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Lithium Hydride Powered PEM Fuel Cells for Long-Duration Small Mobile Robotic Missions

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***Abstract*— This paper reports on a study to develop power supplies for small mobile robots performing long duration missions. It investigates the use of fuel cells to achieve this objective, and in particular Proton Exchange Membrane (PEM) fuel cells. It is shown through a representative case study that, in theory, fuel cell based power supplies will provide much longer range than the best current rechargeable battery technology. It also briefly discusses an important limitation that prevents fuel cells from achieving their ideal performance, namely a practical method to store their fuel (hydrogen) in a form that is compatible with small mobile field robots. A very efficient fuel storage concept based on water activated lithium hydride (LiH) is proposed that releases hydrogen on demand. This concept is very attractive because water vapor from the air is passively extracted or waste water from the fuel cell is recycled and transferred to the lithium hydride where the hydrogen is "stripped" from water and is returned to the fuel cell to form more water. This results in higher hydrogen storage efficiencies than conventional storage methods. Experimental results are presented that demonstrate the effectiveness of the approach.**

I. INTRODUCTION

Small mobile robots operating for long durations have the potential to perform many important missions in field environments, such as post disaster search and rescue, exploration, border patrol and sentry duty [1], [2] (Figure 1). Many of these missions require nearly continuous operation for long periods, days and weeks rather than hours. Most commonly mobile robots are powered with batteries, sometimes with internal combustion engines and in a few cases (such as the Mars explorers) with solar photovoltaic panels [3]. Combustion engines have high power and high energy but are noisy and produce toxic exhaust that makes them unsuitable for most applications. Solar panels are rarely used because of the large surface areas required and variability in insolation. Hence, batteries are currently the power source of choice.

Weight and size constraints usually prevent current batteries from powering long range and/or long duration missions. Batteries are able to provide relatively high power for short periods, but the total energy they can provide is limited due to their size and chemistry [4].

Important research has been done to improve battery technology [5]. However, as shown from the case studies in this paper, batteries will not be able to meet the mission needs of long duration small mobile robots in field environments in the near future. Hence, new means for powering field robots need to be considered.

Fig. 1. Example of small robots (Left) A ball shaped hopping robot concept for exploration of extreme terrains and caves developed for NASA. (Right) iRobot 110 Firstlook used for observation, security and search and rescue.

This paper explores the use of fuel cells, and in particular Proton Exchange Membrane (PEM) fuel cells powered by stored, on-demand hydrogen in the form of metal hydrides for mobile robots. The robots considered are small sized systems weighing between 5 and 20 kg.

A PEM fuel cell converts the chemical energy of the fuel and oxidizer directly to electrical energy. The main advantages of a PEM fuel cell is that it is highly efficient, operates at ambient temperatures and pressures and is stealthy, is quiet, produce clean exhaust and has a low thermal signature. A discussion of various types of fuel cells is beyond the scope of this paper [6]. In this study the fuel is hydrogen, that is oxidized using ambient air. The hydrogen is produced on demand from a water activated metal hydride - lithium hydride (LiH) carried by the robot as a powder at ambient temperature and pressure. The fuel has a theoretical usable energy density of 4,200 Wh/kg, 30 times the energy density of lithium ion batteries.

A battery uses a different chemical process to convert chemical energy to produce electrical energy. Fundamentally, the chemistry of a fuel cell using hydrogen and oxygen produces more specific energy than the best batteries. However fuel cell technology is not as mature as batteries and their peak power levels tend to be lower than batteries.

Its important to note that fuel cells have the potential to provide power over long time periods as required for long duration missions. PEM fuel cells have high operating efficiencies of 50-70% for practical use [6] requiring very little fuel, in the order of 10^{-4} g/s of hydrogen to generate a few watts required for powering small mobile robots. This low and on-demand production rate of hydrogen simplifies hydrogen safety, storage and handling. An effective way to

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use fuel cells in robotic missions that have time variable power demands is in a hybrid configuration with a battery [7], [8]. The fuel cell continuously charges a battery, which meets the short term high power demands. This also protects the fuel cell from highly variable power demands that has been shown to stress PEM fuel cells and shortens their lives [9].

II. BACKGROUND

Fuel cells have been proposed for various robotic and field applications such as for powering unmanned underwater vehicles [10], humanoid robots [11], hopping robots [7] and ground robots [12]. These studies have shown some promising results. For example, fuel cell power systems with high specific energy have been applied to improve the mission lengths of unmanned ground, air and underwater vehicles. A PEM fuel cell powered Autonomous Underwater Vehicle (AUV), with hydrogen stored in metal hydrides completed a record-setting 317 km (56 hours) continuous cruise [10]. A fuel cell powered unmanned air vehicle (UAV) set an unofficial flight endurance record of 23 hours. Its fuel cells provide 7 times the energy compared to batteries [13].

