Solar Energy as an Alternative Energy Source to Power Mobile Robots

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Abstract. Solar energy can provide a viable alternative energy source to meet the special energy demands that are typically required to operate mobile robots. Conventional energy sources cannot fulfil these demands as satisfactorily as solar energy can, given the disfavour that conventional energy sources find in an eco-conscious world, and also given the practical limitations associated with conventional energy sources which cannot conveniently be accessed in places where mobile robots are normally put to use which are often inaccessible and beyond human reach. This study seeks to demonstrate that solar energy can be harnessed and stored using hydrogen as a medium to store an otherwise intermittent supply of energy that is characteristic of solar energy. In this study, an Industrial Mobile Robot Platform (IMRP) was designed to run on fuel cells using a low-pressure metal hydride hydrogen storage system which would store more energy on board than a rechargeable battery could.

Keywords: Energy, Solar, Hydrogen, Mobile Robot, Fuel cell.

1 Introduction

In an ever more eco-conscious world, the quest for cleaner and environmentally-friendly energy sources has become increasingly pressing. Conventional energy sources, with all the negative connotations associated with the toxic nature of its production, are being shunned in favour of renewable energy sources.

Solar energy, as one form of renewable energy, offers enormous potential as an alternative to conventional energy sources. It does not have all the negative draw-backs of traditional energy sources such as fossil-based electricity and petroleum oil which carries a huge threat of pollution to the environment [1, 2].

Apart from environmental concerns, there are other draw-backs to conventional energy sources which are key limiting factors for a mobile robot which requires versatility to be efficient. Electricity, for instance, may not be available in a disaster area, or it may not be practical for a robot to be constantly attached to a power source by

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means of an electrical cord in situations where it is required to be manoeuvred in difficult areas of access. Petroleum also, has its own draw-backs as it would necessitate the storing of bulk fuel on-board, thereby hampering the operation of a mobile robot which, by its very nature is required to be light, compact and versatile enough to be able to manoeuvre in the tightest of spaces [1, 3].

Rechargeable batteries on the other hand, appear to offer a more practical alternative in that they are light, and therefore can be taken on-board without making the mobile robot cumbersome as would be the case if bulk fuel like petroleum had to be taken on-board. Also, since batteries are a portable source of power, they do not have the draw-backs of electricity which requires the mobile robot to be constantly attached to a power source, thereby limiting its range of movement and distance. But batteries too, have their draw-backs. Rechargeable batteries, by nature, have very low densities and high rates of discharge, thereby making them ineffective to sustain a mobile robot's energy demands in times of high peak demands and over long duration missions.

As for nuclear energy, there is very strong global political pressure against its use, and hence, it has become the central aim of world energy policy today to seek alternative sources of energy, preferably from renewable forms such as solar.

But solar energy presents certain challenges. It cannot provide a constant supply of energy, since it is dependent on available sunshine, which is not always present. This means that solar power is intermittent and unreliable. But if suitable means can be developed to store this energy, it could offer a viable alternative that could address all the draw-backs to be found in the energy sources already covered above [4, 5].

2 Research

The research presented here will demonstrate that solar energy can indeed provide a constant and reliable source of energy to meet the energy demands of a mobile robot. The challenges posed in finding a suitable method of storing that energy can be overcome by the use of hydrogen as a medium for storage, using metal hydride.

3 Methodology

As a first step, sunlight is converted to electricity by the use of photo-voltaic (PV) cells. Apart from the high initial cost in setting up the PV panels, once built, the system has the advantage of very low operating costs and the energy produced by the PV panels are cost-free, and also free of any waste products.

However, as the availability of sunlight is intermittent, there is a need to devise a back-up power system so as to be able to store the electricity produced by the PV panels and thereby have a readily available source of energy at all times.

Hydrogen offers the best energy storage solution. Hydrogen is an ideal energy carrier. To produce hydrogen, the process of electrolysis is used to split water or $H^{2}0$ into its constituent elements of hydrogen and oxygen. The electricity that will be required for this process of electrolysis, would already be available from the electricity produced by the PV cells from sunlight, as described above.

