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Fuel Cell Racing: Imperial College London Presents the Racing Green Team

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Abstract

Imperial Racing Green is a major initiative at Imperial College London to design, build and race zero emission vehicles in order to give students hands-on experience in the design, development and construction of fuel cell and battery vehicles, and win competitions like Formula Zero and Formula Student Class 1A, run by the Institute of Mechanical Engineers. The former competition is a time trial series for fuel cell go-carts, the latter is for single seat race cars and accommodates a wider range of technologies. The Imperial Racing Green entry to Formula Zero, codenamed IRG02, is a go-cart powered by a Hydrogenics 8kW PEM fuel cell coupled via a DC/DC converter in a current control loop to two banks of 165F Maxwell ultra-capacitors. Overall vehicle control is achieved with a National Instruments CompactRio, which also acts as a data logger. The Imperial Racing Green entry to Formula Student Class 1A, codenamed IRG03, has a modular 25kW electric drive, braking and suspension assembly at each corner. Racing Green will continue to compete in the Formula Zero Championship throughout 2009, and will compete in Formula Student Class 1A at Silverstone in July 2009. This project has demonstrated that new approaches to project based learning can generate enormous student interest and international media attention, while being rewarding to the academics and researchers involved too. This paper gives detailed information of the design of IRG02 and presents data recorded during the Formula Zero race of August 2008. A summary of the design of IRG03 is also given, concluding with lessons learnt and future plans.

Fuel Cell, Battery, Car, Education

1 Introduction

The world's first fuel cell vehicle race took place on 22nd August 2008 in Rotterdam as part of the new Formula Zero Championship, for pro-kart sized vehicles powered by an 8kW PEM fuel cell. The event was a great success for the Imperial Racing Green (IRG) team with the official results showing that in the six-lap endurance races the Racing Green team were fastest in the first round, second fastest in the second round and fastest in the final [1]. In the single lap sprint races Imperial posted third fastest time overall. The reliability of the IRG go-cart set the standard for the event, showing remarkable consistency and being the only vehicle to complete the full endurance distance without stopping on track. Imperial College London is proud of the achievements of their undergraduate students, who designed, built, tested and raced the go-cart in a single year and fully expects them to improve on their performance and results in the next event in the Formula Zero Championship. The team is also building a four wheel drive electric single seat race car with a small range extender fuel cell for Class 1A of the Formula Student competition. The purpose of this paper is to describe how the final design of the Formula Zero go-cart was arrived at through simulation work and package studies; present the problems encountered in testing and how they were solved; outline areas of performance enhancement; review some of the data logged by the on-board diagnostics during the races and present the new vehicle currently under construction for Formula Student.

1.1 Vehicle Concepts

Systems engineering theory asserts that decisions made in the concept phase ultimately determine how successful a project is. If a product does not meet required deadlines or is inadequately tested before release it can usually be traced back to poor decision making and risk analysis in the concept phase. The challenge with an emerging technology like fuel cells is that the technology maturity and cost have large uncertainties associated with them. Risk minimisation and risk mitigation strategies were an important part of the project planning from the outset, and continue to be a key part of the project control strategy. Using a fuel cell as the prime mover leads to a cascade of design changes and opportunities that affect every aspect of the vehicle. In order to maximise the fuel cell efficiency and lifetime it is usually hybridised with an electrical storage system. Two main scenarios for this present themselves: a *fuel cell heavy* system consisting of a large fuel cell that can provide the a substantial proportion of the peak power required by the vehicle and ultra-capacitors to provide rapid response and allow kinetic energy recovery; the other option is a *battery heavy system* that uses a large battery to supply a significant proportion of the onboard energy storage and vehicle peak power, with a smaller fuel cell as a range extender.

1.2 Formula Zero

The Formula Zero (FZ) championship is a zero emission time trial series for go-carts powered by polymer electrolyte membrane (PEM) fuel cells and sustainably generated hydrogen. The regulations prescribe the use of an 8kW fuel cell from Hydrogenics. The vehicles are permitted to store electrical energy on board in batteries or ultracapacitors with a restriction on the useable energy of 250kJ. This is not to say that a larger nominal storage capacity cannot be used, but the team must demonstrate that only 250kJ is accessible. This defines a fuel cell heavy vehicle architecture. Apart from the limited amount of on-board energy storage, the rest of the design choices are quite open

1.3 Formula Student Class 1A

Formula Student is an educational initiative organised by the Institution of Mechanical Engineers (IMechE). It attracts universities from all over the world to design, build and compete with single-seat race cars. The IMechE are keen to introduce the principles of engineering for sustainability and low carbon technology into this extremely successful program. Historically in Class 1 of Formula Student internal combustion engine race cars are designed and built by student teams, and compete over four days through a number of static and dynamic tests, including cost and design judging. The more progressive Class 1A was introduced in 2008 and allows petrol, diesel, hybrid, electric, fuel cell and hydrogen internal combustion engine vehicles to compete against each other under one rule set. The points in Class 1A are allocated according to both speed in an event, and CO_2 emitted during the event, with an emissions equivalence table levelling the playing field between fuels. A full life cycle energy cost analysis is also part of the judging.