Theoretical energy calculations suggests fuel cell powered mobile robots can last long durations on the order of weeks to months but this has not been achieved. Studies point to two limitations that prevent fuel cells from meeting the requirements of long duration robot missions under field conditions. First, is that the fuel cells operating under field conditions, with varying ambient temperature and humidity and load power demands will fail prematurely [14], [8]. Second, current methods for storing hydrogen for PEMs are inefficient in terms of weight and volume to meet the design constraints of mobile field robotics [15].

Recent studies have shown that PEM fuel cells can have long life for long duration field missions if they are properly designed and key operating variables are well controlled [9]. These variables include: the temperature of the cells; the temperature and humidity of the hydrogen and air supplies; operating voltage, fluctuations in power demand and electronic noise reflected back to the fuel cell from attached electronics. The effects of the variations in the power demand can effectively be controlled by a hybrid configuration. The hybrid system electronics need to prevent electrical noise such as from a DC-DC convertor from being seen by the fuel cell thus mitigating their degrading effects [8]. As detailed discussion of fuel cell degradation and its mitigation is beyond the scope of this paper, the reader is referred to [9].

The second limiting factor in long-life PEM fuel applications is hydrogen fuel storage [15]. Storing hydrogen as a liquid at cryogenic temperatures or at very high pressures is not practical for relatively small mobile robots. For such applications, storing the hydrogen in solid form is attractive.

Storing hydrogen in a solid hydride form that releases hydrogen through depressurization has been considered. However, storage efficiencies (weight of hydrogen to the weight of the hydrides) have been low, ranging from 0.5 % to 2.5 % hydrogen and as a result remains unattractive [16], [17]. Hydrides that use heat to release hydrogen need to reach temperatures of 70 to 800 ^{o} C or higher and can yield up to 18 % hydrogen storage efficiency [16]. However these methods require substantial energy and infrastructure and the yields have been reported to be unreliable.

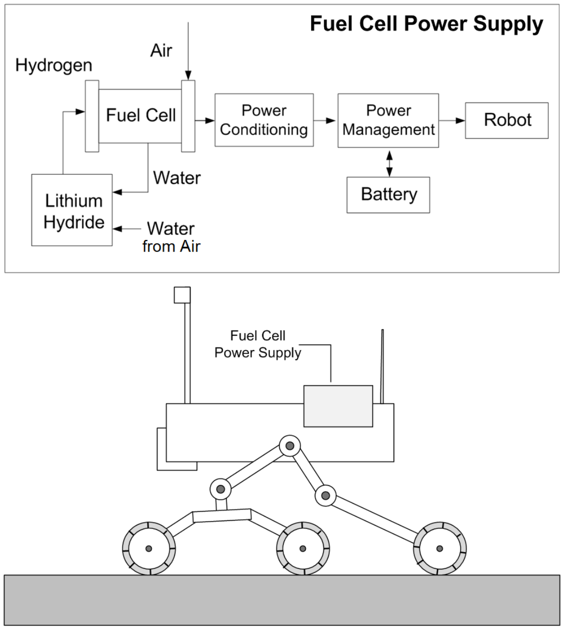

Fig. 2. A mobile robot with a fuel cell power supply system.

This work focuses on developing a lithium hydride based hydrogen storage system for use with PEM fuel cell power supplies (Figure 2). With lithium hydride, the hydrogen is released by exposure to water [18]. There are other water released metal hydrides including sodium borohydride ($\mathrm{NaBH_4}$) [19] and magnesium hydride ($\mathrm{MgH_2}$) [20]. However these materials have lower weight efficiencies and require complex reactions. Magnesium hydride has a theoretical 15.4 % storage efficiency, but less than 8 % has been achieved. The appealing feature of water activated lithium hydride is that the fuel cell produces theoretically enough waste water for activating the lithium hydride. As will be discussed below, the lithium hydride extracts the hydrogen from the water to provide additional hydrogen for the fuel cell. Hence recycling the water and/or passively extracting it from the air provides a theoretical 25 % storage efficiency discussed in Section IV. It is shown below that PEM fuel cells fueled using lithium hydride have the potential to power long range and long duration mobile robots in field environments.

III. ROBOT POWER - CASE STUDY

A. Robot Power

Here a simple small mobile robot is modeled and the performance of current rechargeable batteries is compared with a fuel cell power supply for representative missions (see Figure 3). The robot is assumed to consist of a power supply, drive system (consisting of motors and servos) and computer and electronics. The robot's computers and electronics operate continuously during its mission. The electronics interface the various robotic components such as switches, power regulators and bridges. The power consumed by these electronic components is assumed to be constant. The six wheels of the robots are individually driven by geared conventional DC brushless motors for good traversability in challenging terrains. The motor torque required is a function of the gear ratio, wheel size and force required to overcome friction and the normal force. Here the robot is assumed to move at a constant velocity of 1.0 m/s (3.6 km/h) and the mass excluding the power system is 5 kg.