So, during periods of high availability when there is abundant sunlight, the excess electricity that is produced from solar will be directed to the electrolyzer to produce hydrogen, thereby rendering the surplus electricity in a form that would be capable of storage [6].

Next, a medium must be found to store the hydrogen. Metal hydrides are the most compact way to store hydrogen. They can be used as a storage medium for the hydrogen, often reversibly so that when the renewable source isn't available, the hydrogen can be converted back to electricity to provide constant power. Reversible metal hydrides offer several benefits over other means of storing hydrogen. They operate at low pressure, especially when compared to compressed hydrogen, and do not need to be kept at the cryogenic temperatures required for liquid hydrogen storage. Reversible hydride storage typically requires less energy on a system basis, is compact, and can be conformable [7] to fit space available on an application such as a mobile robot.

The conversion of hydrogen back to electricity requires a fuel cell. Fuel cells are devices that produce electric power by direct conversion of a fuel's chemical energy. Fuel cell systems offer many potential benefits as a distributed generation system. They are small, and modular, and capital costs are relatively insensitive to scale. A hydrogen fuel cell does not generate any pollution. The only by-product is pure water, which is emitted as both liquid and vapour, depending on the operating conditions (temperature and pressure) and system configuration [8].

Fuel cells are being extensively studied in many research environments for the potential they offer in converting energy without the losses associated with thermal cycles, thereby having the potential to increase efficiency. Compared to other power sources, they operate silently, have no major moving parts, and can be assembled easily into larger stacks.

Fuel cells are essentially energy converters. They resemble batteries in many ways, but in contrast to batteries, they do not store the chemical energy: fuel has to be continuously provided to the cell to maintain the power output. Various designs for fuel cells have been proposed, the most popular being the proton-exchange-membrane (PEM) fuel cell, operating at temperatures up to about 100 °C, and the solid-oxide fuel cell (SOFC), operating at temperatures of about 800 °C or higher. Whereas the underlying principle is always to extract electricity without combustion, each design presents different problems and advantages, and has unique characteristics that make it more appropriate for different environments [9].

Hydrogen and fuel cells are now widely regarded as key energy solutions for the 21st century. These technologies will contribute significantly to a reduction in environmental impact, enhanced energy security (and diversity) and the creation of new energy industries [6].

One of the big advantages of fuel cells and a difference to batteries is that they decouple energy storage from power production. This makes it easy to provide more energy (in the form of fuel) as needed, and as long as fuel is supplied, the power available stays the same. In effect, a fuel cell gives similar benefits as an internal combustion engine, but it is also quieter, more efficient, non-polluting, and more easily scaled-down [2, 10].

4 Case Study : Powering a Mobile Robot with Renewable Energy Using Hydrogen Storage Solutions

4.1 The Proposed System for Hydrogen Storage

The electricity that is produced by the PV panels is direct current (DC). To meet the immediate energy requirements of the mobile robot, this DC voltage is firstly passed to the batteries. From there the DC voltage will need to be converted into alternative current (AC) by means of a DC/AC inverter, so that the current is in the required form to power the mobile robot.

