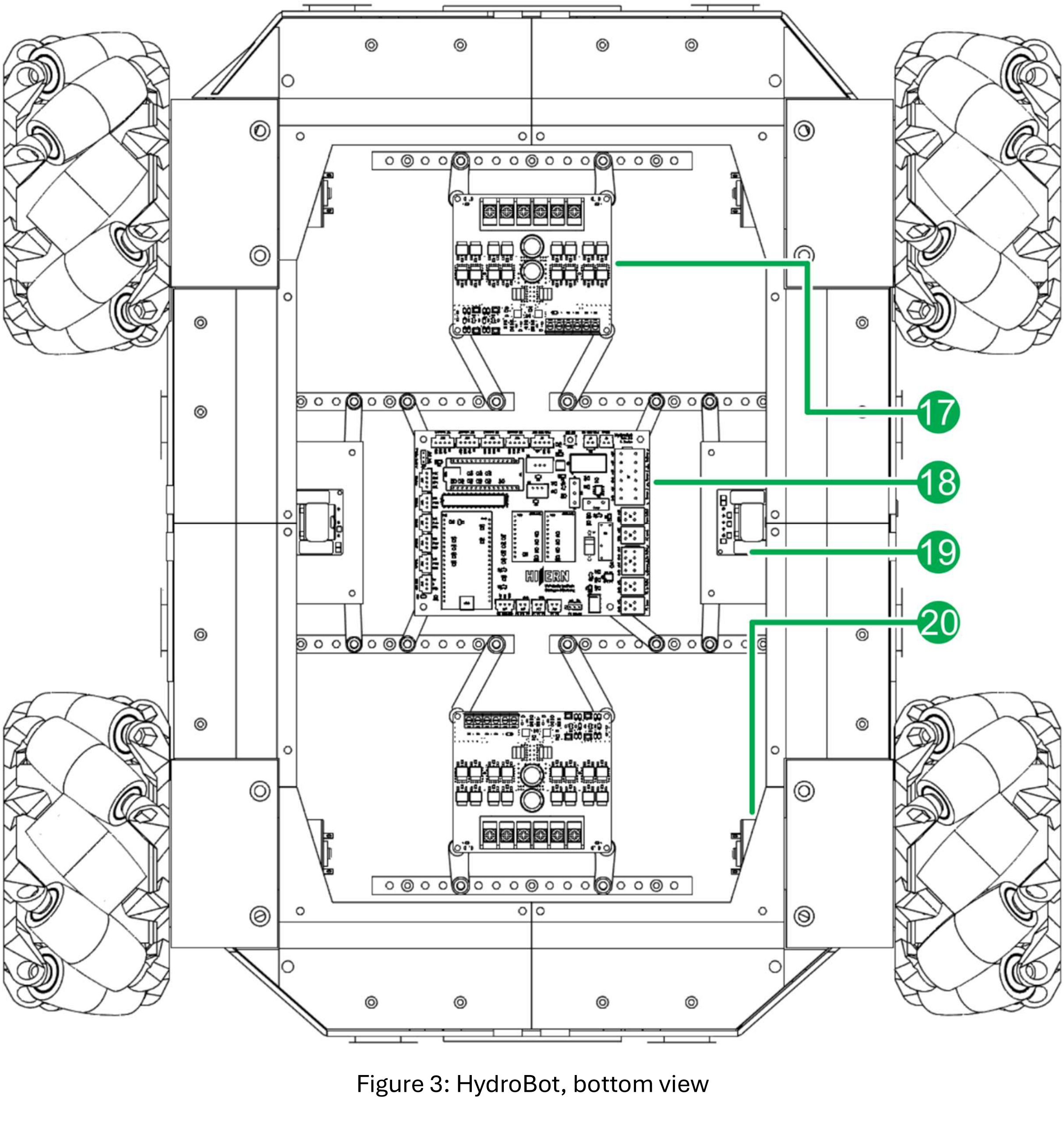

Figure 3: HydroBot, bottom view

Table 1: Component assignment of the robot (Figure 1, Figure 2, Figure 3)

#	Description	#	Description
1	Power button	11	Fuel cell stack
2	Charge port	12	LCD screen
3	Battery	13	Planetary gearbox
4	Fuel cell controller	14	Distance sensor
5	Pressure sensor	15	Fuel cell exhaust
6	Hydrogen storage cartridge	16	LED indicator light (side)
7	LED indicator light (top)	17	Motor driver
8	Hydrogen supply valve	18	Mainboard
9	Mecanum wheel	19	DC-DC converter
10	Emergency stop switch	20	Brushed DC motor

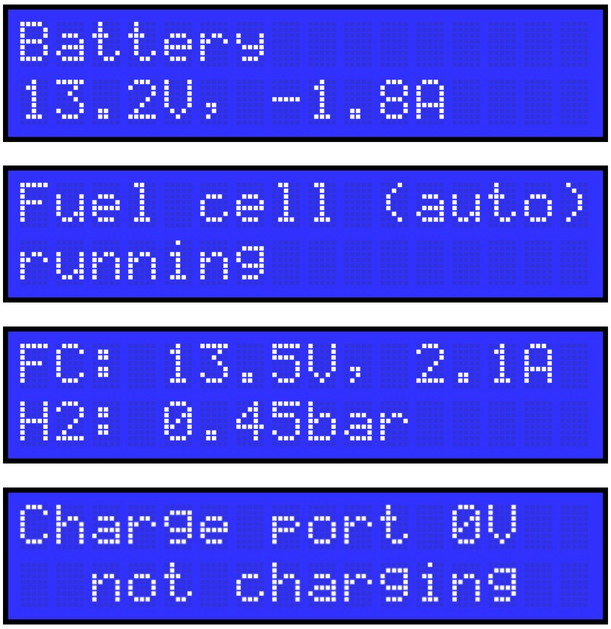

Figure 4: LCD screen pages of HydroBot

Page 1 shows the battery status (voltage, current draw). The battery should be kept between 12.8 and 14.0 V. Positive currents indicate power consumption, and negative currents indicate battery charging. HydroBot's idle current draw is ~0.3 A.

Page 2 shows the fuel cell status. It indicates the operation mode (auto vs. manual) and the status of the stack (manual: relay on, relay off; auto: offline, standby, start, running, shutdown, H2 is low, and OCV too low).

Page 3 shows the fuel cell sensor data (voltage, current draw, and hydrogen pressure). Hydrogen pressure should be within 0.45 and 0.55 bar. Fuel cell idle voltage (open circuit voltage) should be ~18.5 V. Fuel cell voltage under load should be ~0.3 V higher than the current battery voltage. Fuel cell current at idle is 0; current under load is <4 A.

Page 4 shows the charge port status. It indicates power supply voltage and status (charging, not charging). The voltage of a connected power supply must not exceed 32 V. The acceptable range for battery charging is 10 to 32 V. The power supply needs to provide at least 60 W.