2 IRG02

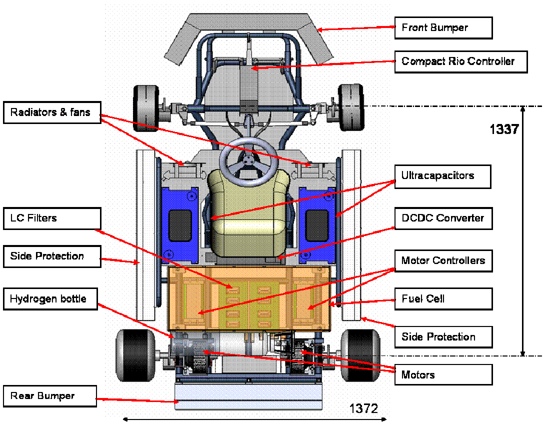
The overall design concept for the Formula Zero vehicle was to be compact with a small wheelbase and low polar moment to maximise agility.

Optimisation for cornering speed in go-carts is different from 'normal' race cars, in which the CoG is made as low as possible. Go-carts differ from 'normal' vehicles in one key respect: on a go-cart there is a rigid rear axle, which means that it cannot drive around a corner without slipping one of the rear wheels. In order to overcome this, go-cart chassis' are designed to have low torsional stiffness so that the inside rear wheel can be made to lift under hard cornering, allowing the vehicle to round the corner on three wheels. A high centre of gravity helps to twist the chassis in cornering and therefore lowering the CoG of the vehicle is not as important as with traditional vehicles.

As the go-cart was going to be heavy relative to a petrol one the decision was taken to split the rear axle and have one motor driving each rear wheel with an electronic differential, thus removing the requirement to lift the inside rear wheel. The flexibility of the chassis was then employed to keep both rear wheels in contact with the road.

2.1 IRG02 Architecture

The layout of the go-cart and bill of materials are shown in figure 1.



Chassis	Biz Pro-Kart
Fuel Cell	(1x) Hydrogenics HyPM8 – 8kW PEMFC
Supercapacitors	(2x) Maxwell 48V 165F
Electric motors	(2x) Lemco LEM200-127
Motor controllers	(2x) Navitas TPM 400 28-48V
DC/DC	(1x) Zahn Electronics Custom
Vehicle Controller	(1x) National Instruments cRIO

Figure 1 – IRG02 layout and bill of materials

The choice between batteries or supercapacitors as the electrical energy storage was a key factor in determining the performance of the kart. Batteries are generally used for electric vehicles because they have a higher *energy* density than capacitors, which gives the vehicle greater range. Supercapcitors conversely have a much higher *power* density than batteries. Supercapacitors have a power density of approx 5-8kW/kg [2] and energy density of approx 3-4Wh/kg [2], compared to lithium ion batteries which have approx power and energy densities of 1kW/kg and 100-120Wh/kg [3]. Although the power densities are of the same order of magnitude, at high charge and discharge rates the internal resistance of lithium ion batteries becomes significant, generating large amounts of heat, whereas the internal resistance of supercapacitors changes very little with discharge rate. At extremely high discharge rates lithium ion batteries can become chemically unstable and combust. In this particular application, where the fuel cell provides the mean power demand but has slow transient response, high power density is required to enable the vehicle to accelerate quickly and maximise braking energy recovery, hence supercapacitors are the obvious choice.

Regarding the choice between supercapacitors and batteries, a point of practical interest is that, due to the nearly constant voltage across a large state of charge window exhibited by lithium ion batteries, it is very difficult to determine how much energy is stored in the cells, so the design, construction and operation of a charge monitoring system for the vehicle power management is complex.

To keep the vehicle simple and robust, two 9kW brushed DC motors were used, coupled with four quadrant pulse width modulated (PWM) controllers. The function of all of these devices can be found in many textbooks on electric motors and drives.

The schematic of IRG02 (figure 1), shows the two largest masses, the driver and fuel cell, being placed as close as possible to the point half way between the front and rear axles on the car centreline in order to distribute the vehicle weight evenly between the front and rear axles and reduce the vehicle polar moment. The final weight distribution was dictated by packaging constraints at 60% rearwards.