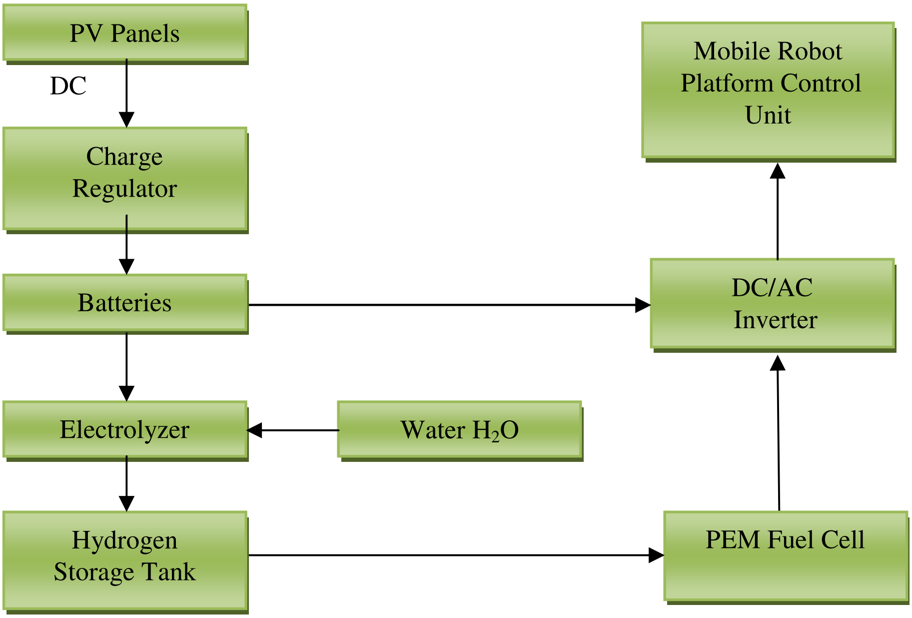

Fig. 1. Block diagram of the proposed power supply for the Mobile Robot

As for the storage of the electricity, the system will operate as follows : The electricity that is obtained from the PV panels, which is in DC voltage, will be used for the electrolysis unit to generate hydrogen. The hydrogen obtained by electrolysis is stored in hydrogen tanks containing the metal hydrides. Thereafter, a Proton Exchange Membrane (PEM) fuel cell is used to re-convert hydrogen back to electricity, as illustrated in Figure 1. This electricity is in DC voltage and will then be converted to AC voltage, using the DC/AC inverter, which can now be applied to meet the electrical demands of the mobile robot platform.

The PV system includes, in total, 6 PV modules and the total installed power is 1.2kWp in standard conditions. The specifications of the solar modules are determined as follows: maximum power is 200 W; Open circuit voltage (V_{oc}) is 59.5V;

Optimum operating voltage (V_{mp}) is 46.1V; Optimum operating current (I_{mp}) is 4.37A.

The DC energy obtained from the PV panel groups is stored in 4 units of solar batteries such that each unit has 12 V to 350 Ah.

The electricity required for electrolysis is supplied from the PV system. The electrolysis process will be facilitated by an electrolyser. The hydrogen that is produced from the electrolysis process will be stored in hydrogen tanks.

Current hydrogen storage methods include gas compression and liquefaction, and are not optimal because not only are they energy-intensive and expensive but present safety issues. A promising alternative is solid-state hydrogen storage, which utilizes metal hydrides to absorb/desorb hydrogen at relatively low pressure offering safety and cost advantages with potentially unparalleled hydrogen storage density.

Metal hydrides are used for hydrogen storage whereby the hydrogen is chemically bonded to one or more metals and released with a catalyzed reaction or heating. The hydrides can be used for storage in a solid form or in a water-based solution. When a hydride has released its hydrogen, a by-product remains in the fuel tank to be either replenished or disposed of. Hydrides may be reversible or irreversible [7]. Reversible hydrides act like sponges, soaking up the hydrogen. They are usually solids. These compounds release hydrogen at specific pressures and temperatures. They may be replenished by adding pure hydrogen. Irreversible hydrides are compounds that go through reactions with other reagents, including water, and produce a by-product. Metal hydrides can hold a large amount of hydrogen in a small volume. [7, 8].

This technique is very advantageous because of the safe handling of hydrogen and the convenience it provides for mobile applications [10, 11]. The hydrogen stored in metal hydride tanks is used to run the fuel cell system, which in turn provides the power to operate the Mobile Robot. The experiment set-up for this system is shown in figure 2. It consists of a metal hydride hydrogen tank, a hydrogen supply valve, a pressure regulator, a controller, a PEM fuel cell, power recording and analyzing instruments.