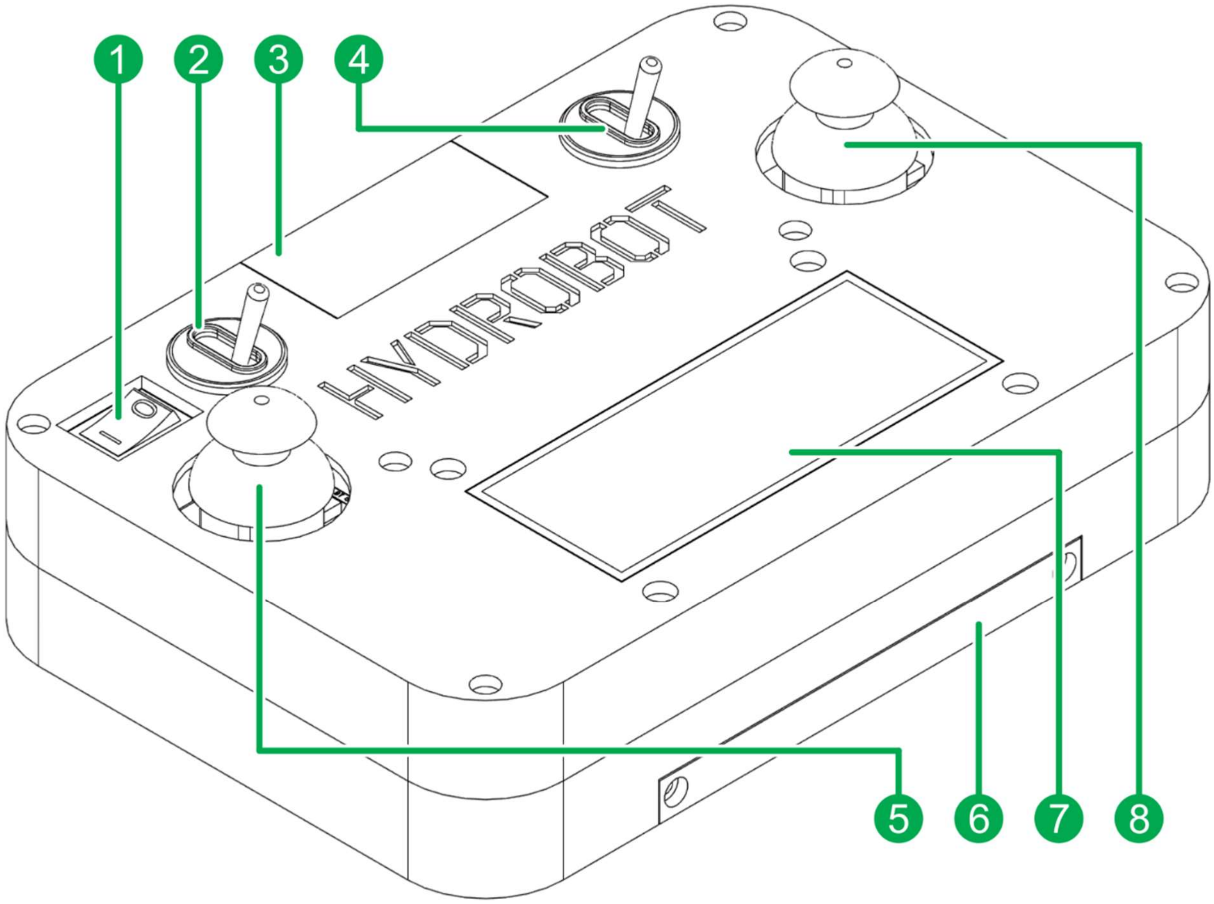

Figure 5: HydroBot remote control

Table 2: Component assignment of the remote control (Figure 5)

#	Description	#	Description
1	Power switch	5	Left joystick and push button
2	Left toggle switch	6	Battery cover
3	ESP32 cover	7	LCD screen
4	Right toggle switch	8	Right joystick and push button

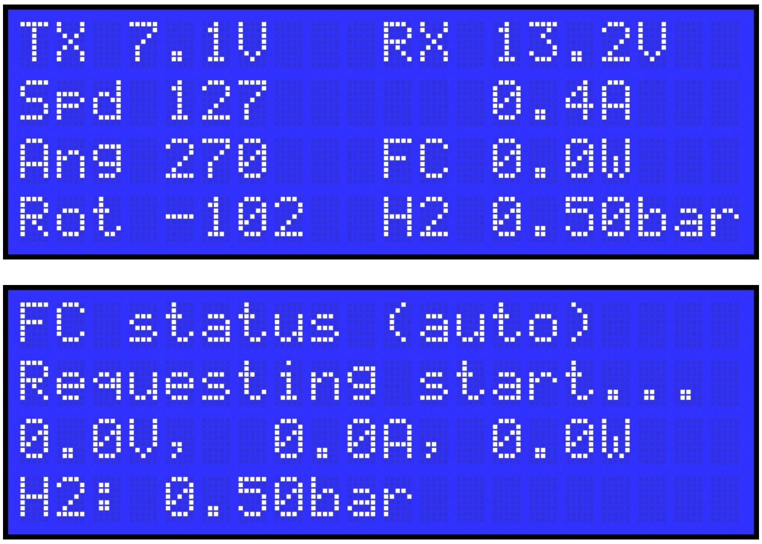

Figure 6: LCD screen pages of the remote control

Page 1 shows the battery voltage of the remote control (TX voltage) and the drive inputs from the joysticks (speed and angle are the computed polar coordinates from the x- and y-axes of the right joystick, rotation is the x-axis of the left joystick). The battery voltage should be between 8.4 V and 6.9 V. Speed inputs are mapped between 0 and 255. Angle inputs are between 0 and 360°. Rotation inputs are mapped between -255 and 255. On the right side, the status of the robot is displayed (battery voltage and current, fuel cell power, and hydrogen pressure). The battery should be kept between 12.8 and 14.0 V. Positive currents indicate power consumption, and negative currents indicate battery charging. HydroBot's idle current draw is ~0.3 A.

Page 2 shows detailed information on the robot's fuel cell. It indicates the operation mode (auto or manual), the status of the stack (manual: relay on, relay off; auto: offline, standby, requesting start..., starting cell..., online, shutting down..., battery full, H2 pressure low, OCV is too low), and the hydrogen pressure. Hydrogen pressure should be within 0.45 and 0.55 bar. Fuel cell idle voltage (open circuit voltage) should be ~18.5 V. Fuel cell voltage under load should be ~0.3 V higher than the current battery voltage. Fuel cell current at idle is 0; current under load is <4 A.

