Hydrogen – Hybrid Miniature Locomotive

Project Report

UNC CHARLOTTE

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Disclaimer

My participation in 4th IMechE Railway challenge, UK, 2015 was under the research collaboration formed between the Lee College of Engineering's Infrastructure, Design, Environment, and Sustainability (IDEAS) Center, Civil and Environmental Engineering Department at UNC Charlotte and the Birmingham Centre for Railway Research and Education (BCRRE) at the University of Birmingham (UK).

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Abstract

Hydrail vehicles convert the chemical energy of hydrogen to mechanical energy, either by burning hydrogen in a hydrogen internal combustion engine vehicle, or by reacting hydrogen with oxygen in a fuel cell to run electric motors. Recent advancement and compact design in fuel cell technology motivates researchers for fuel cell based hydrogen powered locomotives. This technology is clean, green and environment friendly. To check the feasibility and future development, one such project was carried out at University of Birmingham. This project is actually "Small Testbed for a Testbed"; it is a miniature locomotive powered by hydrogen, which was developed to conduct further research.

This report is a summary of general design and my involvement of the 2015 IMechE Railway Challenge locomotive entry by the University of Birmingham, Centre for Rail Research and Education.

A Brief introduction of hydrogen powered locomotive design is presented in section 1 with electrical and mechanical systems integrated in it. Section 2 deals with miscellaneous work which was conducted by me. Section 3 concludes the work.

Acknowledgements

I would like to express my sincere thanks to department of Civil and Environmental Engineering & Electrical and Computer Engineering for allowing me to participate in IMechE Railway Challenge 2015. Specifically, Dr. Martin Kane and Dr. Keith Barson who supported me during every stage of my participation. I would like to thank staff of office of Education Abroad at UNC Charlotte for helping me in completing the formalities for this visit. Further, I would like to acknowledge Sara Watson for her administration and helping us getting financial support for tickets and other expenses.

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I am very much thankful to Dr. Stuart Hillmansen for being my supervisor and adviser during this visit at University of Birmingham. Also, I am very grateful to team lead by Ivan Krastev (Ph.D. Student at U of B) for allowing me to contribute for this design challenge.

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Glossary of Terms / List of Abbreviations

Term	Explanation / Meaning / Definition
EECE	Electronic, Electrical and Computer Engineering
IMechE	Institution of Mechanical Engineers
PEM	Proton Exchange Membrane
STP	Standard Temperature and Pressure

1. Introduction

The Hydrogen Pioneer locomotive was first designed in 2011 as a proof of concept for a fuel cell powered locomotive. The basic idea behind the vehicle was to provide a project that contained multiple engineering aspects that are encountered in the railway industry, giving the chance for engineers from different backgrounds to experience and learn new skills beyond their daily research area. University of Birmingham has a strong research history in hydrogen powered transport, and it was decided that fuel cell technology would be highly appropriate for a locomotive. This is principally due to increased pressure on transport industries to reduce carbon output and the inevitable scarcity of fossil fuels.

1.1 Design of the Locomotive

The design of the locomotive was approached keeping mind the rules and the railway challenges which incorporates the following key features and benefits:

- Low cost modular aluminium frame.
- Primary and secondary suspension designed to minimise high frequency wheel rail interface impact vibration.
- Emissions free hydrogen power supply.
- Regenerative braking capability via super-capacitor bank and on-board battery pack (disabled for energy storage challenge).
- Simple control system & Robust control and power electronic design.
- High performance pneumatic brakes – currently used for emergency braking only but capable of assisting dynamic brakes.
- Gear drive with axle suspended traction motor.

1.2 Mechanical Components and Structural overview

1.2.1 Frame

The locomotive frame is constructed with extruded aluminium beams, which support each of the decks. It incorporates a heavy-duty steel plate upon which these components are mounted. The middle deck supports the fuel cell unit, regulator and compressor. The top deck supports the 200bar hydrogen tank. The chassis is shown in bellow figure.

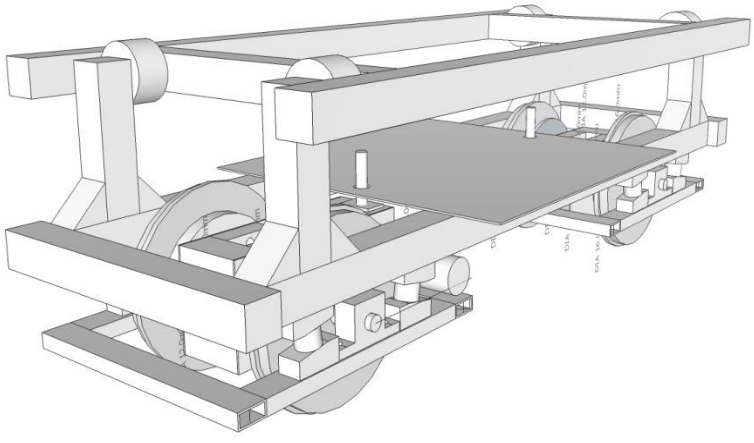

Figure 1: Main Structural Frame with running gear

The main frame is 640 mm wide, maximising internal space and minimising overall wheelbase length in order to improve curving performance. These dimensions are currently configured to meet the loading gauge requirements of the Stapleford Miniature Railway, but could easily be re-configured for other loading or track gauges if required. The vertical load is transmitted directly from the wheels to the chevron spring suspension on the lower running gear bogey. Rubber buffers were chosen to provide load capability of 1.5kN peak when shear loaded. The shear loading provides substantially greater deflection and response to high frequency vibrations that are expected from the track joints. Vibrations are transferred to the secondary suspension large buffer springs. These springs are set to be completely shear loaded to give maximum deflection for the upper frame, where the fuel cell, hydrogen tank and sensitive electronics are housed. Rubber was chosen for springs as it gives a measure of damping that coil springs would not provide, and are relatively inexpensive compared to alternative air and coil spring options. The greatest benefit of the rubber suspension is its ability to deform in any direction, meaning that with a minimal amount of springs (8 on the running gear, 4 on the middle deck) movement in all directions can be accounted for.