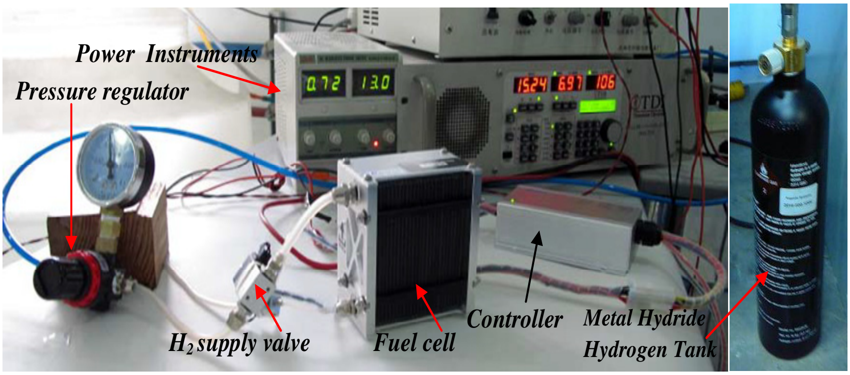

Fig. 2. Experiment set-up showing the hydrogen fuel cell power supply system

4.2 Hydrogen Fuel Cell System Simulation Model

To analyse the performance of this system, a simulation tool is used in the form of the TRNSYS (Transient Energy System Simulation Tool) software. TRNSYS has a wide range of use in renewable energy systems, and has been used extensively to simulate solar energy applications. The TRNSYS model simulates the performance of the entire energy-system by breaking it down into individual components. To create a model, the end user is able to create custom components or choose from the TRNSYS standard library of components. It is a very flexible tool that allows any user with a FORTRAN compiler to define their own elements into the software if necessary. Each component in the software is a FORTRAN sub-routine with input, output and calculation parameters. Every component can be linked to each other with output/input relations. A fuel cell component reads its input such as inlet pressures, physical properties, cell current, number of cells, cooling data and membrane properties, and then runs the sub-routine and calculates the output data such as cell voltage, power and temperature, hydrogen consumption or energy efficiency. By linking the hydrogen consumption output of the fuel cell, and hydrogen production output of the electrolyzer to the hydrogen outflow and hydrogen inflow inputs of the hydrogen tank respectively, the hydrogen tank sub-routine can calculate the hydrogen level in the tank. Upon linking the hydrogen tank output, user power demand and electricity production output of the PV panels to the system controller, the controller can decide how the system should work. The hydrogen fuel cell system TRNSYS simulation model is shown in figure 3.

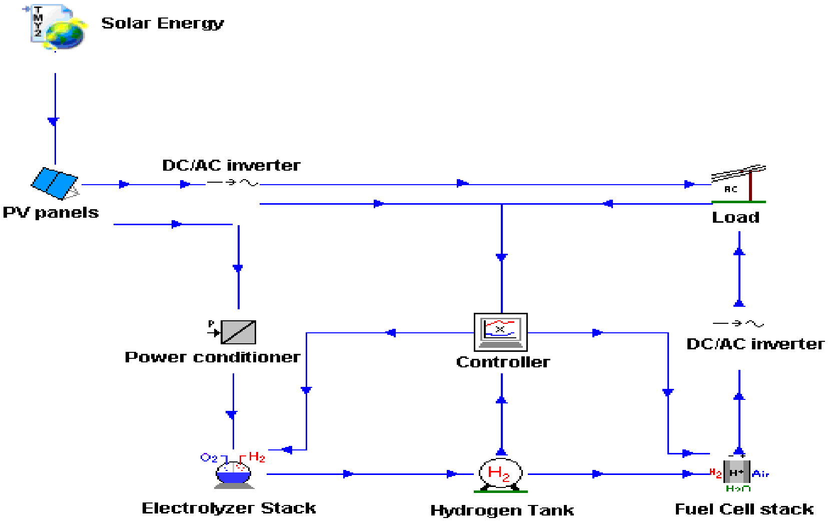

Fig. 3. Hydrogen fuel cell system simulation model

TRNSYS calculates the state of each component at every step. The system consists of several inter-connected components. The components used in the model are: a photovoltaic array module, a fuel cell module, and a hydrogen storage module [12]. The fuel cell converts chemical energy to electricity, in much the same way as a battery. The difference between a battery and a fuel cell is that the fuel cell does not have any internal storage of chemical energy, but is supplied externally by the fuel. The fuel is pure hydrogen supplied from the hydrogen storage tank. It is possible to use the excess heat from the fuel cell. The cell voltage takes the form:

$$\mathrm{U_{cell}} = \mathrm{E} + \eta_{\mathrm{act}} + \eta_{\mathrm{ohmic}} \tag{1}$$

$$\mathrm{U_{cell}} = \mathrm{U_{low}} + \left(\mathrm{U_{high}} - \mathrm{U_{low}}\right).\frac{\mathrm{T_{fc}} - \mathrm{T_{low}}}{\mathrm{T_{high}} - \mathrm{T_{low}}} \tag{2}$$

Where:

η_{act}	Activation voltage loss
η_{ohmic}	Voltage loss due to resistance
U_{cell}	Cell voltage at the given temperature
U_{low}	Maximum voltage for low temp I-V curve
U_{high}	Maximum voltage for high temp I-V curve
T_{fc}	Temperature of fuel cell
T_{high}	Temperature for high temp I-V curve
T_{low}	Temperature for low temp I-V curve

The current for the high (I_{high}) and the low temperature (I_{low}) curve is calculated from this equation 3. To find the current at the working temperature of the fuel cell, the current is calculated by linear interpolation [13-15]:

$$\mathrm{I_{temp}} = \mathrm{I_{low}} + \left(\mathrm{I_{high}} - \mathrm{I_{low}}\right).\frac{\mathrm{T_{fc}} - \mathrm{T_{low}}}{\mathrm{T_{high}} - \mathrm{T_{low}}} \tag{3}$$

Where:

E	Thermodynamic potential
I_{high}	Maximum current for high temp I-V curve
I_{low}	Maximum current for low temp I-V curve
I_{temp}	Maximum current at the given temperature
U_{low}	Maximum voltage for low temp I-V curve
U_{high}	Maximum voltage for high temp I-V curve
U_{temp}	Maximum voltage at the given temperature
T_{fc}	Temperature of fuel cell
T_{high}	Temperature for high temp I-V curve
T_{low}	Temperature for low temp I-V curve

Two main efficiencies are calculated, the electric efficiency, η_{el} and the total efficiency η_{eff}. The reason for calculating two efficiencies is that it is only the electric efficiency that will heat up the cells. The total efficiency also includes the loss of hydrogen that will not heat up the fuel cell (the electric efficiency and the total efficiency will be very close at normal or high production, but will differ at a very low production rate). Thus:

$$\eta_{\mathrm{el}} = \frac{\mathrm{V_{fc}} . \mathrm{I_{fc}}}{\mathrm{V_{fc}} . (\mathrm{I_{fc}} + \mathrm{k_{kurloss}} . \mathrm{V_{f_c}})}_{\dots} \tag{4}$$

$$\eta_{\mathrm{eff}} = \frac{\mathrm{V_{fc}} . \mathrm{I_{fc}}}{\mathrm{V_{ref}} . (\mathrm{I_{fc}} + \mathrm{k_{kurloss}} . \mathrm{V_{f_c}} + \mathrm{k_{hydloss}} . \mathrm{I_{min}})}_{\dots} \tag{5}$$

where:

I_{fc}	Current for fuel cell
K	Constant for Temperature-Voltage equation
V_{fc}	Voltage over fuel cell
V_{ref}	Reference voltage
η_{el}	electric efficiency
η_{eff}	total efficiency

The hydrogen energy storage sub-system, comprising an electrolyzer, hydrogen storage tank, and a fuel cell, is an integral part of a solar-hydrogen power supply system for supplying power to the Mobile Robot. This energy storage is required due to variation of the intermittent and variable primary energy source [15].

