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DEVELOPMENT OF SOLAR HYDROGEN ENERGY FOR MOBILE ROBOTS

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Abstract— **Mobile robots have demonstrated their versatility in a wide range of applications and situations. However, they are limited due to their reliance on traditional energy sources such as electricity and petroleum which cannot always provide a convenient energy source in all situations. Moreover, in a more eco-conscious modern world, these energy sources, which require the burning of a fuel in order to generate the output of electricity, are increasingly being shunned in favour of cleaner alternative energy sources such as solar energy. This study seeks to demonstrate the viability of an alternative, renewable, energy source for the operation of mobile robots. For the purposes of this study, an Industrial Mobile Robot Platform (IMRP) was designed that would run on solar power making use of an array of photovoltaic panels. In order to overcome the limitations of solar power, which is dependent on the availability of sunshine and thus cannot provide a constant source of energy, an energy storage medium was employed making use of metal hydrides. The advantage of this medium is that it is able to store energy in the form of hydrogen produced from solar energy, thus providing a reliable and constant energy source to power the IMRP. The IMRP was fabricated to run on hydrogen fuel cells using a low-pressure metal hydride hydrogen storage system that can store more energy on board than current conventional energy storage methods. The results show that solar energy can indeed provide a viable renewable energy source to power IMRPs, and that its limitations due to solar being an inconstant energy source can be overcome by the use of energy storage materials in the form of metal hydrides that store energy produced from solar power, and thereby satisfying the constant demand for energy.**

Keywords—Energy; Solar; Hydrogen; Mobile Robot;Fuel cell.

I. INTRODUCTION

In an ever more eco-conscious world, solar energy offers the most environmentally clean option of all energy sources. Further research and development is therefore warranted regarding this cleaner alternative energy source in order to make it more viable and practical for the world's energy requirements. Solar energy has enormous potential and very definite advantages. Solar power does not have all the negative effects of traditional energy sources currently in use such as electricity and petroleum oil. Electricity presents threats of pollution resulting from its production process, and petroleum oil poses a huge threat to the environment [1]. Not only does it pose harm by the toxic emissions it produces in the combustion process necessary to produce energy, but there is the ever present risk of oil-spillages and damage to eco-systems in having to transport large volumes of this commodity due to the limited area where it is to be found geographically, as compared to the places where it has to be made available world-wide [2].

Solar energy systems do, however, come with their own limitations, and it is the challenge of this study to find in solar energy, a viable alternative to traditional energy sources such as electricity and petroleum. The problem with solar energy is that it is dependent on the availability of sunshine, which unfortunately is not always constant. Hence it cannot meet a constant demand for energy.

Using hydrogen as an energy source can come turn solar energy into a viable energy source. Solar power can be utilized to provide electricity for electrolysis, which produces the hydrogen that fuels hydrogen energy systems [3]. Hydrogen can be stored using metal hydrides, which have the ability to store hydrogen reversibly in a solid state at relatively low pressures and ambient temperature. Therefore, metal hybrid hydrogen storage systems have the potential to serve as safe and reliable sources of hydrogen energy. The use of metal hydrides as a hydrogen storage material has been under consideration for some years now [4]. Various studies have been found in the available literature on sustainability aspects of hydrogen energy systems, albeit that some studies have been undertaken by several researchers [5]. They do, however, give some overview of the potential of hydrogen systems. Hydrogen fuel cells have yielded promising test results for the use in space robots. Through reverse electrolysis, water and energy is created. The energy provided through reverse electrolysis can be utilized for sensors and other systems aboard a mobile robot platform [6].

In this study, a modelling approach is presented in conjunction with experiments to establish a framework to conceptualize, design, test and analyze fuel cell systems over a wide range of operational conditions. Development of fuel cells, one of the emerging trends in distributed generation technologies, has been slow due to high costs. However, costs are expected to decline as manufacturing capacity and capability increase and designs and integration improve. Fuel cell systems offer many potential benefits as distributed generation systems. 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 leaves the system as both liquid and vapour, depending on the operating conditions (temperature and pressure) and system configuration.

Fuel cells are devices that produce electric power by direct conversion of a fuel's chemical energy. They are being extensively studied in many research environments [6] 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 resemble batteries in many ways, but fuel has to be continuously provided to the cell to maintain the power output. Various designs for fuel cells have been proposed [6]; the Proton-Exchange-Membrane (PEM) fuel cell has been used in this MRP power system.