1.2.2 Motors & Drivetrain

Each of the two permanent magnet motors generates 4Nm of torque, which is transmitted via a two-gear system. The drivetrain assembly has a 2-part sleeve that houses the axle and the bearings. This design was chosen for ease of maintainability. In order to deal with axial loads, that are unavoidable during cornering, tapered roller bearings were used.

Figure 1: Vertical pin that connects the assembly to the body

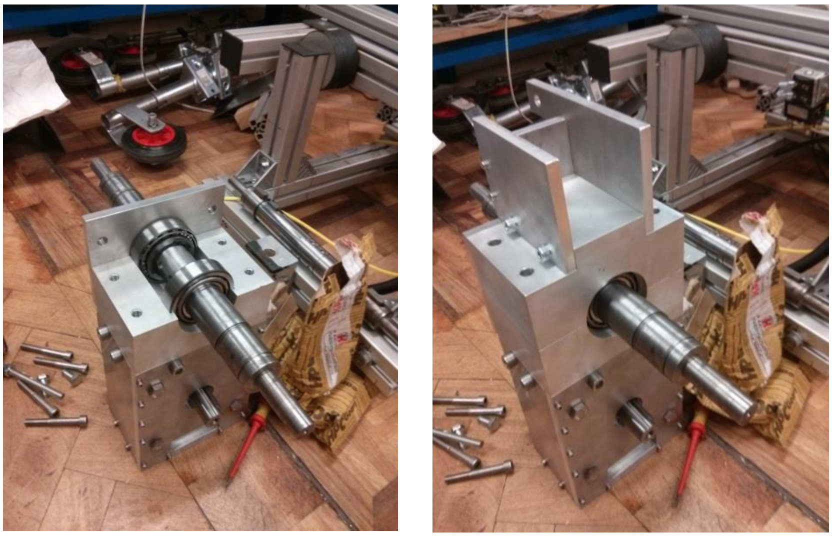

Figure 2: Axle sleeve housing and roller bearing arrangement

The motor axle has a 14-tooth gear that drives a larger 120 tooth gear, giving a gear ratio of 8.57. Traction forces are transmitted to the body by a vertical bright steel pin connected to the lower deck and to the nose of each motor. The wheels are 300mm diameter steel with the profile stated in the competition rules.

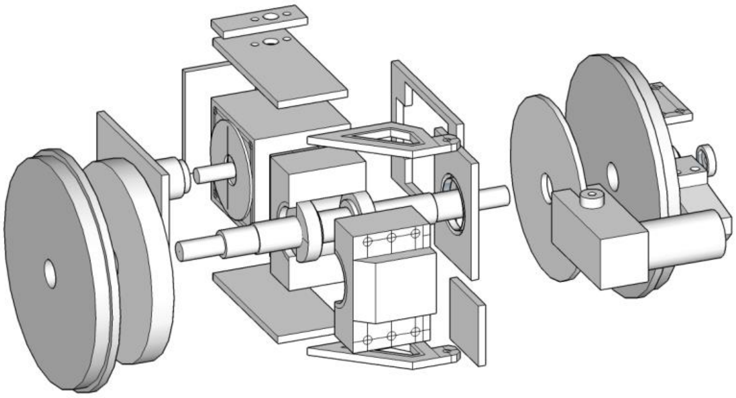

Figure 3: Mechanical Drivetrain

1.2.3 Braking System

The braking system consists of two independent braking systems: (1) Mechanical brakes mounted to the axle, and (2) a dynamic service brake. The dynamic service brake uses the traction motors as generators, and the braking energy to re-charge the batteries. The mechanical breaks consist of two Twiflex springs applied pneumatically and pressure released callipers which apply braking force to two axle mounted 8 mm thick disks. The brakes are failsafe and will automatically be applied in the event of power loss. These brakes serve as emergency brakes and will be connected to the e-stop system. The friction brakes are capable of producing a braking force of up to 650 N, per axle. The vehicle will lose rail adhesion and begin to slide with braking forces of over 330 N. This requires the use of a flow rate control on the brake cylinder exhaust. Brakes are pressurised at 5 bar to achieve a braking rate of 1.3 ms^{-2} .The cylinder pressure must be exhausted at a pressure of 1.3 bar to reduce braking force to 260 N per axle.

1.3 Electrical System overview

1.3.1 Power system

The vehicle prime mover is the fuel cell stack, which is hybridized using two 12V leisure batteries and an electrolytic double layer capacitor (super-capacitor) bank.

Power supplies are connected in parallel and provide a 50V DC link. The fuel cell is used to provide the average power, for a given duty cycle, with peak power demands met by the addition of the batteries and super-capacitors.