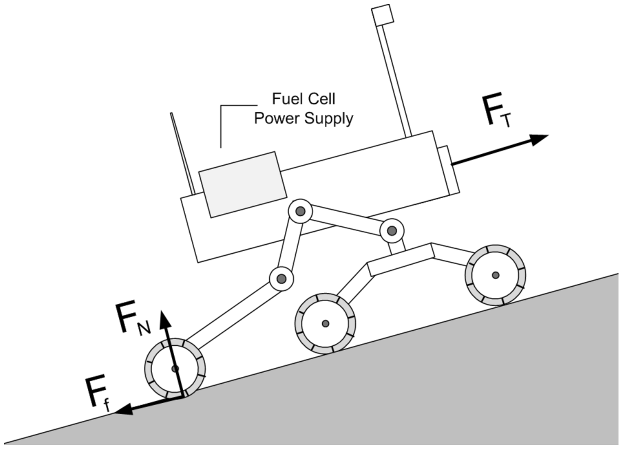

Fig. 3. Free body diagram of the robot model.

The motor power depends on the voltage and current supplied to each motor. The motor drive train efficiency is assumed to be constant. The force acting on the robot is the following (Figure 3):

$$F_{total} = F_{friction} + F_{body} \tag{1}$$

where $F_{friction}$ is the sum of the friction force acting on the wheels, F_{body} is the sum of the normal forces. Aerodynamic drag is neglected in this analysis:

$$F_{friction} = mg\mu_{roll}\cos\theta \tag{2}$$

where m is the mass of the robot, g is the gravitational constant, θ is angle of terrain slope and μ_{roll} is the coefficient of rolling friction and is 0.2. The power consumed by the robot is a function of time and is:

$$P\left(t\right) = \frac{F_{total}(t)v(t)}{\eta_s} + P_{overhead} \tag{3}$$

where $F_{total}(t)$ is the net force acting on the robot, $v(t)$ is velocity of the robot, $P_{overhead}$ is the power consumed by electronics, computer, onboard sensors and is 7.5 W. The net robot drive efficiency, $\eta_s = \eta_{motor} \cdot \eta_{drivetrain}$ and is 68%, where the drivetrain efficiency is assumed to be 85% and motor efficiency is 80%. The total energy consumed by the robot is:

$$E_{total}\left(T\right) = \int_0^T P\left(t\right) \cdot dt \tag{4}$$

B. Fuel Cell Hybrid Power Supply Sizing

The weight of the nominal fuel cell system is given in Table I and consists of the fuel cell stack, fuel, startup water, storage containers, tubing, electronics, battery and controllers. The storage containers are used to house the fuel and tubing is used to transfer fuel to the fuel cell stack. The electronics and controllers consists of the power management system that protects the fuel cell from electrical noise, operates the fuel cell at fixed operating voltage and charges a rechargeable battery that is used to handling high and varying power demands. The system produces hydrogen from lithium hydride by passively reusing waste water from the fuel cell and augmenting this by passively extracting water vapor from the air and will be discussed in Section V. The mass of the fuel required is calculated from the total energy requirements of the mission:

$$m_{fuel} = \frac{E_{total}}{\lambda_{FC\_EH2}} \cdot \frac{\eta_{LiH}}{\eta_{LiH\_RC}} \tag{5}$$

where E_{total} is the total energy required for the mission and λ_{FC_EH2} is the total efficiency of the fuel cell system calculated using the method outlined in [21] and is 55 %. This total efficiency is calculated from the following:

$$\lambda_{FC\_EH2} = \lambda_{FC} \cdot \lambda_{FC\_Stack} \cdot \lambda_{Purge} \tag{6}$$

where λ_{FC} is the fuel cell efficiency and is 0.65, λ_{FC_Stack} is the fuel cell stack efficiency and is 0.9, λ_{Purge} is the hydrogen losses due to nitrogen purging and is 0.95 [21]. Our results show that operating a fuel cell at constant 65% conversion efficiency offers good tradeoff between conversion efficiency and long-life [9]. η_{LiH} is the hydrogen storage efficiency from the lithium hydrolysis reaction (assuming water reuse) and is 0.25. The percentage reaction completion of the lithium hydride is η_{LiH_RC} and is 1.0, confirmed from our experiment presented in Section V.B. This gives a fuel energy density of 4200 Wh/kg for a fuel cell power supply efficiency of 55 %. The fuel cell stack size for the mission is based on nominal power requirements:

$$m_{FC\_stack} = \left\lceil \frac{P_{nominal}}{P_{FC}} \right\rceil \cdot m_{FC} \tag{7}$$

where $P_{nominal} > P_{overhead}$ and is the nominal power requirements, P_{FC} is the power output from each fuel cell and is 16 W at 55 % efficiency, with a 25 cm^2 area (Fuelcellstore.com) and m_{FC} is the mass of each fuel cell and is 0.09 kg. To supply peak power, the hybrid system uses a rechargeable battery sized as follows:

$$m_{FC\_bat} = \frac{P_{peak} - P_{nominal}}{\rho_{P\_bat}} \tag{8}$$

C. Battery Power Supply Sizing

The mass of a battery alone required to power the mission is the following:

$$m_{bat} = \frac{E_{total}}{\rho_{E\_Bat}} \tag{9}$$

where E_{total} is the total energy required for the mission and ρ_{E_Bat} is the energy density of the battery. For lithium ion battery the assumed energy density is 130 Wh/kg.