Hydrogen is a very attractive alternative fuel. It can be obtained from various resources, both renewable (hydro, wind, solar, bio-mass, geo-thermal) and non-renewable (coal, natural gas, nuclear). Hydrogen can then be utilized in high-efficiency power-generation systems, including fuel cells for both vehicular transportation and distributed electricity generation. Fuel cells convert hydrogen directly into electricity by an electro-chemical process [7].

One of the big advantages of fuel cells compared to batteries is that they de-couple 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 to that of an internal combustion engine. However, it is more complex than a battery and its 30-50% fuel efficiency can't compare to the over 90% cycle efficiencies of batteries if a source of electricity is available anyway. Hydrogen and fuel cells have been chosen to reduce CO_2 emissions and improve air quality, to ensure security of energy supply, and to create a new technological energy base for world economic prosperity [8].

II. PROPOSED SYSTEM

The system proposed in this study involves the use of photovoltaic panels to convert sunlight into electricity, coupled with an effective storage medium for such energy using metal hydrides which store energy in the form of hydrogen. Hydrogen fuel cells were designed to provide a constant supply of energy from a stored source to power a mobile robot. The DC voltage obtained by means of photovoltaic panels is stored in batteries with charge regulators. Then voltage is used in the electrolysis unit to generate hydrogen which is used by fuel cell, as illustrated in Fig.1. Hydrogen obtained by electrolysis is stored in hydrogen tanks. DC voltage obtained from fuel cells is converted to AC voltage to meet the demands for electricity needed to power the mobile robot platform. The photovoltaic system includes a total of 6 PV modules and the total installed power is 1.2kWp in standard conditions.

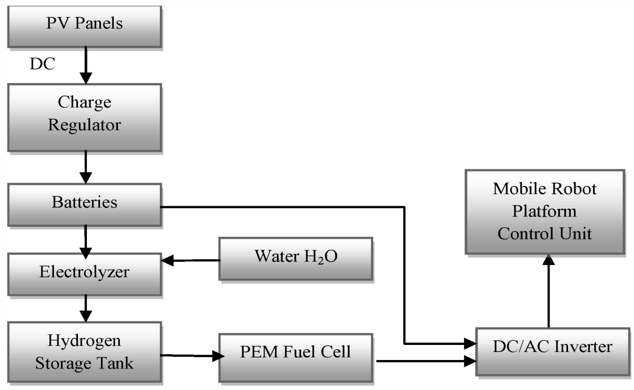

Fig. 1. Block diagram of MRP Hydrogen FuelCell System

The specifications of the solar CHN200-96M modules are determined as follows: maximum power is 200W; open circuit voltage (V_{oc}) is 59.5V; optimum operating voltage (V_{mp}) is 46.1V; optimum operating current (I_{mp}) is 4.37A. DC energy obtained from photovoltaic panel groups has been stored in four units of solar batteries such that each unit has 12 V to 350 Ah. Electrolysis is a reaction, which produces hydrogen and oxygen from water. The electricity required for this reaction can be supplied from the system. A PEM type electrolyser is used to produce hydrogen by utilizing the electricity generated by the PV panels. Hydrogen obtained from electrolysis is stored in metal hydride tanks. This technique is very advantageous because of allowing safe handling of hydrogen and providing convenience with mobile applications [9].

III. STORAGE IN METALS

Metal hydrides provide a storage medium for hydrogen where the hydrogen is chemically bonded to one or more metals and released with a catalyzed reaction or heating. Hydrides can be stored 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. Reversible hydrides, which are usually solids, are easily able to soak up the hydrogen. 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. A metal hydride tank may be one-third the volume of a 5,000 psi liquid hydrogen tank [10].

IV. MOBILE ROBOT SYSTEM HARDWARE ARCHITECTURE

An Automatic Guided Vehicle (AGV) mobile robot frame was designed, with motors and mecanum wheels to make up the mobile robot platform as shown in Fig. 2 and Fig. 3. It is powered by hydrogen fuel cells. The development for this project can be divided into three major processes: the mechanical design for mecanum wheels and mobile robot chassis, electronics design for 4-channel motor driver and interfacing with Basic Stamp micro-controller board and software development for motion control. The AGV is unlike conventional vehicles that are limited to forward and reverse movement [11]. It has the unique ability to move laterally.