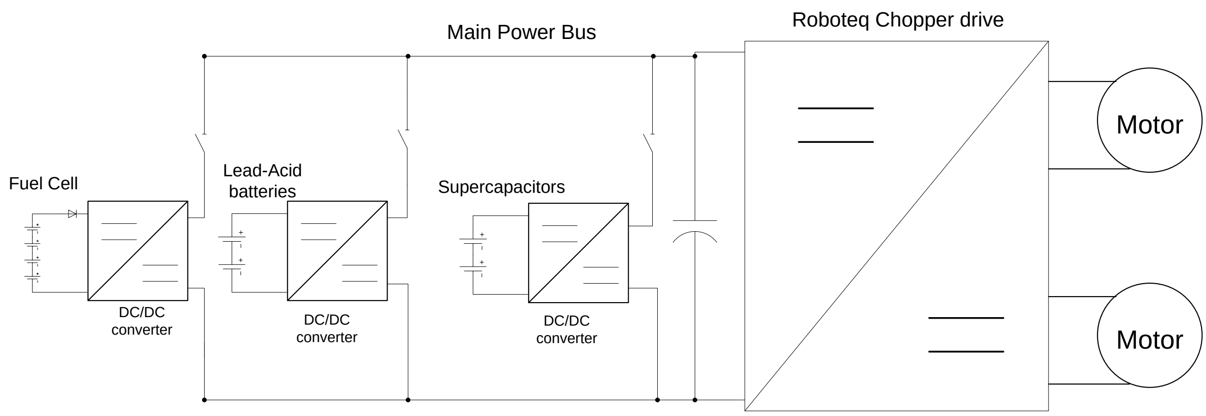

Figure 4: Locomotive power system

On-board electronics require 24 Volts. A converter supplies 24 Volts to necessary components. A Roboteq motor controller receives the driver signals and controls the motor torque accordingly based on a simple bespoke script. An axle-mounted rotary encoder is used to measure wheel speed.

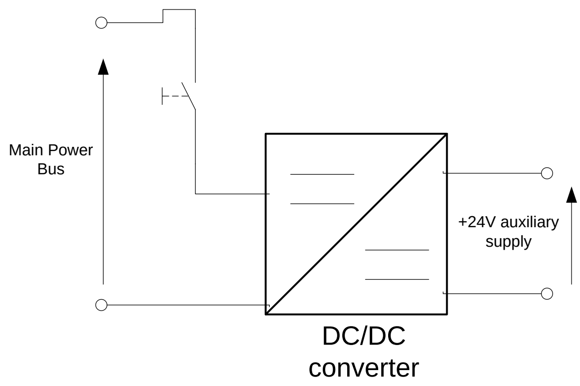

Figure 5: Auxiliary power supply for control electronics and contactors

The emergency stop buttons will disconnect the power from the auxiliary supply, opening all contactors, which in turn, will apply the emergency brake.

1.3.2 Fuel Cell

The most efficient technology to convert hydrogen to electricity is the fuel cell. The most suitable fuel cell for this project is the Proton Exchange Membrane (PEM) fuel cell. It operates at low temperatures and has a fast start up time. In a PEM fuel cell, hydrogen (H_2) is split into two protons (H^+) that diffuse across the electrolyte membrane, whilst the two liberated electrons travel around an electrical circuit. The protons, electrons and oxygen combine with oxygen (typically from the air) to release water. This process only forms water, electricity and heat, see Figure 6.

The fuel cell used on the locomotive is the H1000XP by Horizon. This fuel cell system is designed for the Shell Eco Marathon and is an off-the-shelf product. The unit incorporates various control and status monitoring systems. This simplifies the installation and operation of the unit. It requires no regular maintenance, and with peak loads being met by the on-board batteries, it is expected to provide many years of trouble free service.

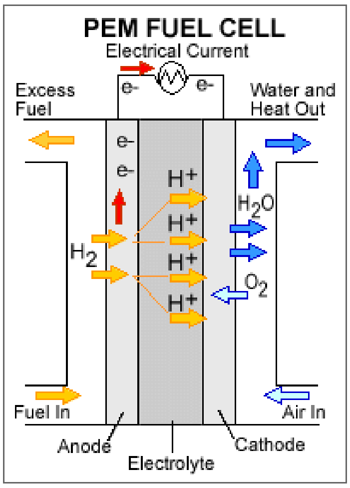

Figure 6: Diagram of Proton Exchange Membrane Fuel Cell

Figure 7: Horizon H-1000XP^{TM} Fuel Cell Stack

1.3.3 Roboteq Motor Controller

Roboteq's HDC2450 controller can convert commands received from a RC radio, Analog Joystick, wireless modem, PC (via RS232 or USB) or microcomputer into high voltage and high current output for driving one or two DC motors. The controller features a high-performance 32-bit microcomputer and quadrature encoder inputs to perform advanced motion control algorithms in Open Loop or Close Loop (Speed or Position) modes.

Figure 9: Roboteq DC motor Controller HDC 2450

The HDC2450 features a high number of Analog, Pulse and Digital I/Os which can be remapped as command or feedback inputs, limit switches, or many other functions. The controller's two motor channels can either be operated independently or mixed to set the direction and rotation of a vehicle by coordinating the motion of each motor.

Numerous safety features are incorporated into the controller to ensure reliable and safe operation. The controller's operation can be extensively automated and customized using Basic Language scripts. The controller can be reprogrammed in the field with the latest features by downloading new operating software from Roboteq.

Roboteq controller can be configured using roborun+ software. For more advanced computing, it supports micro basic scripting language. For more details refer to [3].

2. Miscellaneous Work

2.1 Torque Control Mode for Roboteq controller

The motor controller is a chopper drive, based on input it adjust the duty cycle of the power MOSFET and enables the DC motor to run. The motor controller has got RS232, CAN, USB communication modes. Most of the communication for the configuration is done using USB port and DB25 pin connector was used for data collection from current sensors and encoders etc. The open loop and closed loop parameters can be set through roborun software.

The torque mode is a special case of closed loop operation where the motor command controls the current that flows though the motor regardless of the motor's actual speed. In an electric motor, the torque is directly related to the current. Therefore, controlling the current controls the torque.