The initial risk analysis identified the overall vehicle control as safety critical, which meant that an extremely robust and reliable unit had to be used as the vehicle management unit (VMU). The National Instruments Compact Rio (cRIO) fulfilled all of the requirements of the control and data acquisition system, with sufficient flexibility to allow it to be used in future vehicles, together with proven reliability in environments where it is subjected to physical shock. The control software was written in LabView before being embedded onto the cRIO real time processor to run as a stand-alone application. The safety critical elements were included on the field programmable gate array (FPGA) of the cRIO to make them fail-safe by eliminating the risk of a software crash.

In accordance with the technical regulations of Formula Zero, the hydrogen and electrical circuits had manual and automatic safety systems that failed 'safe', these will be described in more detail in later sections.

2.1.1 Low Voltage Circuit

The low voltage circuit shown in figure 2, has its own power source and supports the active safety equipment, the cRIO and sensors. The circuit was completely de-coupled from the high voltage circuit and care was taken to avoid running high voltage and low voltage wires in parallel and in close proximity. This is to avoid interference on the low voltage circuit and, more seriously, capacitive coupling between the high voltage AC circuit and low voltage circuit.

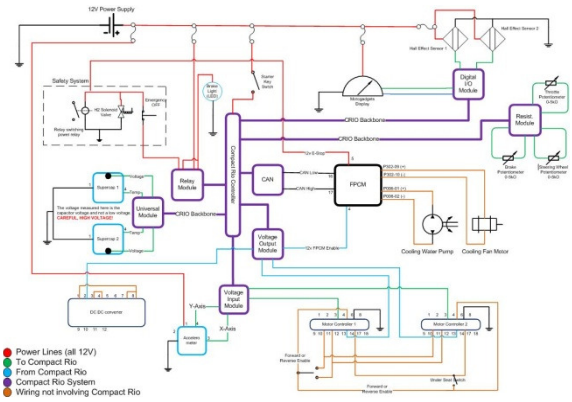


Figure 2 – IRG02 low voltage circuit

2.1.2 High Voltage Circuit

The high voltage circuit, shown in figure 4 has an operational voltage range up to 48V, chosen for safety reasons as it is non-lethal. The DC bus is allowed to float depending on the capacitor state of charge between 28 and 48V fulfilling the Formula Zero requirement that no more than 250kJ of energy storage be accessible for the drive. This also eliminates the need for a second DC/DC converter between the supercapcitors and motor controllers, but means that at low SOC the current demand for a given motor power increases substantially.

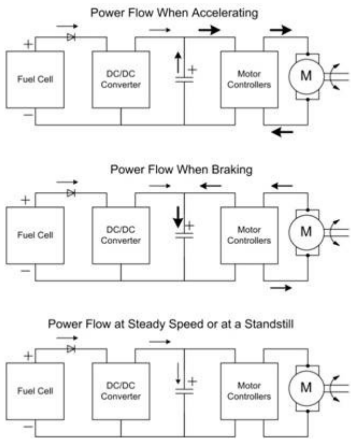


Figure 3 – IRG02 power flow

Figure 3 shows schematically the 3 main conditions of the circuit: acceleration, braking and steady speed. When accelerating the motor draws power from the fuel cell and supercapacitors. When decelerating the energy from the fuel cell and the energy recovered via regenerative braking charges the supercapacitors. In the third state at a steady speed or standstill, little or no current is being drawn by the motor and the fuel cell charges the supercapacitors. Using supercapacitors to smooth the load allows the fuel cell to run at maximum power for most of the race. When the capacitors are fully charged the fuel cell must ramp down, however the system has been designed with enough storage so that this does not happen in the 1-4 seconds of each braking event. Figure 4 shows the motor controller charge circuits, required to energise the smoothing capacitors within the controllers. These were designed with delay timers rather than fixing resistors across the poles of the contactor so that the circuit could be fully isolated when required.