5. Operating principle

5.1 Fuell cells

Fuel cells are electrochemical energy converters, which means they convert chemical energy into electrical energy. Their fuel is an energy-rich substance, and by oxidation within the fuel cell, it turns into a low-energy product. This reaction within a fuel cell occurs spontaneously (without having to apply external energy), which is why they are also termed galvanic cells. Fuel cells can operate with different kinds of fuels, the most common being hydrogen (H_2). If hydrogen reacts directly with oxygen (O_2) from the atmosphere, it burns or explodes, releasing energy in the form of heat, and forms water (H_2O) as a product (Equation 1) [1].

$$2\,H_2 + O_2 \rightleftharpoons 2\,H_2O + energy \tag{1}$$

A fuel cell catalyzes the same reaction but differs from this direct combustion by spatially separating the fundamental reactions involved. In one of the most common types of fuel cells, proton exchange membrane fuel cells (PEMFCs), these are the oxidation of hydrogen to form protons (H^+) and electrons (e^-) (Equation 2), and the reduction of oxygen by recombination with the protons and electrons from hydrogen to form water (Equation 3) [1].

$$2\,H_2 \rightleftharpoons 4\,H^+ + 4\,e^- \tag{2}$$

$$O_2 + 4\,H^+ + 4\,e^- \rightleftharpoons 2\,H_2O \tag{3}$$

Separating these two reactions allows for harvesting electrical energy by bypassing the electrons through an electrical circuit, thereby producing a usable electric current (Figure 7). The protons travel from the hydrogen side of the fuel cell, which is also called anode, through an ion-conducting medium, the so-called electrolyte, to the oxygen side of the cell, which is termed cathode. Anode and cathode are the two electrodes of a fuel cell, and they require catalysts such as platinum to allow the reactions to occur at usable rates. Catalysts are materials that reduce the activation energy of a reaction without being consumed within the reaction, meaning they accelerate the reaction. The electrolyte is a flexible polymer membrane, usually a polymer called Nafion, a derivative of the very durable plastic Teflon, which not only allows proton conduction but also offers the required chemical and mechanical robustness needed for long-term fuel cell operation [1].

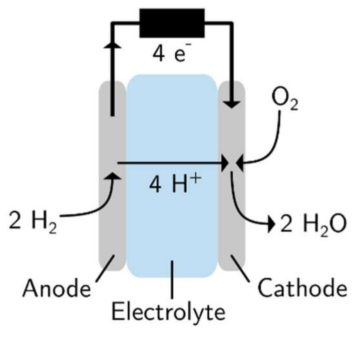

Figure 7: Fuel cell schematics. Anode and cathode are the two electrodes of the fuel cell, where the reactions occur. The electrolyte between the electrodes only allows protons but not electrons to pass, forcing electrons to travel through an external circuit.

Fuel cells are a promising means to convert chemical energy into electrical energy. For example, PEMFCs are locally emission-free, meaning they do not produce greenhouse gases or toxic exhaust fumes. They only produce water. On the other hand, they come with certain limitations. For instance, thermodynamics states that the maximum efficiency of a PEMFC is less than 83 % [2], with real-world efficiencies of around 60 % and less [1]. This is significantly lower than the efficiency of a battery, which can reach more than 90 % within a charge-discharge cycle [3]. Notably, this consideration does not account for the means of hydrogen production for the fuel cell or electricity production for the battery, which is highly dependent on the use case and location. Hence, each technology has benefits and drawbacks, and a direct comparison is always difficult.

An important difference between fuel cells and batteries is that the fuel of a fuel cell is stored separately from the electrode-electrolyte compartment, the actual fuel cell, whereas a battery combines both. Therefore, the output power of a fuel cell is uncoupled from its energy storage capacity, whereas increasing the capacity of a battery typically also increases its maximum output current. Consequently, increasing the size of the fuel tank of a fuel cell does increase the runtime but not the peak power output of the system. It may sound advantageous to increase power and energy capacity simultaneously like when increasing the size of a battery, but uncoupling both also has its benefits. In a battery, the costs increase directly with capacity since the battery only becomes bigger. In the fuel cell, the fuel cell and the components required for the balance of plant stay identical, irrespective of the size of the fuel tank. Hence, increasing the capacity of a fuel cell can be cheaper than increasing the capacity of a battery.

The voltage of a PEMFC is typically around 0.9 to 1 V when no load is applied to the cell (open-circuit voltage), and it drops with increasing current to around 0.6 to 0.7 V at its peak power output [1]. Therefore, like single-cell batteries such as cylindrical AA batteries, multiple cells must be arranged in series to reach usable voltage ranges. In fuel cells, the assembly of multiple single cells is termed a stack. Further, a fuel cell also needs peripheral components, such as its fuel tank, a means to feed fuel and oxidant to the cell in a controlled way, and active cooling during operation. Hence, a controller and an external power source are needed to safely start, operate, and stop a fuel cell, which is significantly more sophisticated than a multi-cell battery that only needs a battery management system to ensure voltage equality between the different cells and that disconnects the load/charger if exceeding the tolerated voltage window.

HydroBot aims to showcase the application of a fuel cell as a power source for an electric vehicle, to get practical insight into the requirements and limitations of PEMFCs. HydroBot uses fuel cell hardware from Horizon Educational, which provides fuel cell stacks, controllers, and hydrogen storage containers. HydroBot employs custom electronics to integrate its fuel cell and battery into an electric Mecanum wheel drive train, which are explained in more detail in the upcoming sections.

5.2 Fuel cell electric vehicles

Three main types of (partially) electric vehicles can be differentiated: BEVs (battery electric vehicles), FCEVs (fuel cell electric vehicles), and PHEVs (plug-in hybrid electric vehicles). BEVs are solely powered by a battery that supplies energy to their electric motors. PHEVs use an internal combustion engine as a main power source for propulsion, which is supported by an electric motor and a battery that are used to provide additional power when needed and increase the car's range and efficiency. FCEVs are electric vehicles that use hydrogen as a chemical energy carrier (fuel), like gasoline or diesel. However, instead of burning this fuel like an internal combustion engine vehicle (ICEV), they use a fuel cell to directly convert the chemical energy stored in compressed hydrogen gas into electrical energy.

BEVs have the advantage of a very simple and very efficient power train (compared with ICEVs) but recharging them takes more time than refueling gasoline- or diesel-powered cars, and their achievable drive range is typically shorter than for ICEVs. PHEVs combine the advantages of combustion engines (fast refueling, long range) with the higher efficiency of BEVs, but at the cost of a more complex and heavy combined power train, and their overall efficiency is poorer than that of a BEV. FCEVs operate locally emission-free, like BEVs, outperform ICEVs in terms of efficiency, can reach drive ranges like ICEVs, and can be refueled as quickly as ICEVs. However, they are significantly less efficient than BEVs, and their power systems are expensive, large, and complex. Therefore, each propulsion system has its advantages and disadvantages, and the ideal choice highly depends on the use case [4].

HydroBot is a demonstrator platform intended to showcase the operating principle of FCEVs. This robotic platform is powered by a battery that is used to drive its motors and auxiliary systems, and that also fuels the balance of plant of the onboard fuel cell. The fuel cell can be activated on demand to charge the battery and power the robot.