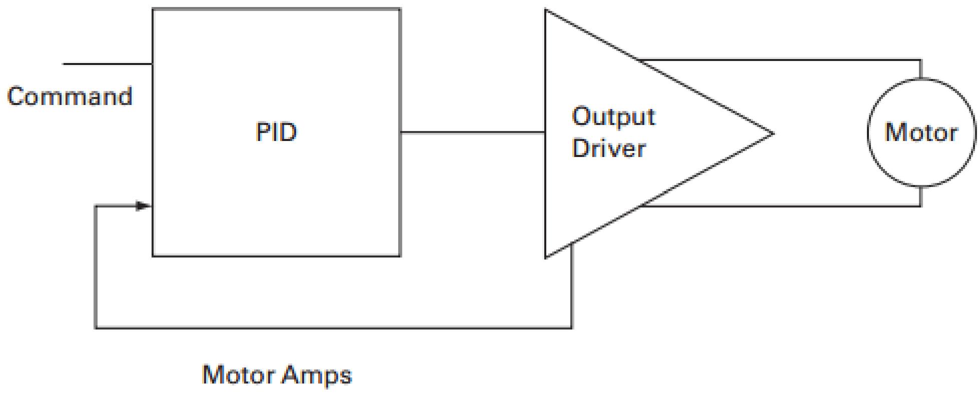

Figure 10: Torque control mode PID control loop

Torque mode is mostly used in electric vehicles since applying a higher command gives more “push”, similarly to how a gas engine would respond to stepping on a pedal. Likewise, releasing the throttle will cause the controller to adjust the power output so that the zero amps flow through the motor. In this case, the motor will coast and it will take a negative command (i.e. negative amps) to brake the motor to a full stop. External feedback sensor are used for overcoming the limitation mentioned in manual as shown below configurations. Care must be take while configuring the current sensor in to the feedback for proper control.

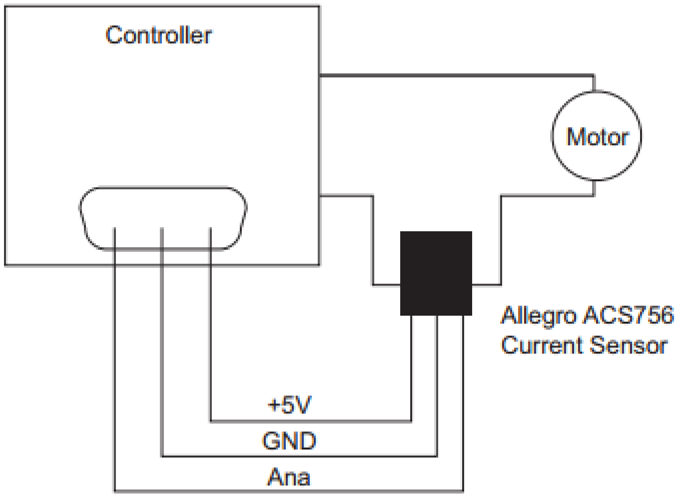

Figure 11: External feedback sensors

2.2 CAN Communication

There are various CAN communication that is supported by roboteq motor controller, but the CAN open being a standard protocol was used for the communication command from the locomotive. CAN has 3 lines; CAN high, CAN low, and GND. The CAN has no transmitter or receiver. The Can device has a buffer which gets dumped to the lines and as a part of bit pattern, the SID (Standard Identifier-11 bit) is send with the data. With SID information a child device know that this message is for it, and it decodes it likewise. CAN communication can be configured in roborun+ configuration window and can be enabled by micro-basic script.

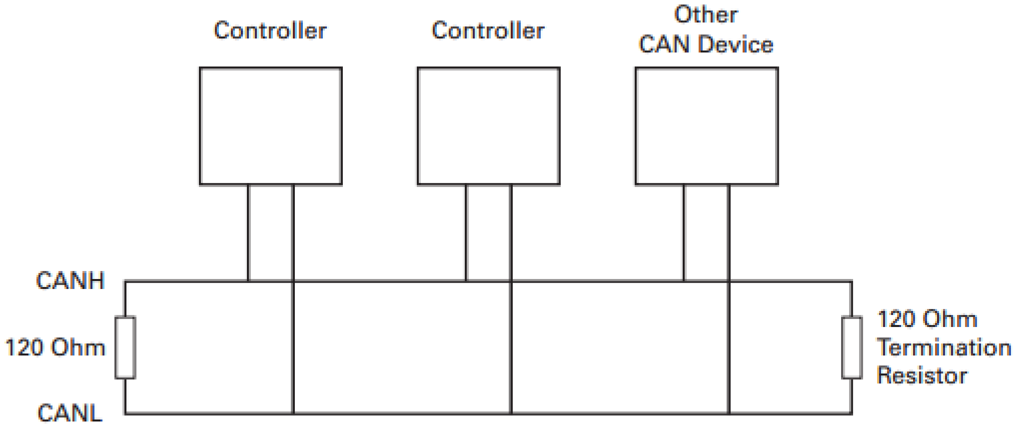

Figure 12: CAN hardware configuration

By setting a node id and transmission rate CAN needs be configured to send the data or receive the data at the said rate.

2.2.1 TPDO (Transmit Process Data Object)

Transmit PDO (TPDO) messages are one of the two types of PDO messages that are used during operation. TPDOs are runtime operating parameters that are sent automatically on a periodic basis from the controller to one or multiple nodes. TPDOs do not alter object data; they only read internal controller values and transmit them to the CAN bus. TPDOs are identified on a CANopen network by the bit pattern in the 11-bit header of the CAN frame.

TPDO1: 0x180 + Node ID

TPDO2: 0x280 + Node ID

TPDO3: 0x380 + Node ID

TPDO4: 0x480 + Node ID

CANopen allows up to four TPDOs for any node ID. TPDO1 to TPDO4 are used to transmit up to 8 user variables which may be loaded with any operating parameters using Micro Basic scripting. Each of the 4 TPDOs can be configured to be sent at user-defined periodic intervals. This is done using the CTPS parameter.