4.3 Mobile Robot System Hardware Architecture

An Industrial Mobile Robot Platform (IMRP) is used for this case study, and consists of an Automatic Guided Vehicle (AGV), Mobile Robot Frame, motors and mecanum wheels, as shown in figures 4 and 5. The development for this case study can be divided into the following major processes: the mechanical design for the mecanum wheels and mobile robot chassis; the electronics design for the 4-channel motor driver; interfacing with a Basic Stamp micro-controller board; and software development for motion control. The AGV has the unique ability to move laterally. It is unlike conventional vehicles that are limited to forward and reverse motion.

This is advantageous at decision points in manufacturing environments where branching routes are employed for routing purposes. Lateral movement was made possible by the AGV's mecanum wheels. Each wheel consists of a steel rim with eight nylon rollers. The rollers were positioned at 45 degrees to the rotation direction and rotated freely about their own longitudinal axis. A small area of contact was made between a single roller and the floor when the wheel was stationary. As the wheel rotated, during forward or reverse motion, a particular roller left the floor and the contact area was picked up by the next roller and so on. When the AGV moved laterally or rotated about its own axis, the forces from the counter-wheel-rotation caused the contact area to rotate the particular roller. When the roller left the floor the area was picked up by the next roller and it starts to rotate [16].

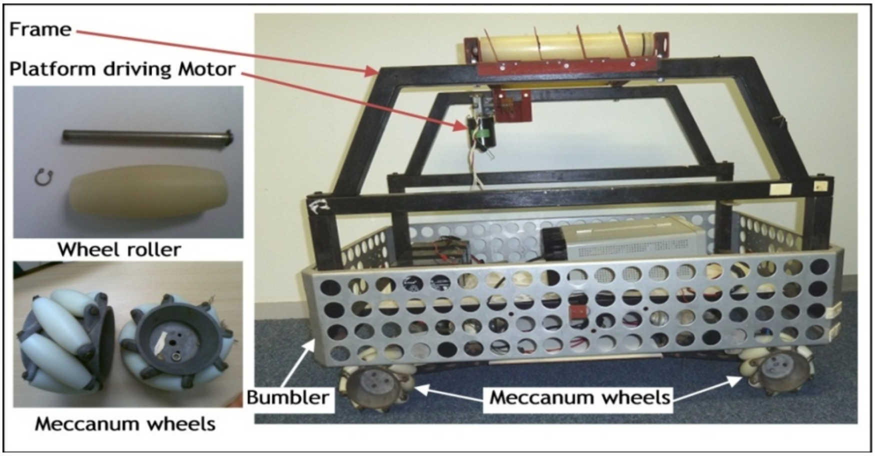

Fig. 4. Mobile Robot system mecanum wheels

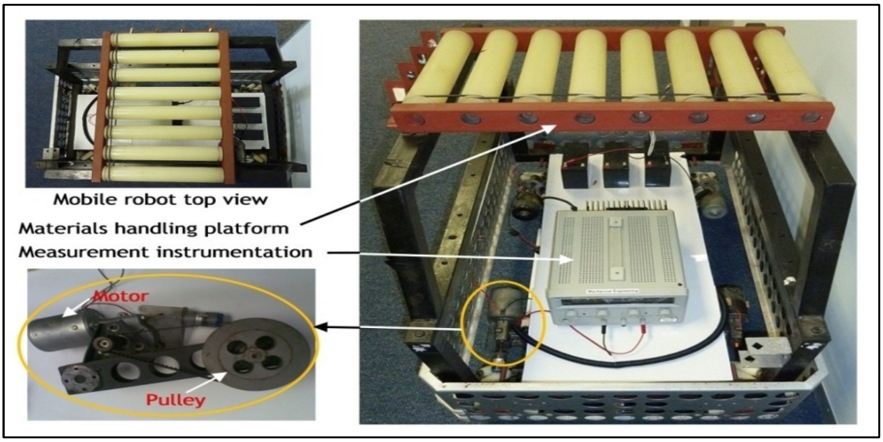

Fig. 5. Mobile robot system front and top view

The Electronic design of the Mobile Robot, which consists of a four-channel bi-directional motor driver, is designed to drive all four mecanum wheels, as illustrated in figure 6. The slave devices consist of five Motor Boards, two light-sensor boards, four ultra-sonic sensor boards, and a Limit Switch Board. An LCD module acts as a diagnostic device and verifies signal transfer to the robot, as illustrated in figure 7. Digital signals are sent back to the main computer via Radio Frequency (RF). The inputs are interpreted and used accordingly in the main program.