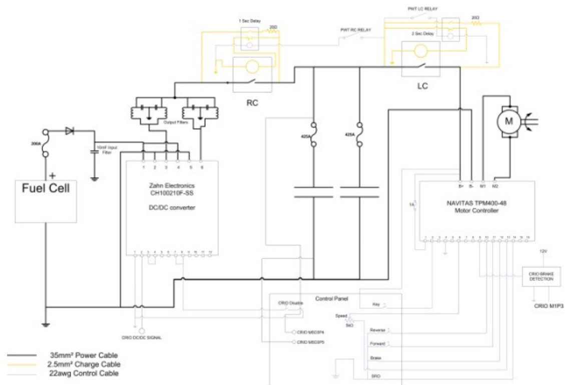


Figure 4 – IRG02 high voltage circuit

2.1.3 Hydrogen System

In order to satisfy the requirements of the University safety officers and Formula Zero scrutineers the peak hydrogen system pressure was 200 bar. High pressure was not allowed to exist outside the cylinder, requiring a cylinder mounted step down pressure regulator. Cylinders used in the race event were supplied by the organisers, and a specific hydrogen safety marshal was employed by the organisers to leak test the hydrogen system before racing, and after every cylinder change. Cylinders used in testing were standard steel cylinders supplied by BOC. However there was no technical reason why the cylinder pressure was limited to 200 bar other than local facility restrictions and safety regulations. A typical cylinder size of 5 litres gave a run time of approximately 20 minutes with the fuel cell at continuous full power.

A diagram of the hydrogen system is shown in figure 5. A pressure reducer from Swagelok was set to give a maximum 5 bar (absolute) pressure on the low pressure side. The low pressure safety systems incorporated an excess flow valve, a solenoid valve operated in fail-safe mode, a manual valve and a pressure relief valve before the fuel cell. The excess flow valve prevents dangerous release velocities from occurring in the event of a leak. The solenoid valve is opened upon vehicle activation and automatically closes in the event of vehicle shutdown, failure event or hydrogen leak. The manual valve enables the driver to shut down the hydrogen system if needed. The pressure relief valve prevents over-pressure from damaging the fuel cell. Electronic hydrogen sensors were positioned near the hydrogen system and connected to the control system so that the solenoid valve would be closed in the event of a positive signal from the hydrogen sensor.

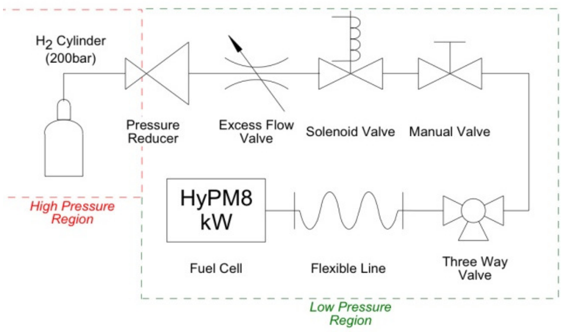


Figure 5 – IRG02 hydrogen system

2.1.4 Cooling system

The fuel cell was the only component that required a liquid cooling loop, the layout of which is shown in figure 6.

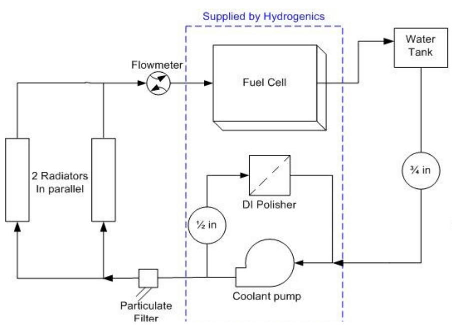


Figure 6 – IRG02 coolant circuit

The coolant was de-ionised water, and a de-ionising filter (DI polisher) was necessary to keep the resistivity of the coolant above 20MΩ/m, a common requirement in PEM fuel cells to avoid internal short circuits. Standard aluminium radiators of 200 x 200 x 30mm were used with electric fans controlled directly by the fuel cell. In the final vehicle build a third radiator was added in parallel.

2.1.5 Sensor diagram

A number of sensors were required on the vehicle for correct operation and safety, shown in the layout in figure 7. The most important sensor for the fuel cell control algorithm was the supercapacitor voltage, this enabled the control software to determinate the state of charge of the capacitors and ramp the fuel cell up or down accordingly. Accelerometers were installed as part of the prescribed safety system and are described later. Finally the motor controller current sensor was installed so that the brake light could be operated when the vehicle was regenerative braking.

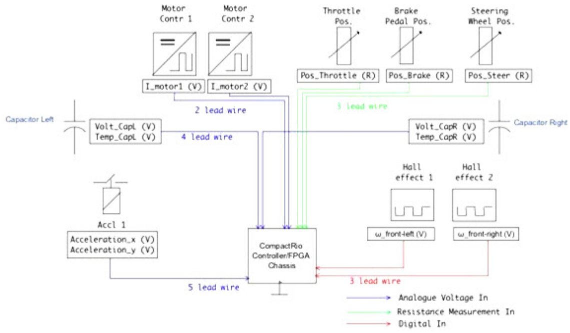


Figure 7 – IRG02 sensor diagram

2.1.6 Control Logic

All communication with the fuel cell was performed using the standard CAN protocol used in the automotive industry. The Hydrogenics HyPM fuel cell power module has two modes of operation: one in which the load is followed and another in which a current request is sent to the fuel cell, which it then tries to supply. The fuel cell was used in the load following mode for ease of integration with the DC/DC converter. Thus the current output on the DC/DC converter, set by a dedicated 0-5V signal from the cRIO, was the fuel cell power controlling factor. The concept for the control logic implemented by IRG02 and used in the race in Rotterdam was for the fuel cell to consistently increase its power output until the super-capacitors became full, shown in figure 8.