TABLE II

Power System Comparison for the Nominal Round Trip Boston Marathon

	Lithium Ion Battery	Fuel Cell - Lithium Hydride No Water Capture	Fuel Cell - Lithium Hydride 80 % Water Capture	Fuel Cell - Lithium Hydride 100 % Water Capture
Power System	12.4 kg	0.6 kg	0.47 kg	0.43 kg
Robot Mass	17.4 kg	5.6 kg	5.5 kg	5.4 kg

TABLE III

Various Fuel Cell Power System Comparison for the Nominal Round Trip Boston Marathon

	Fuel Cell - Sodium Borohydride [21]	Direct Methanol Fuel Cell [21]	Fuel Cell - Lithium Hydride
Fuel Mass	0.6 kg	0.4 kg	0.11 kg
Power System	1.1 kg	0.9 kg	0.43 kg
Robot Mass	6.1 kg	5.9 kg	5.4 kg

TABLE I

Mass Breakdown of Fuel Cell Power System for Nominal Mission

Components	Mass (kg)
Fuel Cell Stack	0.18
Lithium Hydride Fuel	0.11
Electronics, Battery, Control	0.04
Containers Valves and Tubing	0.09
Water	0.01
Total	0.43

D. *Boston Marathon*

For our case study, we consider a round-trip 85.4 km circuit covering the Boston Marathon route. The elevation and power demands for the scenarios are shown in Figure 4 and 5. The mass of the power system required to travel the path is the metric of comparison.

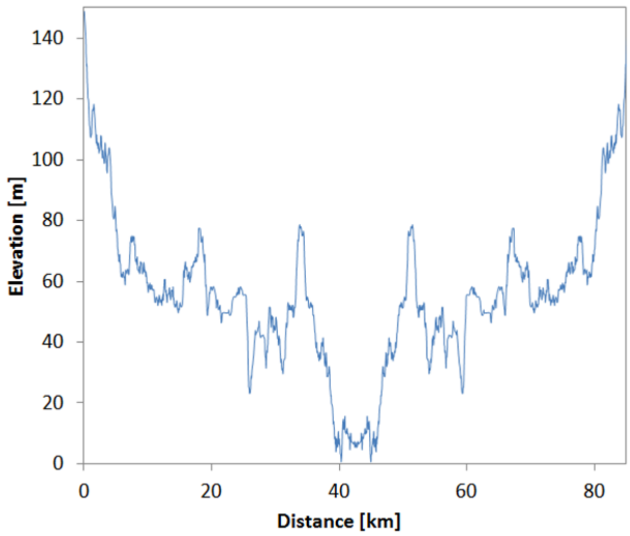

Fig. 4. Elevation map of the Boston Marathon circuit.

With a 12.4 kg power system mass for a 17.4 kg robot, a lithium ion battery power system has sufficient energy to finish one lap of the round trip marathon (Table II). A robot with a fuel cell power system, weighing only 0.6 kg

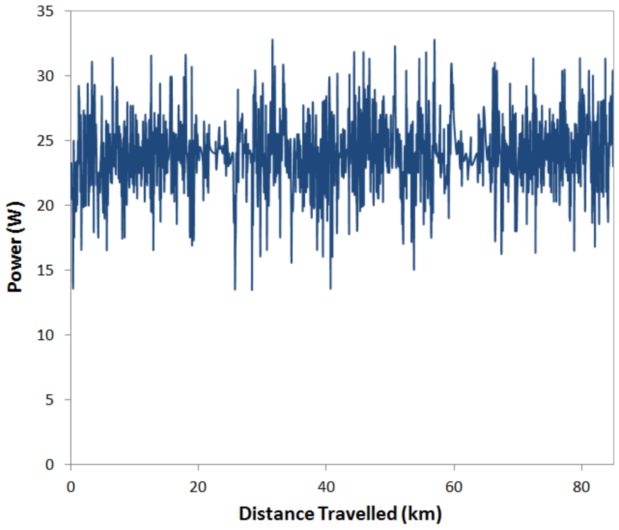

Fig. 5. Power demand profile of a fuel cell powered robot on a round-trip circuit of the Boston Marathon. The average power consumed is 24 W.