HydroBot requires a battery because fuel cells are not suited to power vehicles directly without a buffer battery: They need external electrical components to start, control, and stop their operation safely. Hence, a mobile platform always requires a battery to run a fuel cell power system. Once the fuel cell is running, it can power its own balance of plant, but an external power source is needed at least during startup and shutdown. Further, while proton exchange membrane fuel cells (the fuel cell technology most commonly used in mobile applications) can adapt to load changes quickly, they are prone to damage when left at idle for longer times (open circuit voltage, when the fuel cell is active but either no or only a very small current is drawn), and its efficiency drops significantly when operated at very high loads [1,5]. Thus, for an FCEV, a buffer battery is essential, for example, to act as a load while idling, or as an additional energy source when very high currents are needed (like during fast accelerations). Also, a battery can make use of the energy released from braking an electric vehicle (regenerative braking), whereas a fuel cell can only release but not store electrical energy.

A careful selection of the size and capacity of the fuel cell and battery allows the design of an efficient power system: The conversion efficiency of a fuel cell drops with its current density (current output per cell area), meaning the fuel cell should not be operated at very high loads [1]. On the other hand, the larger the fuel cell, the more space is needed for the stack, the more weight is added, and the more expensive its components become. For a battery, the capacity directly scales with its size and weight. On the other hand, adding additional hydrogen storage capacity requires less space than increasing battery capacity. Hence, when aiming at long drive ranges, FCEVs can outperform BEVs in terms of size, weight, and fueling time [4]. Therefore, an efficiency-focused FCEV power system consists of a medium-sized fuel cell compared to the car's power demand that allows powering the car *on average* at the fuel cell's ideal operation point, which is the sweet spot between low current (equals high efficiency) and high current output (equals a small fuel cell footprint). The battery capacity must be chosen according to the expected power draw spikes of the car's drive profile, so that it can buffer intervals of high current draw and be recharged in between without adding unnecessary weight and costs to the vehicle.

HydroBot is not intended to reach these efficiency goals, but it is meant to showcase the principle of this type of power system. Therefore, it makes use of a comparably simple fuel cell setup, which does not reach the technically possible conversion efficiency of chemical into electrical energy, which is up to ~60 % for proton exchange membrane fuel cells [1]. Instead, it reaches a peak conversion efficiency of around 40 % [6]. On the other hand, it does not require sophisticated auxiliary components such as a feed gas humidification unit [2]. The robot's fuel cell peak power output is rated as 60 W [6], and the combined capacity of the eight hydrogen cartridges offers up to 88 Wh of electrical energy [7]. The balance of plant of the active fuel cell requires around 10 W. Considering the battery capacity of 92 Wh [8], the fuel cell system can be considered as a range-extender for HydroBot that increases the run time by up to a factor of two when neglecting the costs for balance of plant of the fuel cell. This comparably large battery is chosen to offer reasonable operation time and to be able to cover possible current spikes when all four motors of HydroBot's Mecanum wheel drive system are operating. HydroBot has an idle power draw of 4 W, typically consuming around 30 W while driving at a constant speed on an even surface.

Essentially, HydroBot has two operation modes. In the first mode, it is a BEV. This is the operation mode when starting the system. The robot is solely powered by the battery, which supplies energy to the motors as well as to its onboard electronics (Figure 8). This mode is required since the fuel cell cannot be started without powering its control unit. Once the robot is active, it monitors its components: state-of-charge of the battery, fuel cell status, and hydrogen supply pressure (Figure 9). If the battery voltage, which indicates its state-of-charge, drops below a certain threshold, and if the hydrogen supply pressure is high enough, its fuel cell can be activated. In a commercial FCEV, this is done automatically, while it is manually controlled for HydroBot.

The fuel cell delivers energy to the onboard electronics, the battery, and the motors (Figure 10). In a commercial FCEV, the power distribution between the different components is closely monitored and adjusted to maximize efficiency, but in the case of HydroBot, the circuit is kept simpler. Here, the fuel cell is directly connected to the battery. However, by selecting fuel cell stack and battery correctly, a reasonable operation point for the fuel cell can be guaranteed: The fuel cell consists of a stack that offers its peak power density at 12 V and 5 A [6], and it is known that the peak power density of a fuel cell is obtained at around 0.6 V/cell [1]. Since the battery operates in a voltage window between around 12.8 to 14.0 V [8], and the fuel cell is connected to this load by a diode that causes a voltage drop by approximately 0.45 V [9], the fuel cell stack is kept at around 13.2 to 14.4 V. Assuming the stack consists of 20 individual fuel cells, this equals around 0.7 V/cell, which is an ideal operation point for proton exchange membrane fuel cells [1].

This operation point is kept irrespective of the robot's current power consumption since the fuel cell is directly coupled to the battery. Hence, at low power consumption, the fuel cell provides energy for the robot's operation and charges the battery. However, if the robot's motors require more current than the fuel cell can provide, they additionally draw current from the battery. This power distribution is solely controlled by the different voltage levels and resistances of the components (Figure 11). Once the battery is fully charged, or when the fuel cell runs out of hydrogen, the robot automatically shuts down the fuel cell, and HydroBot is again powered solely by battery.

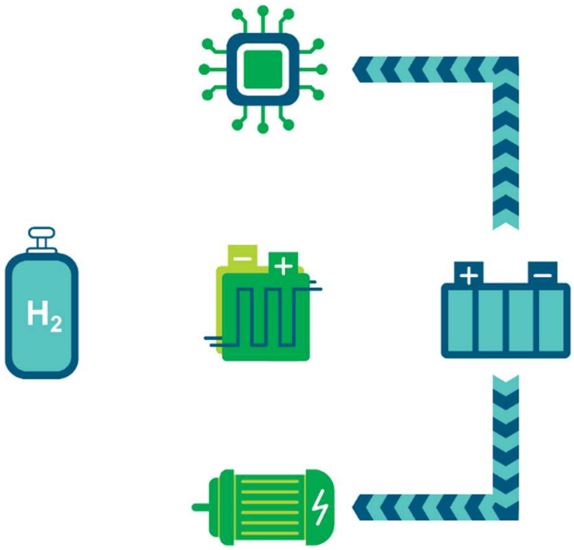

Figure 8: HydroBot in battery mode: The battery provides energy to the robot's onboard electronics and motors. The fuel cell is not in use.