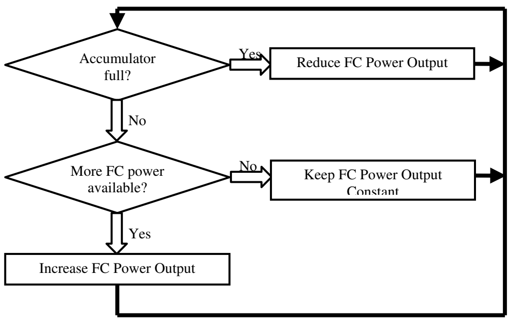


Figure 8 – Control logic flow chart

The process of requesting more current is limited by the fuel cell itself which feeds back a value determining the maximum allowable load at that point in time. This power limiting factor is mainly to protect the stack from large jumps in load current and is hence highly dependent on the actual current being drawn, stack temperature, fuel availability, etc. Further feedback loops were added such as temperature and stack under voltage control. If preliminary calculations had shown that there might be a shortage of energy available in the amount of fuel allowed then a more fuel conservative approach could have been taken e.g. the fuel cell could have been run at peak efficiency rather than peak power but, as is shown in the race data analysis, maximum power was more important than fuel economy.

2.1.7 Safety Systems

The safety system onboard IRG02 comprised these main components:

- an accelerometer measuring both horizontal directions
- an easily accessible manual emergency stop
- a solenoid valve situated on the low pressure side of the hydrogen system
- a relay isolating all high voltage components
- the FPGA of the cRIO

An automatic emergency shut-down comprising:

- emergency fuel cell shut down
- isolation of high voltage components cutting all power to the transmission
- closure of hydrogen solenoid valve

can be caused by:

- a >5G deceleration in the horizontal plane (detected by the accelerometer)
- activating the manual emergency stop

In addition a low pressure manual hydrogen shutoff valve was positioned close to the driver, and the hydrogen cylinder also had a high pressure manual shutoff valve before the regulator. As a secondary safety measure the hydrogen pressure relief valve positioned before the fuel cell should trigger a vehicle shutdown and close the solenoid valve via the hydrogen sensor.

2.2 Sub-system testing on the bench

All sub-systems were tested on the bench in order to become familiar with the components, calibrate them, and establish their correct operation. Initially the efficiencies of the motors and motor controllers were tested on a rig using a flywheel to simulate the inertia of the vehicle and (4x) 12V lead acid batteries as a power source. After establishing that the DC/DC converter could charge the capacitors correctly, the gain of the internal feedback loop in the DC/DC was calibrated so that the maximum 5V control signal corresponded to the maximum fuel cell output of 210A. The system of capacitors, motor controllers and motors was tested with simple hardware control in a standard engine test bay. This represented all drive train components apart from the fuel cell, which was tested in the hydrogen safe laboratory at Imperial College with a 12kW computer controlled load bank to simulate the motor loads in order to establish the start up and CAN bus communication protocol, the typical power output, ramp rates and required cooling.

2.3 Rotterdam Data

Vehicle operating parameters such as voltages, currents, temperatures, fuel cell fault codes and warning messages were recorded by the cRIO via the CAN bus. Figures 9 to 11 present fuel cell power, coolant temperature and supercapacitor energy from vehicle runs in Rotterdam. These data sets have been chosen to highlight the control system operation and the problems encountered on the track.

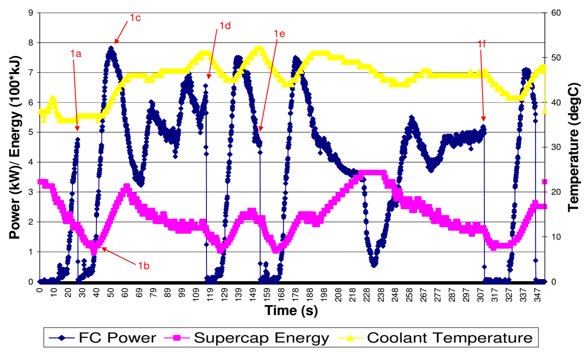


Figure 9: Fuel cell power, supercapacitor energy and fuel cell coolant temperature during test run on race track

Figure 9 shows data from the first and longest test run before the main race. Large fluctuations in both the super-capacitor charge level and fuel cell power show the highly transient power demands under race conditions. There are several instantaneous reductions in fuel cell power, indicated by pointers 1a and 1e-f. These can be seen in nearly all runs throughout the Rotterdam weekend and were traced to a faulty relay in the power electronics affecting the fuel cell 'load enable' signal. This is the reason that the super-capacitor energy level drops very low soon after the start of the run, indicated by pointer 1b. The second peak in fuel cell power, at pointer 1c, shows the fuel cell module ramping to full load quickly after the drop and how the control software limits the power output as the super-capacitors become full.