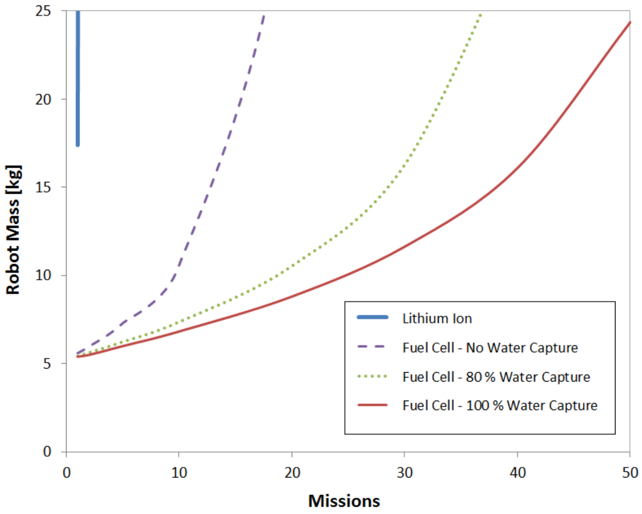

Fig. 6. Mass of robot versus number of mission laps of the 85.4 km Boston Marathon circuit.

TABLE IV
LONG DURATION POWER SYSTEM COMPARISON FOR BOSTON MARATHON

	Lithium Ion Battery	Fuel Cell - Sodium Borohydride	Direct Methanol Fuel Cell	Fuel Cell - Lithium Hydride No Water Reuse	Fuel Cell - Lithium Hydride Water Reuse
Power System	12.4 kg	12.4	12.4	12.4 kg	12.4 kg
Robot Mass	17.4 kg	17.4	17.4	17.4 kg	17.4 kg
Mission Laps	1	5	8	16	45
Range	85.4 km	430 km	680 km	1,400 km	3,800 km
Duration	23.7 hrs	5 days	8 days	16 days	44 days

can travel one lap (assuming water is carried). The fuel cell power system would weigh 0.43 kg if the fuel cell waste water is reused or passively extracted from the air. Figure 6 shows the mass of the system for increased number of mission laps. A battery system can only complete one lap. For longer missions, our results show that a battery system cannot be used. As seen, the three fuel cell options scale well to the number of mission laps compared to a battery system. It is important to note that the water captured or carried has significant impact on the performance of the fuel cell system. Even without water capture (i.e. water carried on board), the fuel cell system has a 16 folds advantage over lithium ion batteries. With 80 % water capture, it is a 28 folds advantage and with 100 % water capture a 31 folds advantage.

The mass of the fuel cell power supply is also compared to previously reported fuel cell power supplies from [21] (Table III). These previously reported numbers are extrapolated to the required energy for one mission. This includes a PEM fuel cell powered using sodium borohydride and Direct Methanol Fuel Cells. The comparison show that the presented lithium hydride powered fuel cell system offers nearly a 6 folds savings in fuel mass over sodium borohydride and nearly a 4 folds advantage over methanol. However the required overhead mass for these fuel cell systems is nearly the same. The advantage of the lithium hydride fuel cell system is reduced mass for long duration missions.

Consider a long duration mission. If the power system is allocated 12.4 kg, then a fuel cell power supply with water reuse can supply power for 44 days continuously, consisting of 45 laps of the 85.4 km circuit (Table IV). This is in comparison to a lithium ion powered system that can only last one mission for 23.7 hours, PEM fuel cell using sodium borohydride (extrapolated from [21]) can do 5 missions and a direct methanol fuel cell system (extrapolated from [21]) can do 8 missions.

Based on this scenario, lithium hydride powered fuel cell systems have a significant advantage over current fuel cell and battery systems. Batteries however have higher power outputs and lower cost. As discussed above, the power limitations of fuel cells can be effectively compensated using a hybrid system. The fuel cell power system presented is a hybrid system that protects the fuel cell from fluctuations in the power demand, electrical noise and thus operates the fuel cell at optimal conditions throughout a mission to minimize stresses on the fuel cell and maximize life [8]. The costs of fuel cells are expected to decrease with time. Nevertheless, there are important robotic missions where cost is not the most important factor compared to feasibly completing a mission.

The following sections report on research that demonstrates the feasibility of using lithium hydride-water reaction to generate hydrogen for a PEM fuel cell. While the above case studies show that ideally the fuel cell power supply can make very long duration missions feasible, these calculations are dependent on making the lithium hydride generator concept scalable in size for the specified energy requirements.

IV. LITHIUM HYDRIDE HYDROGEN GENERATOR CONCEPT

There are two types of metal hydrides for storage of hydrogen: reversible hydrides that release hydrogen through changes in pressure or temperature, and chemical-release or nonreversible hydrides that release hydrogen through chemical reaction [23]. While reversible hydrides are valued because of their ability to be recharged with hydrogen, they are not ideal for long-life mobile robots because they normally have low hydrogen densities (defined as the weight of the hydrogen divided by the total weight of the hydride) on the order of 1-2% [17].