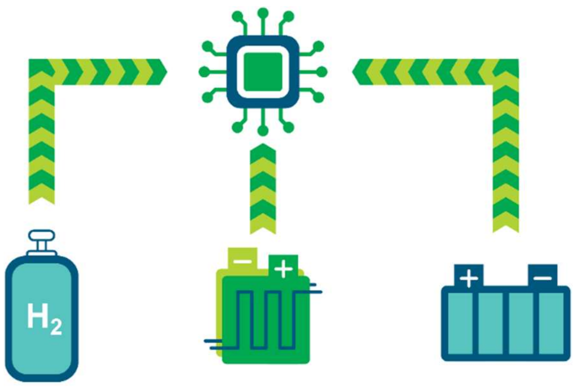

Figure 9: HydroBot's sensors: The onboard electronics receive data from the hydrogen storage cartridges (pressure), from the fuel cell (voltage, current), and from the battery (voltage, current), which is used to ensure safe operation of the fuel cell.

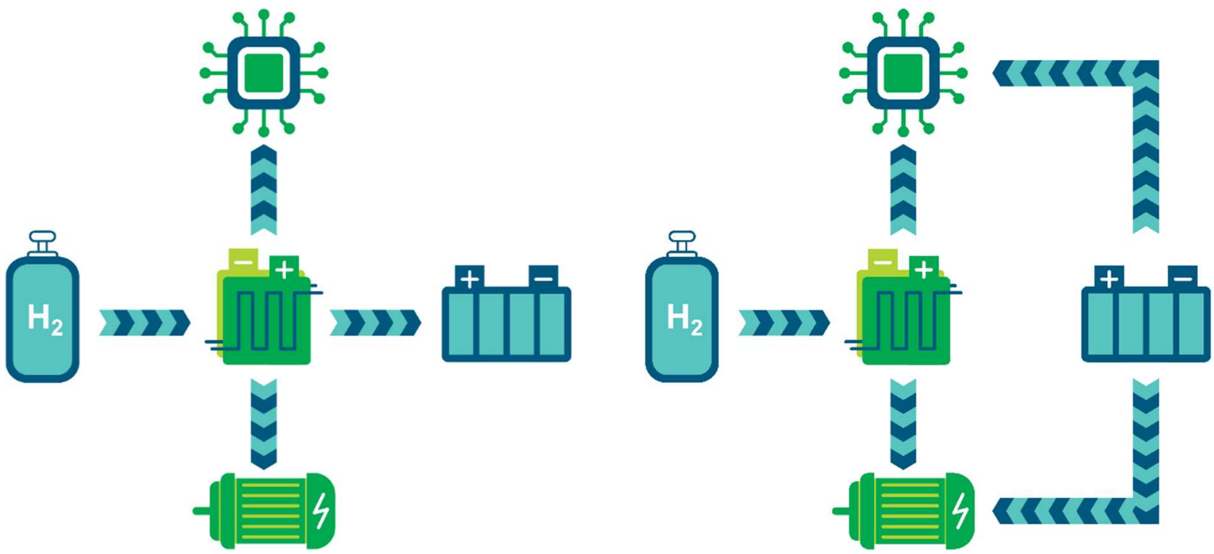

Figure 10: HydroBot in fuel cell mode: The fuel cell receives hydrogen and converts the chemical energy from this fuel into electricity that is distributed to the onboard electronics, the battery, and the motors (left). If the power draw of the motors is larger than the power output of the fuel cell, the battery is not charged any longer but supplies electricity to the system to cover these current spikes (right).

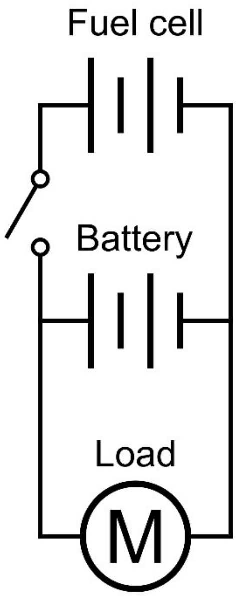

Figure 11: Simplified circuit diagram of HydroBot's power supply. The fuel cell and battery are connected in parallel to the load (onboard electronics and motors). Once the fuel cell is activated, it charges the battery and powers the robot. The current flow between battery and load is determined by the robot's power draw versus the fuel cell's power output. If the robot consumes more energy than the fuel cell can provide, the battery provides the missing energy. If the robot consumes less energy than the fuel cell provides, the surplus in energy charges the battery. The fuel cell operation point is governed by the robot's system voltage, which depends on the battery's state-of-charge and the robot's current draw.

5.3 Mecanum wheel drive system

HydroBot's drive system relies on Mecanum wheels, which are driven wheels including rollers that are aligned perpendicular to the main wheel's orientation, with their side walls facing the ground, mounted at 45° relative to the vehicle's front (Figure 12). These rollers can freely spin. Since the vehicle employs four Mecanum wheels, all with their own independent power train, this propulsion system allows the robot to cover 360° transversal driving (omnidirectional driving) without requiring a classical steering linkage to alter the angle of the wheels. Instead, steering is conducted by adjusting the speed and direction of the single Mecanum wheels relative to each other. Equally, this adjustment of speed and direction also allows the robot to rotate on the spot (Figure 13).

The robot is controlled by inputs from two joysticks. One of the joysticks is used to read the desired speed (tilting angle of the joystick relative to its center (z-axis)) as well as the desired direction (tilt direction along x- and y-axis). This input is provided on a Cartesian coordinate system and internally converted into polar coordinates, which provide a vector length (speed) and orientation (drive direction). These two inputs are used to compute the required rotation direction and speed of each Mecanum wheel. Hence, HydroBot can freely drive in 360° based on a single joystick input. The second joystick is used to add rotation to HydroBot's movement. Here, only the x-axis of the joystick is read, and its input is used to modify the transversal movement of the robot. It allows the robot to rotate stationarily but also to turn at variable radii while driving transversally. The geometry of the Mecanum wheels was calculated based on [10]. The motor control algorithm for HydroBot is adapted from [11].

Mecanum wheels offer advantages for vehicles that must navigate in narrow spaces, like a forklift in a warehouse. On the other hand, Mecanum wheels are not suited for harsh off-road applications or driving at high speeds. Since HydroBot is meant as a demonstration platform, it does not need to perform either of the latter but rather drive indoors at fairs and conferences. Thus, Mecanum wheels are a perfect choice for this robot's drive system.