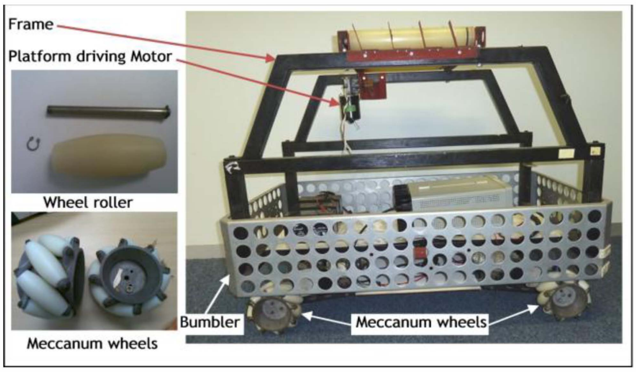

Fig. 2. Mobile robot system mecanum wheels.

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 consisted 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 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 which started to rotate.

Electronic design of the industrial mobile robot platform is shown in Fig.3consisting of a four-channel bi-directional motor driver which has been designed to drive all four mecanum wheels. As illustrated in Fig. 4, the slave devices consist of five motor boards, two light sensor boards, two line sensor boards, four ultrasonic sensor boards and a limit switch board. An LCD module acted as a diagnostic device and verified signal transfer to the robot. Digital signals were sent back to the main computer via Radio Frequency (RF).

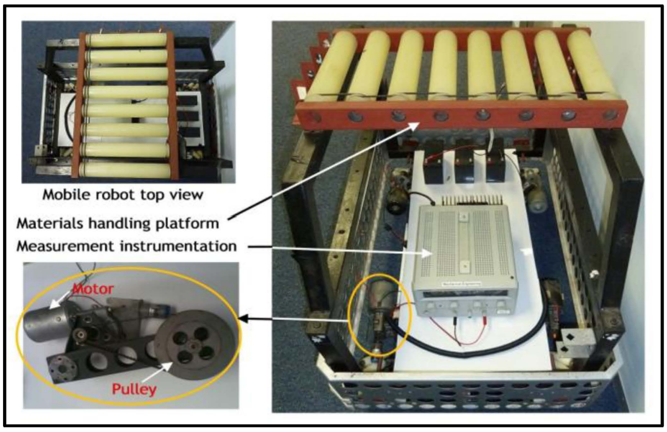

Fig. 3. Mobile robot system front and top view.

The inputs were interpreted and used accordingly in the main program. The specifications developed for the necessary driver board were:

a) The circuit should be 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) The circuit should be able to operate with a high PWM carrier frequency from the microcontroller to provide inaudible operation.

c) The circuit should include four independent H-Bridge drivers for bi-directional motion.

Each H-Bridge driver circuit must be capable of providing suitable continuous current at 12V DC. The motor controller board is illustrated in Fig. 4. A maximum of eight motor boards were addressable by the robot CPU. The AGV [12] had five 12V DC motors. Four motors drove the four wheels, one motor per wheel, and one motor drove the materials handling platform. Five motor controller boards were used. Each board was individually addressed and had a microcontroller.

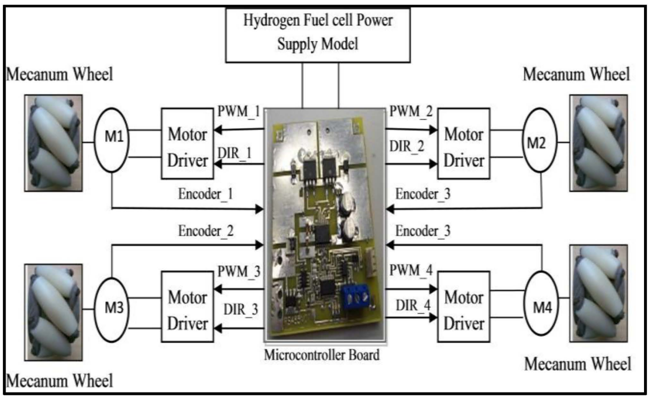

Fig. 4. Mobile robot system hardware architecture.

The research study Industrial Mobile Robot Platform (IMRP) is designed along the lines of a unit load carrier Automated Guided Vehicle (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 can be picked up at a pre-determined station and deposited at another. To achieve mobility, an electronic drive controller unit was designed. It provides the vital link between the motors and the computer system. A microcomputer was used to control this unit with the aid of appropriate software via a computer interface card. This allowed the IMRP to move in any desired planar direction. The IMRP will follow pre-determined paths to transport the incoming raw materials and outgoing machines parts between the work stations. It was envisaged that the research 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.