Nonreversible hydrides normally have higher weight percent of hydrogen, and of these, lithium hydride, has one of the highest hydrogen densities of 12.5%. Other chemical-release hydrides, such as sodium and lithium borohydride, also have high weight densities and have been proposed for long-life hydrogen storage. In general these require complex release mechanisms to generate hydrogen [24].

Lithium hydride reacts readily with water at ambient temperatures and pressures to release its hydrogen and the hydrogen of the water as follows [22], [18]:

$$\mathrm{LiH} + \mathrm{H_2O} \rightarrow \mathrm{LiOH} + \mathrm{H_2} \tag{10}$$

This process provides a very high hydrogen density. Also its simple chemistry requires only water, which makes it well-suited for use with PEM fuel cells for small mobile robot power. Recognizing that the supply of water is external to the hydride, for every mole of lithium hydride, the system produces one mole of hydrogen gas, so for every 8 grams of lithium hydride, the system produces 2 grams of hydrogen gas for a weight efficiency of 25%, which is substantially higher than other hydrides.

In the PEM/LiH concept, shown in Figure 7, a simple water management controller transfers water from the fuel cell exhaust and collects it in a reservoir. A pressure sensor monitors the hydrogen supply pressure to the fuel cell. The controller maintains the pressure at a target set point by dispensing water to the hydride. The water dispenser can be a butterfly valve, a pump, or a membrane.

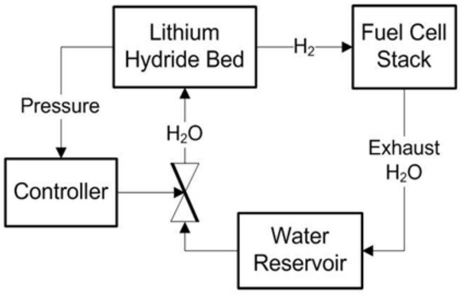

Fig. 7. Simple pressure-based feedback control system that would recycle fuel cell water and lead to 25 % weight efficiency of hydride.

V. Feasibility Experiments

A. Reaction Completion

The feasibility of LiH storage is demonstrated here. In order for the LiH to provide the calculated energy density, nearly all of it must react to produce hydrogen. It has been suggested that byproducts of the LiH process (lithium hydroxide) will form an impenetrable layer on the LiH and prevent diffusion of water into the yet unactivated lithium hydride [25]. This would effectively slow or stop the reaction before all the LiH could be used.

This question was experimentally studied. A commercial lithium hydride powder (95% purity) was exposed to water vapor as shown in Figure 8. Of the 1.2 cm^3 lithium hydride bed, 98+% reacted to form 4 liters of hydrogen gas over 130 hours (Figure 9). This clearly demonstrates that the issue of lithium hydroxide smothering the reaction is not a problem.

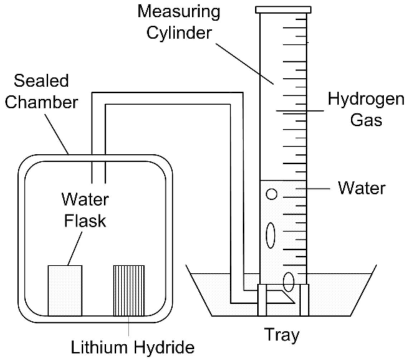

Fig. 8. Experimental setup to test percent completion of reaction.

B. Control of Reaction

For LiH to effectively work in the proposed concept, it must release hydrogen on demand at a specified pressure. The concept is shown in Figure 10. An experiment was performed to show that the reaction can be controlled. In the experiment, the target pressure is set at 1.1 bar with an error bound of ± 0.01 bar. Readings from a pressure sensor located in the chamber provides the feedback signal for the controller. A 100 milliwatt peristaltic pump serves as the water delivery actuator. The pump releases a droplet of 20 microliters into the hydride chamber, which evaporates and reacts with the hydride flasks, as shown in Figure 11. The hydrogen generated is slowly bled from the system using a valve. The control scheme is discrete, in which a droplet of water is released when the system's pressure falls below a threshold.

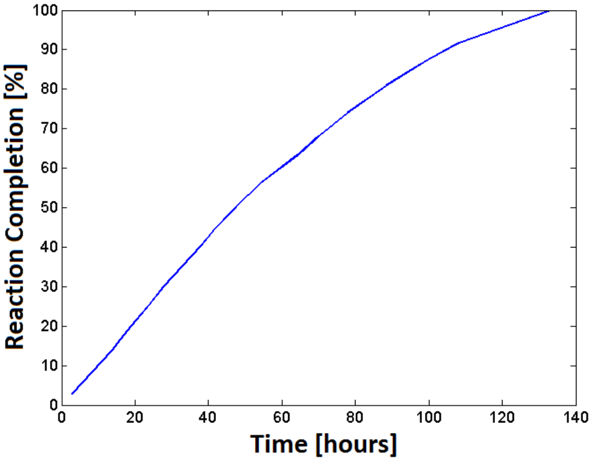

Fig. 9. Experimental results showing percent hydrogen produced from lithium hydride reaction with water.