To make more power available to the driver the control software was modified before the main race to keep the fuel cell at full power for longer. Figure 10 shows the data recorded between 20 and 110s of the first run under race conditions where the fuel cell produces up to 10kW. Again, once the capacitors are full the power level is reduced to avoid over charging, shown by pointer 2a. Even with this modification it is apparent that energy is still drawn from the super-capacitors more quickly than the fuel cell is able to compensate. Pointer 2a also shows that the cooling system was not able to dissipate all of the heat produced in the fuel cell whilst operating at above 9kW for sustained periods as the coolant temperature climbs to the operational limit of 65°C. When this limit is exceeded the fuel cell automatically decreases power to prevent the temperature reaching the absolute limit of 70°C..

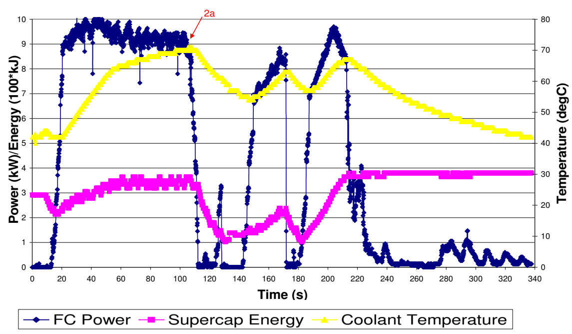


Figure 10: Fuel cell power, supercapacitor energy and fuel cell coolant temperature during qualifying run for main race

Figure 11 shows the data recorded for the fastest lap time recorded by the Racing Green team in Rotterdam during the semi-final of the main race.

The first 120s show the control software operating without fault, varying the power output of the fuel cell to keep the super-capacitors nearly full whilst they are being drained by the motors. The fuel cell power output is then cut four times with the fuel cell subsequently recovering, shown by pointers 3a-d. The last large decrease in power, at 260s indicated by pointer 3e, shows the control system functioning normally to prevent super-capacitor over charge. The fuel cell power is subsequently regulated between 2-4kW to maintain supercapacitor charge.

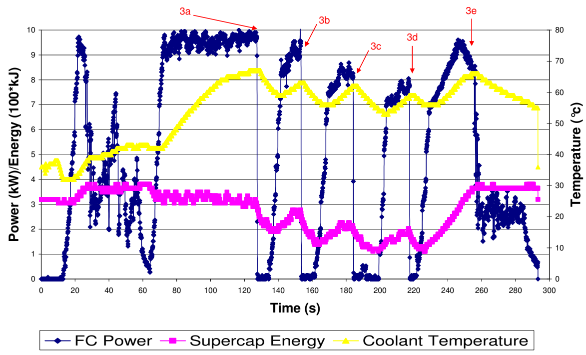


Figure 11: Fuel cell power, supercapacitor energy and fuel cell coolant temperature during best recorded run for IRG02.

The analysis of the data shows that more power was available to the go-cart than was actually harnessed. Problems with the power relays were the main contributing factor, as the control strategy worked well when there were no interruptions. Using a simple control logic kept problems due to complexity to a minimum, this was one of the primary goals as the preparation timescales were short.

2.4 New Functionality for 2009

Development of IRG02 to improve speed is underway, this includes repositioning of the hydrogen bottle to a safer place behind the seat, a completely new set of lightweight bodywork and a redesigned cooling system that will use only one radiator and have greater capacity. Electrical and control changes include a programmable electronic differential based on steer angle to improve cornering. Greatly enhanced data logging will allow more detailed analysis of the car performance and real time wireless communication will allow real time control system modifications. The improved control system has recently been tested and only minor modifications are left before the next race.