Sets the send rate for each of the 4 TPDOs when CANOpen is enabled. Syntax: ^CTPS nn mm Where: nn = TPDO number, 1 to 4 mm = rate in ms Micro-basic Syntax : setconfig(CTPS,1,100)

2.2.2 RPDO (Receive Process Data Object)

RPDOs are configured to capture runtime data destined to the controller. RPDOs are CAN frames identified by their 11-bit header.

RPDO1: 0x200 + Node ID

RPDO2: 0x300 + Node ID

RPDO3: 0x400 + Node ID

RPDO4: 0x500 + Node ID

Roboteq CANopen implementation supports RPDOs. Data received using RPDOs are stored in 8 user variables from where they can be processed using Micro Basic scripting.

2.2.3 Overall programing and communication

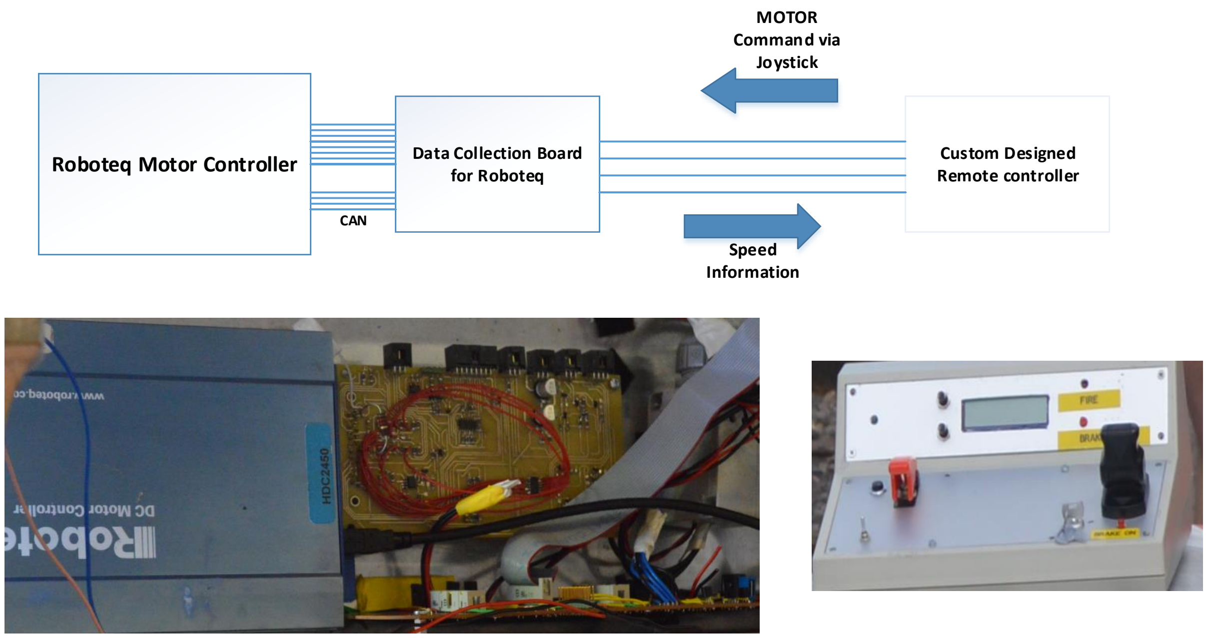

Figure 13: Motor Controller and Remote controller interfacing

The remote controller had PIC microcontroller, which had 12 bit ADC, which converts the joystick analog command to digital and transmit it over CAN. The required SID is given to remote controller team on which they send the command information. The motor controller should identify the correct CAN message which gets delivered to its buffer (RPDOs-32bit) and take necessary action. In order to check whether the PIC on the remote controller is frozen or not, it sends continuous interval counter and motor controller always check for the count as per the interval predefined. If more than 5 counts are missed then, action for emergency stop is performed and set_position (Set_torque) is kept to 0. That means no current is fed to motors. The Encoder Speed collected from the acquisition board is sent over CAN via TPDOs that needs to be identified by remote controller and it prepares for the display of the speed on LCD. If proper choice of devices and transmission rate is not selected then one can get message “CAN bus is heavy”. For hand shaking purpose 125 kbps rate was set in both the CAN devices, and Script was written on controller to do above mention task. The Data collection board collects data from current sensors, which can be configured in feedback for close-loop control mode for motor controller. The control circuit and power circuit board were made separate. Power management board which manipulates connections for DC-DC boost converters, super capacitor converters, relays, safety switches etc. Which also provides power for remote controller. For Safety reason, the logic was made to turn off the traction power and turn on the fail safe break in case of disconnection of remote.

3. Conclusion

Hydrogen powered locomotive was designed and tested for fully working. But, throughout the Care must be taken while designing the individual parts and test needs to be performed when everything connected together. Some of the failures were faced, because transient voltage crossed the limit of the MOSFET channel of the roboteq specified by the data sheet and we lost our one channel of the controller. But, we were able to provide the traction power on one motor with remaining channel.

My contribution was in mainly in circuit board making of DC-DC converters, CAN communication, Motor Controller configuration and programing using micro basic language, and other miscellaneous mechanical and electrical works/jobs. Overlay, it was really good experience with hands on experience and team work. This types of project can be a best source of learning with actual practical experience with interdisciplinary R&D.

Hydrogen powered locomotives are currently in research areas and working successfully, but practical consideration and other analysis needs to be done for larger scale locomotive. Hydrogen safety is also one issue but, with proper safety and protection, hydrogen based locomotives can be practically realized.