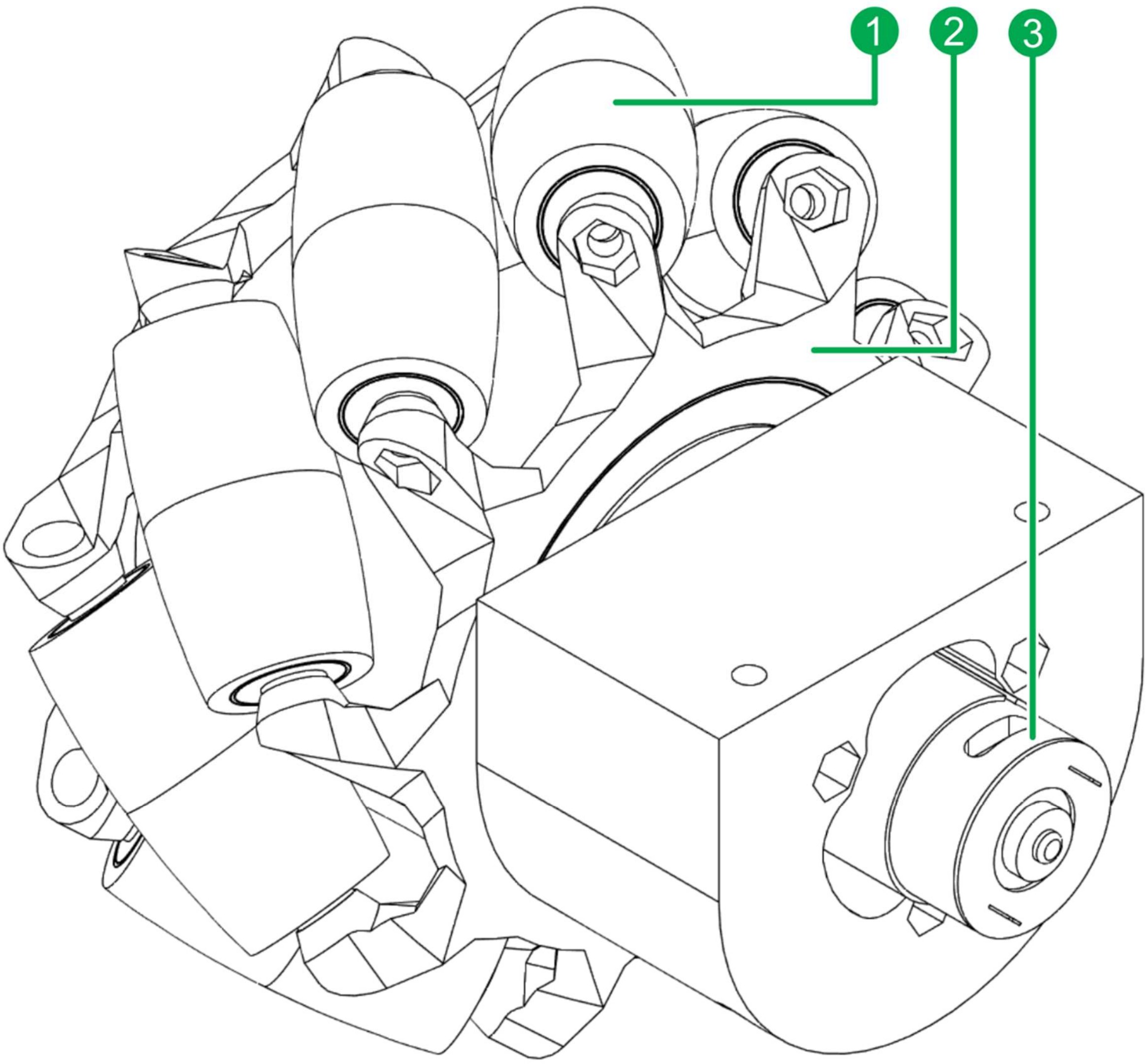

Figure 12: A Mecanum wheel of HydroBot. 1, a freely spinning roller, perpendicular to the main wheel's orientation, at 45° relative to the vehicle's front. 2, the main driven wheel. 3, motor powering the main wheel. The wheel includes a planetary gearbox that reduces maximum speed while increasing the available torque.

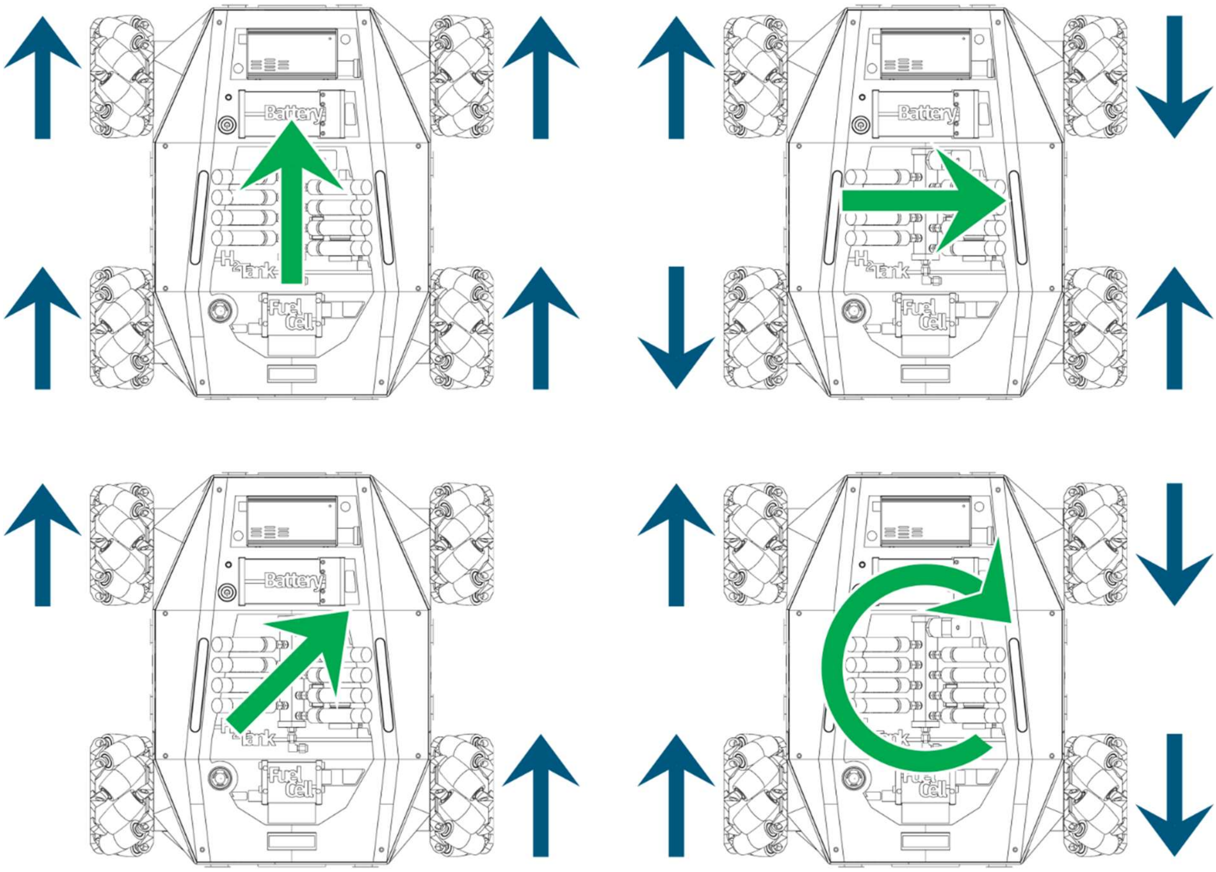

Figure 13: Exemplary wheel spinning and drive directions for a Mecanum wheel drive system. Upper left: All four wheels rotate in the same direction, resulting in the same vehicle drive direction. Upper right: Front and rear as well as left and right wheels spin in opposite directions, resulting in lateral movement of the vehicle. Lower left: Only two diagonal Mecanum wheels rotate in the same direction, resulting in a diagonal movement of the vehicle. Lower right: Left and right Mecanum wheels spin in opposite directions, resulting in a rotation of the vehicle on the spot.