2.5 Lessons learnt

The following practical lessons were learnt during the build of IRG02:

- Reduce the number of soldered connections to a minimum as these are often the first to come loose, and cause intermittent faults (which are the hardest to locate).
- Where possible use screw in type electrical connections as they hold firmly and are easy to replace trackside.
- Use a rugged, dependable microprocessor or FPGA that is designed for this type of environment
- Keep the control system as simple as possible and limit the number of sensors which have feedback loops as when these sensors malfunction there is often control system instability
- A clear simple driver display is essential, IRG02 used a single LED array to indicate capacitor state of charge. LCD screens with large amounts of data on them are not recommended as the driver is too busy to take the information in.
- Attention should be paid to planning the low voltage circuit wiring loom, with fault finding in mind
- No problems with EM interference or capacitive coupling were observed, this was primarily due to good design practice.
- Test all systems on the bench before assembling on the car. Finding suitable testing facilities is challenging and should be arranged early.
- Allow substantial time for assembling tested systems on the car
- Plan several shakedown tests at full power on a track to uncover any problems.

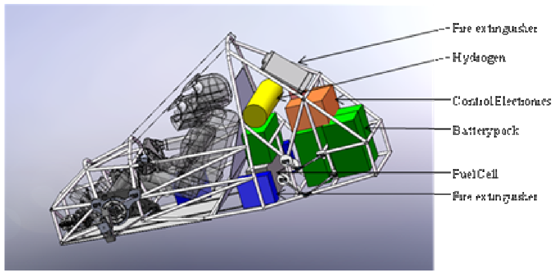
3 IRG03

The vehicle architecture is based around a steel space frame chassis with four electric motors, one driving each wheel, being load bearing members. The high BoM cost of using four motors and inverters is mitigated in this case by the fact that each motor is stressed to a lesser degree, allowing cheaper units to be used with greater reliability. Using the same motor four times also allows a reduction in spares stock.
The energy storage system of IRG03 was battery heavy, with the fuel cell sized to supply the mean power demands of the vehicle in the Formula Student endurance event.

So far IRG03 represents a proof-of-concept that has not been optimised for weight, polar moment, weight distribution or centre of gravity. All of these factors were considered in the design concept, but the primary goal was to have an operating vehicle that was well tested and reliable.
The following sections highlight some of the unique features of IRG03.

3.1 Architecture

The layout of IRG03 and a top bill of materials is shown in figure 12.



Chassis	Custom steel space frame
Fuel Cell	(1x) Pearl 4kW PEMFC
Lithium ion cells	(576x) Kokam 4.8Ah/4.2V SLPB11043140H
Battery Pack	10.2kWh/100kW/192-302V
BMS	REAP Systems
Electric motors	(4x) Perm Motor Company PM120
Motor controllers	(4x) AMC B100A40
DC/DC	(1x) APA 15kW Unit
Vehicle Control Unit	(1x) National Instruments cRIO

Figure 12 – IRG03 and bill of materials

3.1.1 Chassis

A tubular spaceframe concept was chosen to allow maximum design flexibility and development. To minimise the embedded energy in the chassis steel was chosen as the construction material.

3.1.2 Battery

The battery pack has been designed and built by students at Imperial College using 576 individual lithium ion cells in a 72S8P arrangement supplied by Kokam. The pack is air-cooled for simplicity, it is anticipated that this will be changed to liquid cooling in subsequent vehicles to increase power and cell lifetime.
Safety has been the primary objective of the design both in operation and handling, so the pack is split into four series connected modules, each with an 18S8P arrangement giving a voltage of 72.6V. In

order to ensure that only non-lethal voltages (less than 48V) exist at any time other than when the car is ready to operate, the modules have arming plugs in line between the 8th and 9th series cell connection, thereby allowing a maximum of 36.3V to exist until the arming plugs are installed. This is shown schematically in figure 13.

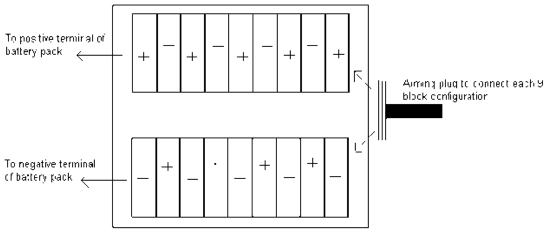


Figure 13 – Battery module arrangement with arming plug [4]

The battery module housing is electrically non-conductive GRP, mounted on anti-vibration feet.

3.1.3 Drive and suspension modules

The design of the modular drive and suspension modules is shown in figure 14, one of these is assembled at each corner of the chassis with modified suspension geometry front to rear. These modules were load bearing members in order to save weight and maximise the space available on the vehicle.