V. MOBILE ROBOT TELEMETRY SYSTEM COMPONENTS

The system was custom-made. It was made according to specifications of the guidance and navigation requirements of a mobile robot. As illustrated in Fig. 5, the telemetry system consists of two main components: a USB-Transceiver unit and a robot CPU unit that communicate 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. The higher level programming to control the mobile robot had to be done by the user.

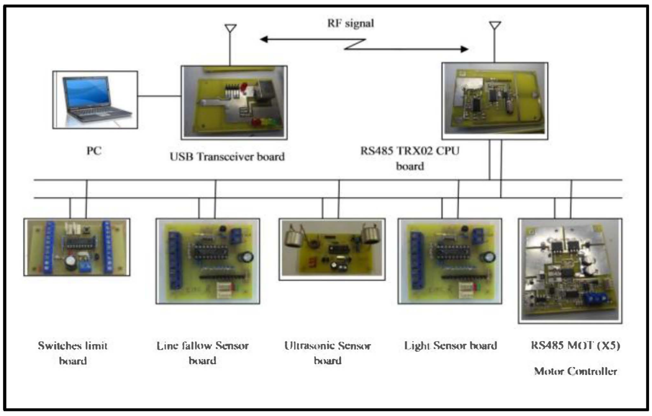

Fig. 5. Mobile Robot Telemetry System Components.

VI. THE MECANUM WHEELS MOBILE ROBOT MOTION.

The IMRP has four mecanum wheels controlled by four DC motors, allowing clockwise/anti-clockwise rotation as well as sideways movement**.** It has the unique ability to move laterally which is useful in industrial and manufacturing environments where branching routes are employed for routing purposes. Each wheel consists of a steel rim with eight new, smooth, convex, high strength plastic 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 mobile robot moved laterally or rotated about its own axis, the forces from 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 started to rotate.

Direction control of the mobile robot was attributed to the resultant forces produced when moving. This is illustrated in Fig. 6. When wheel A rotated forward, two forces, $Fsin(45°)$and $Fcos(45°)$ occurred at right angles to each other.$Fsin(45°)$and $Fcos(45°)$ each yielded $\frac{F}{\sqrt{2}}$ .The forces were parallel to the floor and the resultant was force F_{A2}. Similarly, if wheel A rotated in the reverse direction, force F_{A1} resulted [13].

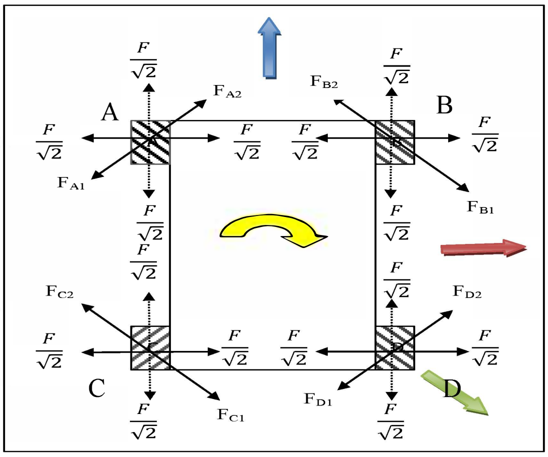

Fig. 6. Mobile robot wheels with resultant vectors and directions.

Movement of the mobile robot in a specific direction is illustrated in Fig. 7.

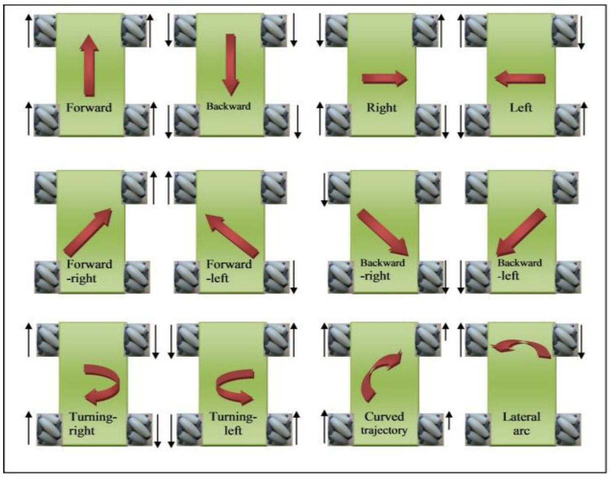

Fig. 7. Mobile robot mecanum wheels movement and directions

Movement was achieved as follows:

i. Forward motion: All wheels rotated in the forward direction. The vector sum of F_{A2}, F_{B2}, F_{C2} and F_{D2} resulted in the forward motion.

ii. Sideways motion: The wheels on the left rotated away from each other and wheels on the right rotated towards each other. The vector sum of F_{A2}, F_{B1}, F_{C1} and F_{D2} resulted in the sideways motion. To move sideways at an angle, the speed of wheels B and C were 'ratioed' with that of wheels A and D. Motion in the direction of the green arrow resulted if wheels B and C rotated faster than wheels A and D.

iii. Rotation about axis: Wheels A and D rotated in the forward direction (blue arrow), and wheels B and C rotated in the reverse direction. The vector sum of F_{A2}, F_{B1}, F_{C2} and F_{D1} resulted in the turning motion, indicated by the yellow arrow.