The specifications developed for the necessary Driver Board are as follows:

a) A circuit which is compatible with a single logic-level PWM input signal for speed control of each wheel, and a single logic-level input line for the direction of motor rotation for each wheel.

b) A circuit which is able to operate with a high PWM carrier frequency from the microcontroller to provide inaudible operation.

c) A circuit which has four independent H-Bridge drivers for bi-directional motion.

Each H-Bridge driver circuit is capable of providing suitable continuous current at 12V DC. The motor controller board is illustrated in figure 6. A maximum of eight motor boards are addressable by the robot CPU. The AGV has five 12V DC motors. Four motors drive the four wheels, one motor per wheel, and one motor drives the materials handling platform. Five motor controller boards are used. Each board is individually addressed, and has a micro-controller [17, 18].

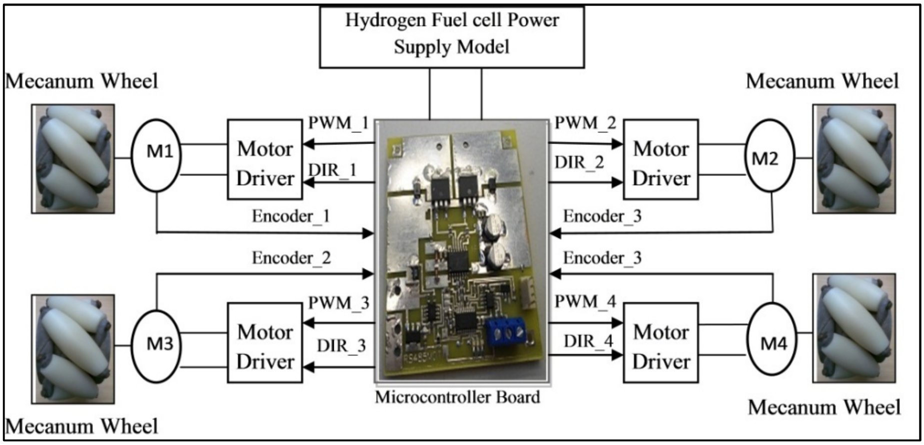

Fig. 6. Hardware architecture of the Mobile Robot system

The IMRP is designed along the lines of a unit load carrier AGV to carry individual loads on a deck. It is suitable for an industrial and manufacturing environment where it can move in confined spaces and travel over short distances. It is designed to move in all directions and carry single loads on its deck. The deck is a moving platform with payloads not exceeding 40 Kg. The loads could be picked up at a pre-determined station and deposited at another. To achieve mobility, an electronic drive controller unit has been designed to provide the vital link between the motors and the computer system [17].

A micro-computer is used to control this unit with the aid of appropriate software via a computer interface card. This allows the IMRP to move in any desired planer direction. The IMRP is able to follow pre-determined paths to transport the incoming raw materials and outgoing machine parts between work stations. It is envisaged that the IMRP would be able to carry a pay load of 40 Kg. Thus a gross weight of 120 Kg was chosen. The frame was made from 38mm x 38mm square tubing and steel joints were arc-welded.

4.4 Mobile Robot Telemetry System Components

The system has been custom-made. It was made according to specifications of the guidance and navigation requirements of a mobile Robot [17, 19]. As illustrated in figure 7, the telemetry system consists of two main components: a USB-Transceiver unit and a robot CPU unit that communicates with each other via RF. The robot CPU unit transfers data to the respective slave modules via the RS485BUS. The robot CPU unit acts as a data acquisition device that one can read and write from. Higher level programming to control the Mobile Robot has to be done by the user.