4. References

1) Design Report for a Hydrogen-Hybrid Miniature Locomotive prepared by Ivan Krastev, Delaram Sharifi, and Krishnan Venkateswaran, University of Birmingham Team
2) Roboteq Motor controller Data Sheet http://www.roboteq.com/index.php/docman/motor-controllers-documents-and-files/documentation/datasheets/hdc24xx-datasheet/60-hdc24xx-datasheet/file
3) Roboteq Motor controller Manual http://www.roboteq.com/index.php/docman/motor-controllers-documents-and-files/documentation/user-manual/7-nextgen-controllers-user-manual/file
4) Horizon H-1000XPTM Fuel Cell Stack manual http://fuelcellstore.com/manuals/horizon-pem-fuel-cell-h-1000-manual.pdf

Appendix

Air tank/brake event performance

Emergency brakes are released using a pneumatic system. This is controlled by switching a solenoid valve that either connects the 6 litre tank (at 6 bar) to the brake cylinders or to the air surrounding the loco (0 bar), Figure 8shows a schematic of the system.

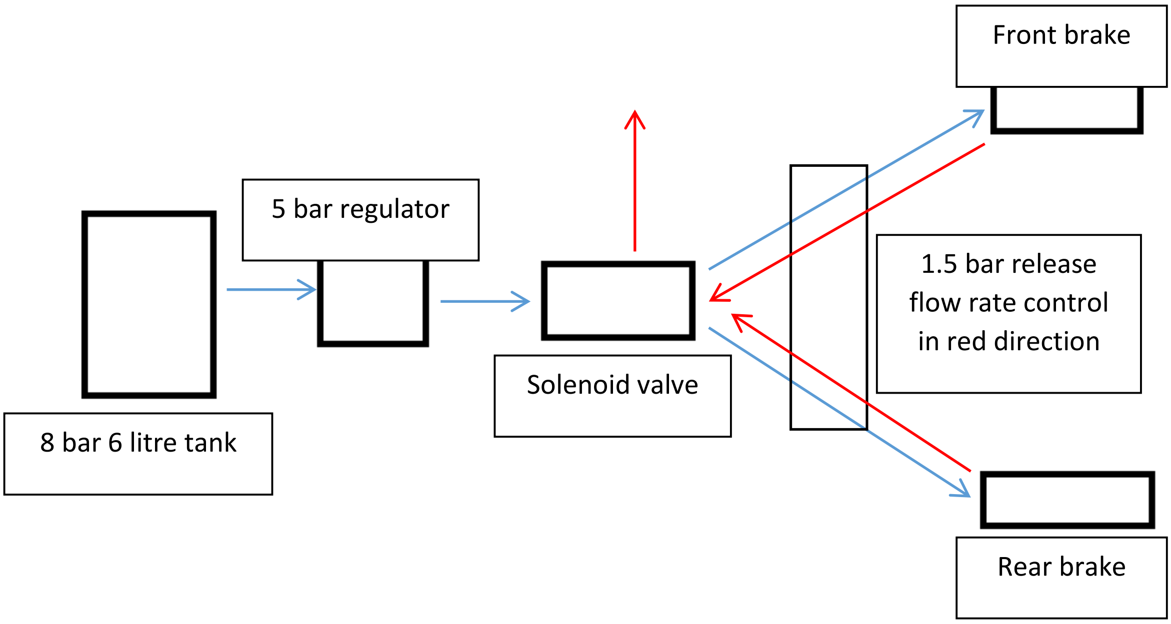

Figure 8 – Schematic diagram of pneumatic braking system

A six bar 6 litre tank is compressed prior to train operation. This tank serves as the main air reservoir for the pneumatic brake system. Brake cylinders have a 20ml capacity. Both brakes and pneumatic piping hold approximately 100ml per braking event. Each time the brakes are used, for an emergency stop or parking, the solenoid valve in Figure 8 is switched, disconnecting the 5 bar supply to the brakes (holding them open), and discharges the air via the solenoid exhaust port. The flow rate is set to allow the brakes to close at a reduced rate reducing the brake force from 600N to 260N per axle. Above figure shows the calliper pressure and the mass flow rate graphs based on 5 flow rate control settings. In order to achieve the desired 1.3ms^{-2} deceleration, a flow rate control setting of 10% open is appropriate. It is necessary for the emergency and parking brakes to have at least 30 breaking events, in a single charge, in order to be considered as inexhaustible.

The 6-litre tank is able to provide 150 separate brake releases, five times the minimum deemed necessary. The system is also spring applied providing failsafe brakes. This ensures that emergency braking can be applied with a complete loss of tank pressure and power to the vehicle. An on-board air compressor will continuously top up the tank. The compressor maintains the tank pressure between 5.5 and 6 bar.

Power calculations

The locomotive uses a standard 200 bar hydrogen cylinder, supplied by BOC, with volume of 1.48m^3. It is assumed that energy density of hydrogen is 0.02GJ/m3, resulting in 29.6MJ in a tank.

The required performance is 3 hours operation, without refuelling, with continuous travel at 5km/h (1.389m/s) on a 5% gradient with a 400kg trailing load. Our vehicle weighs approximately 400kg, and we have assumed Davis coefficients A=50N and B=10N/m/s, based on practical measurements. It is assumed that air resistance is negligible. The total vehicle weight is 800kg.

$$P_{Davis} = \left(50N + 1.389 \times \frac{10N}{ms^{-1}}\right) \times 1.389 = 88W$$

$$P_{Gradient} = \sin 2.86° \times 800 \times 9.8 \times 1.389 = 391W$$

$$E_{total} = (P_{Davis} + P_{Gradient}) \times 3600 \times 3 = 5.173MJ$$

The locomotive’s continuous power rating is 1kW, with 2kW for 2 hours, and 2.5kW for 30 seconds.