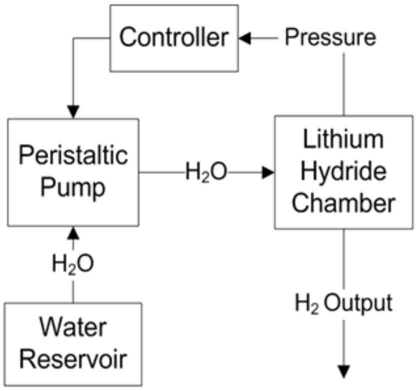

Fig. 10. Feedback control system used for controlling lithium hydride release to maintain a target pressure.

The results of this experiment is shown in Figure 12 and demonstrates control of the reaction at a target pressure. The pump provides a series of droplets every 40 minutes to maintain the system at the target pressure. This results in an average power draw for the pump of 10 microwatts. Therefore, the experiment demonstrates that the reaction can be controlled at a target pressure using very little energy.

C. Water Capture from the Air and Fuel Cell

Water vapor is readily available as waste from the fuel cell and from the air. In this section an innovative, passive lithium hydride hydrogen generator design is presented that consumes water vapor to produce hydrogen (Figure 13). Use of water vapor instead of liquid water simplifies the power supply, by avoiding an energy hungry condensor. A cross

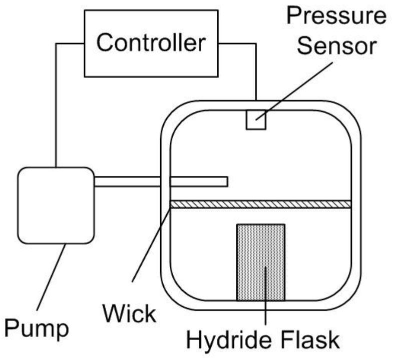

Fig. 11. Experiment to demonstrate feasibility of lithium hydride controlling reaction.

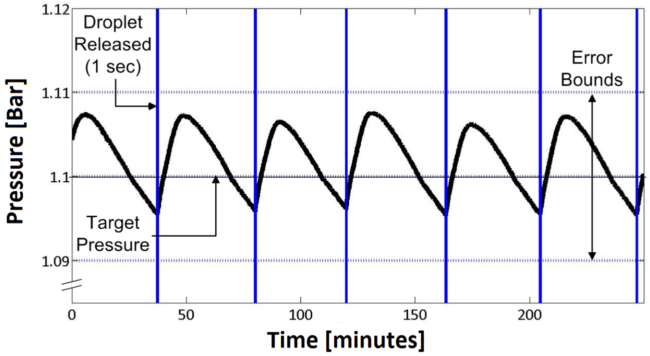

Fig. 12. Graph of pressure versus time of hydrogen release chamber for 1.1 bar target pressure. Vertical lines represent times when droplets of water released into the chamber.

section of the device is shown in Figure 14. The device works using a Nafion® 117 membrane that permits transport of water vapor into a lithium hydride bed due to lower partial pressure of water vapor above the hydride bed compared to the outside, typically 20 % relative humidity or less. The increased hydrogen pressure inflates a latex membrane that increasingly covers the Nafion® membrane enabling the device to produce hydrogen at a target pressure of 1.1 bar. The hydrogen output from this device is shown in laboratory experiments to produce 140 mW of power, at 50 % relative humidity, fuel cell efficiency of 48 % and lithium hydride bed area of 25 cm^2.

This device could extract waste water from a fuel cell resulting in significant mass savings. Effective water capture from a fuel cell requires use of an air permeable vapor barrier around the cathode, where water vapor is produced at 100 % relative humidity. Our laboratory studies suggests this can be accomplished using simple off the shelf vapor barrier foam [26]. This vapor barrier enables the fuel cell to breathe in ambient air without losing water to the atmosphere. The waste water vapor can then be extracted by the lithium hydride hydrogen generator to produce hydrogen This passive lithium hydride generator supplied at 100 % relative humidity doubles the power than at 50 % relative humidity.

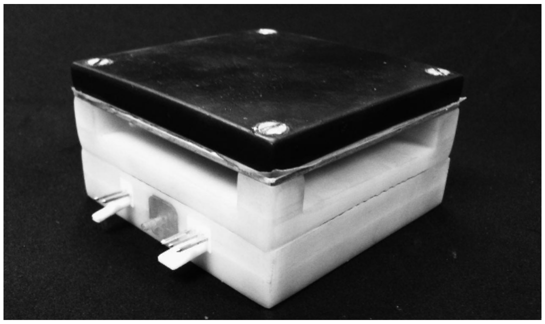

Fig. 13. A Passive 140 mW Lithium Hydride Hydrogen Generator.