6. Operating instructions

Startup procedure:

The hydrogen storage cartridges should be installed directly before switching the robot on. All eight should be loosely attached to the pressure reducers, and once they are in place, they need to be screwed hand-tight in a quick sequence to avoid hydrogen leaking through open pressure transducers. Omit this step if the robot should be operated in BEV mode only.

Press and release the power button of the robot (1, Figure 1) and flip the rocker power switch of the remote control (1, Figure 5) to the “on” position. Note that the remote control’s toggle switches (2,4; Figure 5) must be flipped downwards to start the system. The robot performs a self-test of its LED light indicators upon startup. Sequentially, they must light up in red, green, and blue.

After startup, the remote control’s display shows page 1 (Figure 6), which indicates the robot’s and the control’s sensor and input readouts. The robot is ready to run if neither a low battery warning (Table *3*) nor a connection issue is displayed (Table *3*, Figure *14*). The robot automatically flips sequentially from page to page (Figure 4) to show all relevant sensor data to the user.

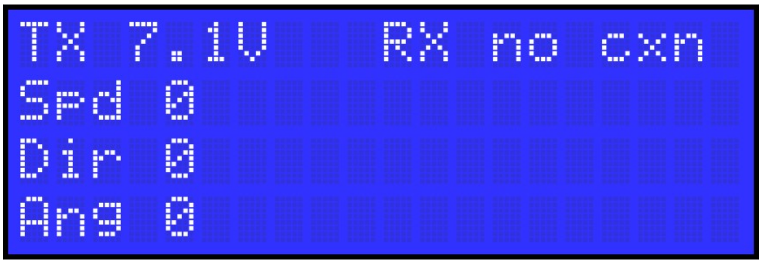

Figure 14: Connection warning in the LCD screen of the remote control. “no cxn” on the right indicates that the remote control is not connected to HydroBot.

Driving the robot:

HydroBot is controlled by the two joysticks of the remote control. The right joystick (8, Figure 5) specifies the direction and speed of transversal movement (combined x- and y-axis), and the x-axis of the left joystick (5, Figure 5) specifies the rotation direction and speed. Note that the sides with the logo plates are the robot’s front and rear. The fuel cell controller faces the front side of the robot, and the LCD display is on its rear side (compare Figure *1*and Figure *2*).

The robot includes four distance sensors mounted on HydroBot’s front, left, right, and rear (14, Figure *2*). The robot will automatically stop transversal movements toward the direction of a sensor if an obstacle is detected. The motors are stopped when a sensor detects an object at ≤25 cm distance. Transversal movements in unblocked directions are not affected by this routine. Further, rotations are not influenced by the distance sensors. HydroBot automatically stops driving if the connection to the remote control is lost or the battery is drained.

Fuel cell control:

The fuel cell can be started if the battery is not fully charged (<13.5 V) and if the hydrogen pressure is >0.4 bar. First, the left toggle switch (2, Figure 5) must be flipped upwards to supply power to the fuel cell controller. Then, the fuel cell is started by pressing the two joystick push buttons (5, 8; Figure 5) simultaneously. The system then triggers the fuel cell controller to start the fuel cell stack. The system waits for the fuel cell to reach its open circuit voltage (20 s) before automatically connecting it to the battery as a load.

The fuel cell status can be viewed in more detail by switching from the default screen page 1 of the remote control's LCD to page 2 (Figure 6), which is done by flipping the right toggle switch (4, Figure 5) upwards. Flipping the toggle switch downwards returns to screen page 1.

The fuel cell automatically shuts down if the battery is full (>13.9 V) or if the hydrogen pressure is low (<0.4 bar). Further, it can be manually turned off by pressing the two joystick pushbuttons (5, 8; Figure 5) once simultaneously, or by flipping the left toggle switch (2, Figure 5) downwards. Pressing the joystick push buttons switches off the cell, and the power supply to the fuel cell controller is cut by flipping the toggle switch downwards. Switching off the fuel cell with the left toggle switch does not instantly cut power to the fuel cell controller, but results in a safe shutdown routine internally before disconnecting the controller from its power supply.

Manual fuel cell control:

HydroBot includes a manual operation mode for the fuel cell, which can be used as an alternative to the standard (automatic) fuel cell control. The manual control option is enabled in the remote control by pressing the right push button (8, Figure 5) once immediately after startup, while the screen shows the welcome page. The LCD shows if the manual operation mode was successfully activated (Figure 15). Note that this setting is not stored permanently in the system. The manual fuel cell control mode must be set every time the remote control is switched on (the automatic mode is entered as a default).

The manual control mode differs from the automatic control by turning off all safety features of the fuel cell and by letting the user manually start/stop the fuel cell and manually (dis)connect it to the battery. In manual mode, the fuel cell is started/stopped by pressing both joystick push buttons (5, 8; Figure 5) once. The fuel cell is connected to the battery by flipping the left toggle switch (2, Figure 5) upwards and disconnected by flipping it downwards. Connecting the fuel cell to the battery before it reaches its final open circuit voltage (>18 V) can cause a low-voltage error of the fuel cell controller, independent of HydroBot's onboard electronics. Note that HydroBot's system does not know if the fuel cell is switched on or off in the manual control mode. Hence, every time the two push buttons are pressed, an on/off signal is forwarded to the fuel cell controller.

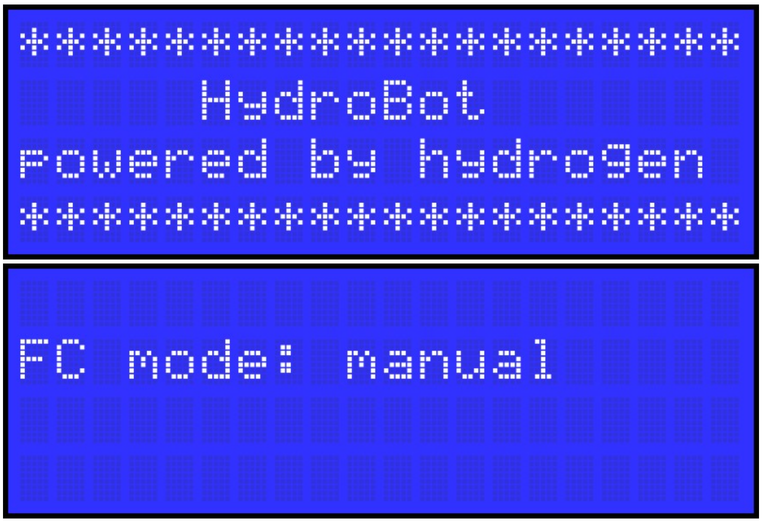

Figure 15: Welcome screen (upper image) and confirmation of fuel cell operation mode change to manual (lower image) in the remote control of HydroBot

Battery charging:

The remote control includes 6 AA NiMH batteries. They can be removed from the remote control by unscrewing its battery cover (6, Figure 5) and charged in a suitable charger. The remote control indicates when its batteries need to be recharged (at <6.9 V, which equals <1.15 V/cell), as shown in Figure 16.