Using four mecanum wheels provides omni-directional movement for a vehicle without needing a conventional steering system. Slipping is a common problem in the mecanum wheel as it has only one roller with a single point of ground contact at any one time. Due to the dynamics of the mecanum wheel, it can create force vectors in both the x and y-direction while only being driven in the y-direction [14]. Positioning four mecanum wheels, one at each corner of the chassis, allows net forces to be formed in the x, y and rotational direction. Fig. 6 illustrates possible motion of the Mobile Robot. Depending on each individual wheel direction and speed, the resulting combination of all these forces produces a total force vector in any desired direction thus allowing the platform to move freely in the direction of the resulting force vector, without changing of the wheels themselves.

VII. HYDROGEN FUEL CELL SYSTEM SIMULATION MODEL

The hydrogen fuel cell system consists of several interconnected components as shown in Fig. 8. TRaNsient SYstems Simulation (TRNSYS) program is a software package designed to model transient systems.

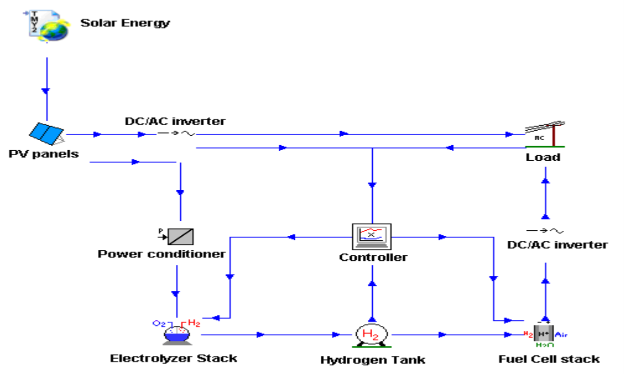

Fig. 8. Hydrogen fuel cell system TRNSYS model

The components of the hydrogen fuel cell system TRNSYS model are: a photovoltaic array module, a fuel cell module, and a hydrogen storage module [15]. 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 [16]. It is possible to use the excess heat from the fuel cell. This heat is not stored and is only used when heat is needed either for hot tap water or space heating. Provided the fuel cell is well insulated, the utilisation of excess heat increases the efficiency of the fuel cell from about 50% to almost 90% (excluding losses due to parasitic loads and the dc/dc converter). Therefore, the cell voltage takes the form:

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

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

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
E	Thermodynamic potential

The current for the high (I_{high}) and the low temperature (I_{low}) curve is calculated from Equation 3. To find the current at the working temperature of the fuel cell, the current is calculated by linear interpolation [17]:

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

Where:

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 [18], 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 [19]. Thus:

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

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

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, a hydrogen storage tank, and a fuel cell, is an integral part of a solar-hydrogen power supply system for supplying power to a mobile robot. This energy storage is required due to variation of the intermittent and variable primary energy source.

VIII. CONCLUSION

The use of renewable energy from solar power offers a viable alternative to traditional energy sources such as electricity and petroleum for the production of hydrogen energy. In this study, solar power has been demonstrated as a viable alternative in providing an alternative energy source to power an Industrial Mobile Robot Platform. Use has been made of fuel cells with low-pressure metal hydride hydrogen storage systems that store more energy on board than current conventional energy storage methods. Solar hydrogen utilization systems for mobile applications are one of the potential options for overcoming current environmental and sustainability issues. Sizing the components such as electrolysers, battery storage capacities and hydrogen fuel cells, controlling the load demand and determining the best path for storage and use have been addressed. There are some challenges in improving hydrogen storage technologies relating 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 a challenge for all hydrogen storage approaches. The energy required to get hydrogen in and out of storage is an issue for reversible solid-state materials storage systems. The cost of on-board hydrogen storage systems is currently too high, particularly in comparison to conventional storage systems for petroleum fuels.

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