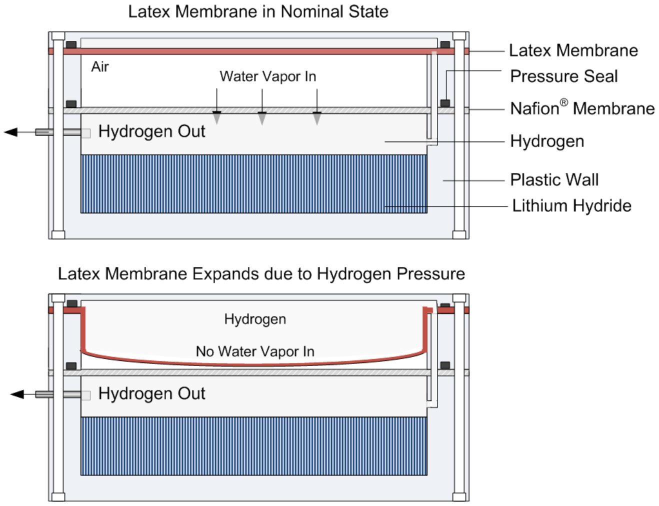

Fig. 14. The passive hydrogen generator uses a Nafion® membrane to extract water vapor from the air to produce hydrogen at a target pressure. As the hydrogen pressure reaches target, a latex membrane expands stopping water vapor transport across the Nafion® membrane.

D. *Scalability*

Our laboratory results show that power output from the lithium hydride generator can be further increased by increasing the lithium hydride bed surface area. An experimental system demonstrates this concept (Figure 15). A cross section of the system (Figure 16) shows a stack of 4 shelves of lithium hydride bed with a total exposed surface area of 730 cm^2 inside a pressure sealed chamber of 282 cm^3 volume, with Nafion® 117 layer (0.05 millimeters thick) of 225 cm^2 area. The flow rate of hydrogen is measured using a Digital Mass Flow Meter (Model 1179A, MKS Instruments, MA). With 100 % input relative humidity to the lithium hydride generator, a hydrogen flow rate of 1.5×10^{-4} g/s is expected to generate 11 W for a fuel cell operating at 65 % efficiency. Our experiments show that this system can generate the required hydrogen flow rates to produce 6 W with water vapor for a few hours. In the current setup, four of these generators (using water vapor) can be combined to meet the 24 W average power requirements of the robot analyzed in the feasibility study in Section III. Further work is underway in making the approach practical by increasing the duration, power output and minimizing volume for increased surface area of lithium hydride.

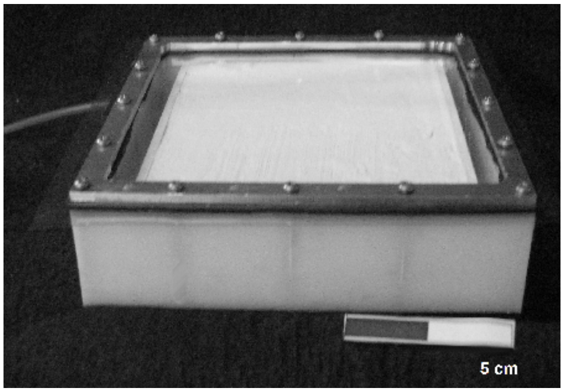

Fig. 15. Multi Watt Lithium Hydride Hydrogen Generator Experimental System.

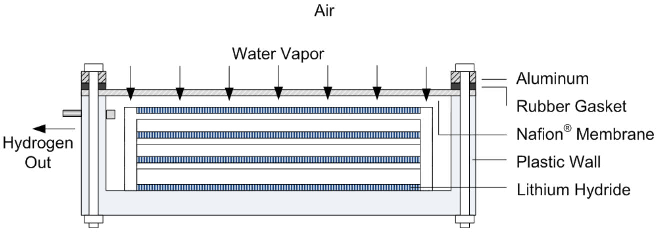

Fig. 16. Cross-section of Multi Watt Lithium Hydride Hydrogen Generator shows 4 Beds of Lithium Hydride used to expand the exposed hydride surface area.

VI. CONCLUSIONS

This paper reports the development of power supplies for small mobile robots performing long duration missions. It suggests that Proton Exchange Membrane (PEM) fuel cells can be the basis of such power supplies. Simulation results presented for a representative small mobile robot performing long duration missions show that a PEM fuel cell power supply will provide much longer range than the best current rechargeable battery technology. A simple, passive hydrogen fuel supply system based on water activated lithium hydride (LiH) is presented and has a fuel weight efficiency six times greater than conventional metal hydride hydrogen storage methods. Experimental results are presented that demonstrate the basic feasibility of this fuel storage approach.

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