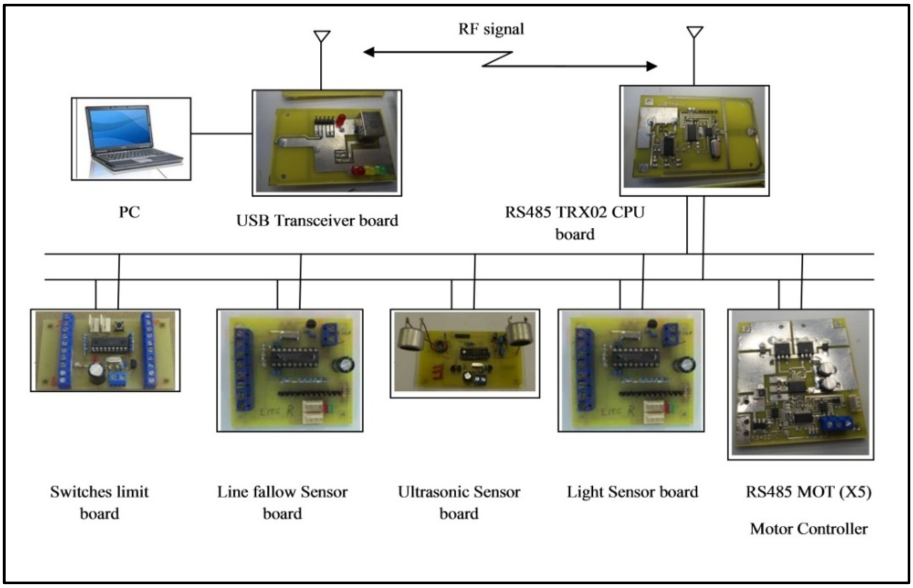

Fig. 7. Mobile Robot telemetry system components

5 Conclusion

The use of renewable energy from solar power offers a viable alternative to traditional energy sources such as petroleum and fossil-based electricity, and is one of the potential options for overcoming current environmental and sustainability issues. Solar energy can efficiently meet the energy demands of modern technologies, as demonstrated in this case study, where it has been shown as an efficient way of meeting the energy demands of an Industrial Mobile Robot Platform. The various challenges associated with developing solar energy in a viable way, can be addressed by the use of efficient storage methods as dealt with in this study. There are, however, some challenges in improving hydrogen storage technologies with regard to their efficiency, size, weight, capacity and, ultimately their cost. Durability remains an issue, as does the development of unified international codes and safety standards to facilitate safe deployment of commercial technologies. Energy efficiency is also a challenge for all hydrogen storage approaches. And although the cost of on-board hydrogen storage systems may be currently too high, particularly in comparison to conventional storage systems for petroleum fuels, world energy policy is gradually driving demand in this area. Increasing demand and mass production is certain to drive down costs and make this source of energy more cost-effective.

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Appendix A: Mobile Robot Power Supply

The electrical power required by the five DC motors, the motor controller unit (RS485MOT and Encoder), the Central Processing Unit (CPU- RS485TRX02), the USB unit, the ultrasonic sensor, the light sensor, the line follow sensor, the limit switch sensor, and LCD (RS485 BUS Monitor) on the IMRP, is 195.72 watt as shown in Table 1.

Table 1. Power consumption

	Component	Description	V	I	Q	Current	Power (w)
1	DC Motor		12V	3 A	5	15A	180
2	RS485MOT & Encoder	Motor controller	12V	0.2A	5	1A	12
3	RS485TRX02	Robot CPU	12V	0.1A	1	0.1A	1.2
4	USBTRX02	USB unit	12V	0.05A	1	0.05A	0.6
5	Add-on Sensors	Ultrasonic Sensor	12V	0.02 A	4	0.08A	0.96
6		Light Sensor	12V	0.02 A	1	0.02 A	0.24
7		Line follow Sensor	12V	0.02 A	1	0.02 A	0.24
8		Limit switch Sensor	12V	0.02 A	1	0.02 A	0.24
9	RS485 BUS Monitor	LCD	12V	0.02 A	1	0.02 A	0.24
	Total power required onboard for Mobile Robot						195.72
10	PC (laptop)		19.5	3.34A	1	3.34A	65.13