The LiFePO4 battery of the robot is not meant to be removed from HydroBot. It is charged by connecting a DC power supply with an output voltage between >10 and <32 V to the built-in charge port (2, Figure 1). Note that the robot must be switched on before connecting a power supply to its charge port. The robot automatically starts charging when a power supply is connected to its charge port. The charger can be removed at any time, but do not cut the robot's power while charging the battery. Once the battery is full, the robot automatically stops charging it. Battery charging is indicated in the robot's LCD (page 4). Battery charging starts when the battery voltage is <13.5 V and stops when the battery voltage is >13.9 V.

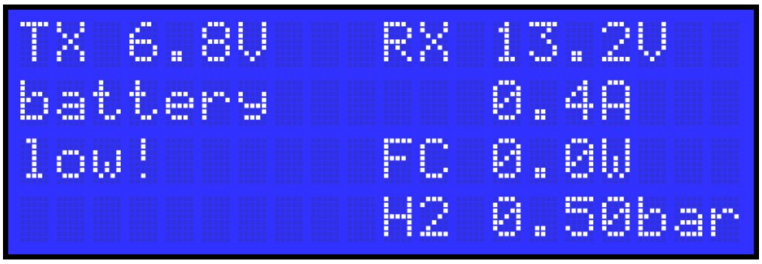

Figure 16: Low battery indication in the LCD screen of the remote control

Shutdown procedure:

The remote control is switched off by flipping its power rocker switch to the “off” position (1, Figure 5). HydroBot automatically switches itself off 30 s after losing connection to the remote control. It can also be manually switched off by pressing the power button (1, Figure 1) for 1 s. Note that the latter is not possible while charging the robot. The remote control can be switched off while charging the robot. In this case, the robot automatically switches itself off upon removing the power supply from the charge port.

Switching off the remote control or losing connection to the remote control does not trigger the robot to switch itself off while the fuel cell controller is powered on (automatic fuel cell mode). Note that no such safety feature is available in the manual fuel cell operation mode.

LED light indicators:

The LED light indicators of HydroBot show important sensor readings, status information, and errors. The upper two LED light indicators (7, Figure 8) show status information of the battery and fuel cell. The LED light indicators in the side panels show information on the connection quality to the remote control and the drive and distance sensor status. Table 3 shows the different light signals and their description.

Table 3: LED light indicator assignment

Position	Light color	Description
Top	Green	Battery voltage good (> 12.8 V)
Top	Red	Battery voltage low (≤ 12.8 V, ≥12.5 V)
Top	Blinking red	Battery empty (< 12.5 V); motors disabled
Top	Blue	Battery charging (via fuel cell or charge port)
Top	Cyan	Fuel cell controller powered on (auto mode)
Top	Yellow	Fuel cell status change (start or stop; only in auto mode)
Top	Blinking purple	Fuel cell malfunction (H2 pressure too low or OCV too low)
Side	Green	No obstacle detected, no drive input in this direction
Side	Yellow	Obstacle detected, no drive input in this direction
Side	Red	Obstacle detected, driving in this direction stopped
Side	White	No obstacle detected, driving in this direction
Side	Blinking red	No connection to the remote control

7. Troubleshooting

Issue	Possible cause(s)	Solution
Remote control does not start	Batteries dead (<1 V/cell)	Replace 6x AA NiMH batteries
Robot does not start	Battery dead (<<10 V)	Disconnect battery from the robot, check voltage; charge externally or replace battery
Robot does not start	Connection issue	Maintenance needed. Contact developer team
RX battery warning (Table 3)	Robot battery is low	Charge battery using charge port
TX battery warning (Figure 16)	Remote control batteries are low	Remove batteries and charge in external charger
Fuel cell does not start	Hydrogen pressure is low (<0.4 bar)	Remove Hydrostik Pro cartridges and refill them with hydrogen (according to manual)
Fuel cell does not start	Open circuit voltage is too low (≤16 V)	Rejuvenate the fuel cell stack by injecting DI water into the stack (according to H60 manual)
Fuel cell does not start	Battery is full	The battery is only charged at <13.5 V
Fuel cell power is low	Stack is too dry	Rejuvenate the fuel cell stack by injecting DI water into the stack (according to H60 manual)
Robot does not charge via charge port	Battery full, power supply beyond voltage window or below power rating	Use a DC switching power supply between >10 and <32 V DC and ≥60 W. The battery is only charged at <13.5 V
Robot does not auto-stop close to an obstacle	Obstacle at wrong angle, height, or shape for detection	n. a.
Robot does not auto-stop close to an obstacle	Ultrasonic distance sensor(s) are defect	Replace sensor(s). Contact developer team
Robot loses connection to remote control	Distance too far, no clear line of sight, interference	Move the remote control closer to the robot, only operate in line of sight, avoid areas with much WiFi traffic at 2.4 GHz
Robot drives without joystick input	Joystick drift (speed or rotation input is not zero at joystick center, Figure 6)	Recalibrate joysticks. Contact developer team
Robot moves or starts fuel cell without input	Interference with other devices that use ESP-NOW	Change MAC addresses of the microcontrollers. Contact developer team
Driving causes loud noise	Loose bolts/connections, drivetrain damage	Maintenance needed. Contact developer team
Motor spins but wheel does not	Drivetrain damage	Repair needed. Contact developer team
Motors do not spin	Battery low (see Table 3)	Charge battery
Motors do not spin	Motor driver defect	Replacement needed. Contact developer team

8. Contact information

HydroBot was developed by Helmholtz-Institute Erlangen-Nürnberg for Renewable Energy, part of Forschungszentrum Jülich.

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LCD screen images were created using this tool:
https://invootechnicaglobal.com/world/home/tool_lcd_view_generator

10. Appendix

- Cytron MDD20A (motor driver), datasheet
- HC-SR04 (ultrasonic distance sensor), datasheet
- Horizon Educational Hydrostik Pro (metal hydride hydrogen container), manual
- Horizon Educational H60 fuel cell (proton exchange membrane fuel cell stack and controller), manual
- pbq LF 7.2-12 ($LiFePO_4$ battery), datasheet
- Servocity brushed DC geared motor (motor), datasheet
- TDK Lambda i7C series (DC-DC converter), datasheet
- Wika PE81.60 (pressure sensor), datasheet