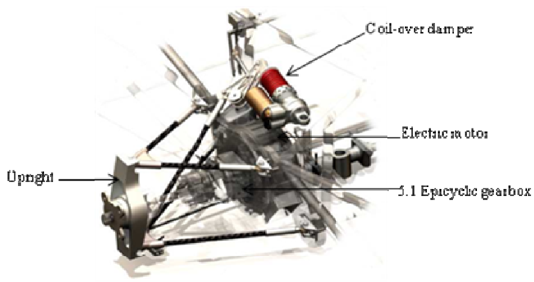


Figure 14 – IRG03 drive and suspension module

4 Future Direction of IRG

Future vehicles will be designed to win the Formula Student Class 1 competition against 600cc internal combustion engine cars on speed and agility testing alone, with significantly lower emissions. The team is committed to the use of fuel cells as prime movers for its vehicles, although the specific type is not restricted to PEM. Bernay et al [5] analysed how appropriate each of the six main types of fuel cell are for automotive applications and concluded that PEMFC and SOFC, in that order, show the most promise. A continuing problem for PEMFC is that of poisoning by carbon monoxide, sulphur and oxides of nitrogen. This requires very pure hydrogen, with a correspondingly high energy investment in producing it. Because SOFCs operate at higher temperatures they do not require platinum as a catalyst, and are therefore more poison tolerant and can be fuelled by natural gas. Brett et al [6] showed that a SOFC coupled with a high temperature battery fuelled by natural gas gives significantly reduced energy consumption compared to internal combustion engines, no matter what their fuel. Their hardware in the loop testing of the system confirmed their model predictions and proved the viability of the system.
The guiding principle for IRG going forward will be to reduce the life cycle energy costs of the vehicle and competing with it.

4.1 IRG04

IRG04 will be the next iteration in the Imperial Racing Green development sequence, shown in figure 15. It will follow the policy of continuous improvement adopted so far, where the lessons learnt from the previous iteration are adopted into the new vehicle. However, whilst IRG03 was proof-of-concept of a vehicle of this size, IRG04 will be the first opportunity to develop a fully optimised and integrated system. Optimisation of weight distribution, polar moment and centre-of-gravity will be achievable.

IRG01- Go-Kart Prototype
1.2 kW Fuel Cell + 1.5kWh Li-Po batteries
40kW Peak Power

↓

IRG02 – Pro-Kart
8 kW Fuel Cell + 330 F Ultra Capacitors.
40kW Peak Power
9kW average power

↓

IRG03 – Single-Seat Race Car
4kW Fuel Cell + 10 kWh Li-Po batteries.
100kW Peak Power
20 kW Average Power

↓

IRG04 – Single Seat Race Car
18 kW Fuel Cell + Li-Po batteries + Ultra Capacitors
≈100 kW Peak Power
≈30 kW Average Power

Figure 15 – Racing Green vehicle progression

The architecture of IRG04 is planned to be a fuel cell, lithium ion battery and supercapacitor triple hybrid. This will enable the vehicle to have a high peak power output, whilst shielding the battery and fuel cell from harmful high current transient loads to improve thermal management and lifetime, and minimising the battery and fuel cell size, thereby reducing cost. It will also allow it to take full advantage of different modes for different types of events, e.g. endurance or sprint. Students will be expected to use Design For Environment (DFE) and each aspect of the car will have to have a demonstrated CO_2 reduction over its IRG03 equivalent. Whether this is through design, material or process changes will be up to the student concerned. The designs of some components of IRG03 have already taken this into account through being designed for re-usability and upgradability. Specifically the battery packs are designed to be a modular system, so that some or all of them can be used in future vehicles. Due to the systems integration nature of the work, many CO_2 reductions will come through working with suppliers and will be of mutual advantage. Through this process of incremental change, the life cycle CO_2 of IRG04 will be significantly reduced.

5 Closing Remarks

Imperial Racing Green is providing a powerful means of enabling top-class students, the technology and business leaders of the future, to work with cutting edge technologies in an interdisciplinary environment, developing team working and engineering management skills, whilst further stimulating the development of low carbon vehicle research at Imperial College and the vertical integration of this research with undergraduate teaching. The project requires students to work across a wide range of disciplines many of which are outside their own degree discipline, allowing for the formation of diverse student projects that, whilst being highly specialised themselves, also have to be able to integrate with other teams working on the same vehicle. The Racing Green team are hoping to perform well in 2009 with an upgrade of IRG02 and the all new IRG03 in the next events of their respective competitions, the Formula Zero race at Brands Hatch on 1st/2nd May and Formula Student at Silverstone on 16th July 2009.

With the successful launch and development of IRG02 and the ongoing build of IRG03 Imperial Racing Green is proving the viability of fuel cells, batteries and electric drive technology in race applications: the short timescales and dedication of the students and academics to the team have produced innovative and elegant solutions to the problems that the automotive industry as a whole is facing. For this reason low or zero emission racing should be encouraged beyond the realms of student projects as a means to quickly develop low carbon vehicle technologies and the supply chain that is so important to an emerging technology.

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