Regenerative energy calculations

A number of simulations were made to provide projections of energy recovery. The recovered energy challenge will rely on the constant torque settings of the electric motors described in section 5.3.3.

$$KE = {}^{1}/_{2}\, mv^2 = 8680\ J$$

The recovered energy was estimated including power converter and super-capacitor losses.

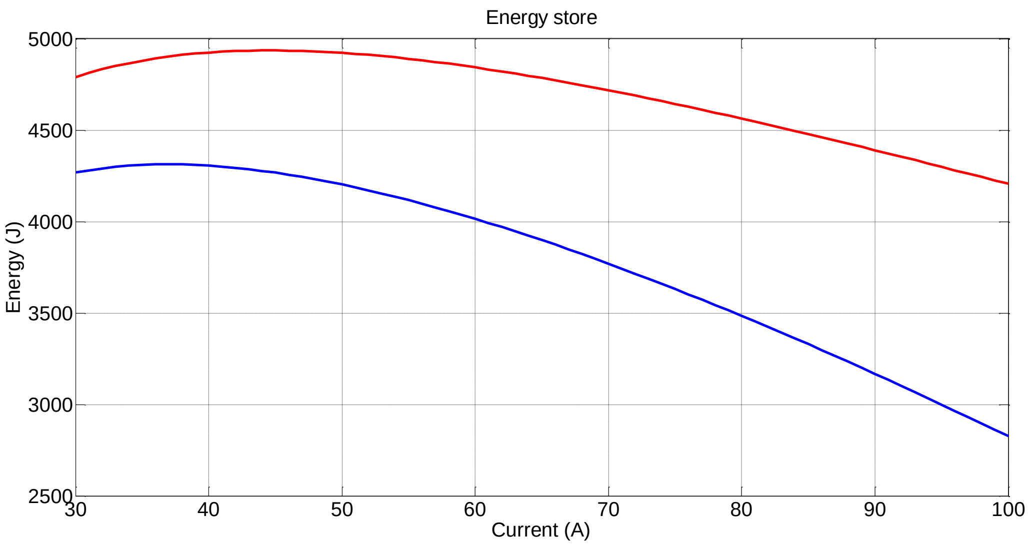

Figure 95 – Recovered energy vs braking motor current. RED shows super-capacitor energy after braking, BLUE shows vehicle kinetic energy after super-capacitor bank has been emptied.

It is estimated that possible round trip (recovering energy into storage then reusing it for acceleration) efficiency is about 50%.

The super-capacitor bank consists of eight 16V modules with 16.66F capacitance giving a total of 12.79kJ energy storage.

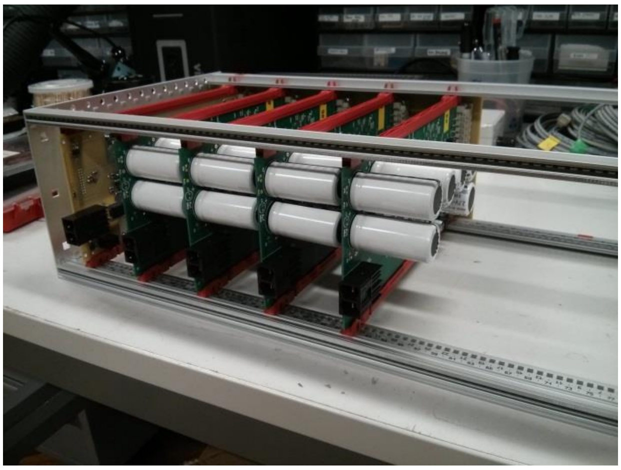

Figure 16- 4 modules of the super-capacitor energy storage bank.

Suspension performance

The suspension system comprises of 8 angled rubber buffers in the primary suspension and 4 shear loaded rubber buffers in the secondary suspension. The angled primary suspension provides a simple chevron spring plus dampener type suspension. The shear-loaded suspension provides a soft secondary layer. Figure shows a single sided free body diagram describing both primary and secondary levels of suspension.

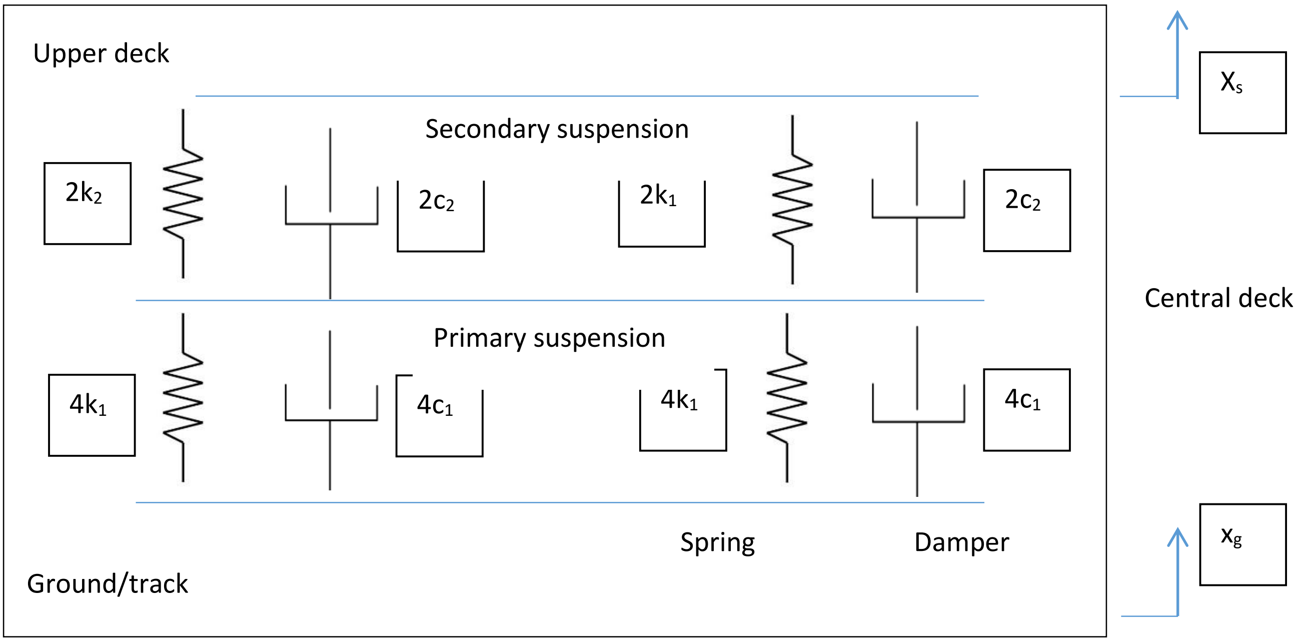

Figure 17– Free body diagram describing primary and secondary suspension

A transfer function has been developed using spring and damper characteristics of the rubber buffers. If it is considered 2 mass system then 4^{th} order model and if 3 mass system then the transfer function model will be consist of 6^{th} order model.

Suspensions are actually a low pass filters, which are designed to supress or reject certain frequency. The Cut off frequencies are designed in order to have desired performance of suspensions. For the design, system identification approach can be adopted and tuning frequencies of this filters can be calculated and be verified with simulation. In the event of high frequency step vibrations caused by rail gaps or track inconsistencies, there is a significant reduction in vibration affecting the upper-deck.

Locomotive Diagrams

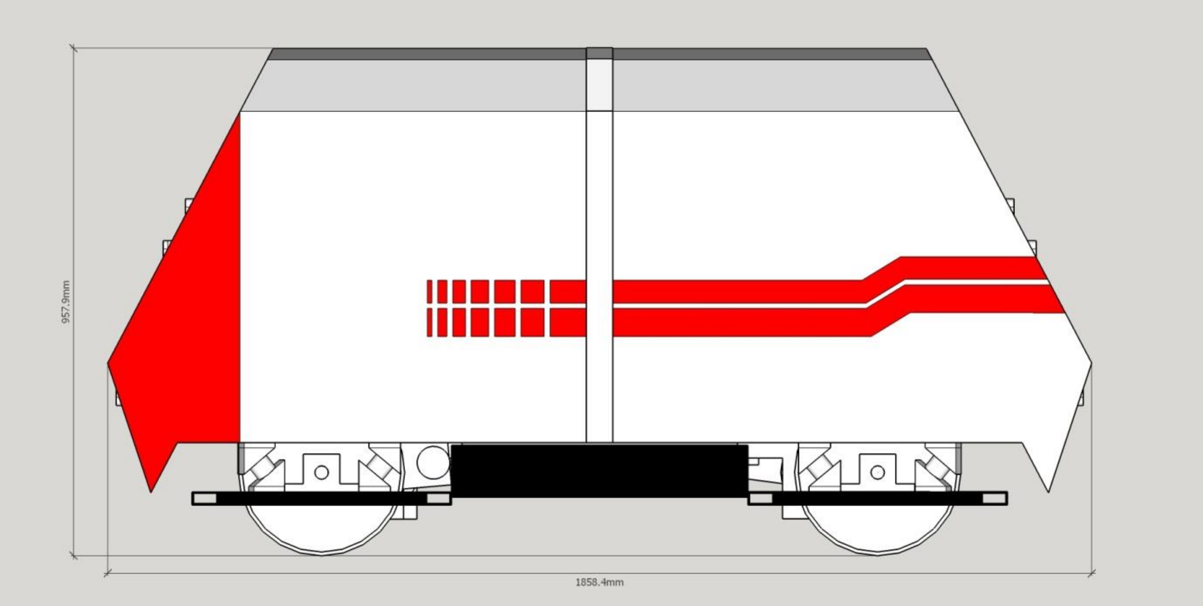

Figure 18 – Locomotive left projection

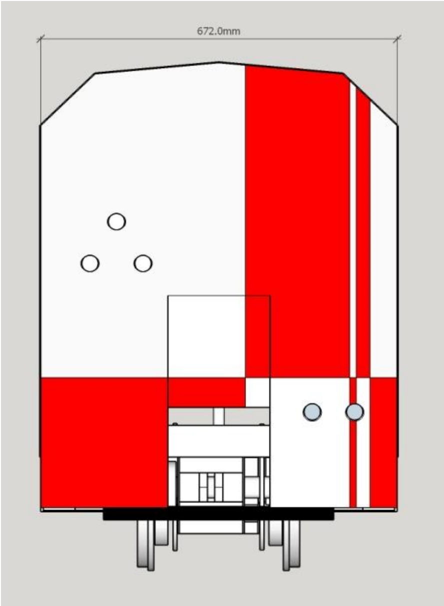

Figure 1910 – Locomotive front projection

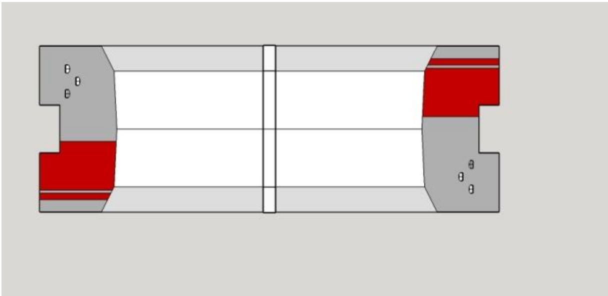

Figure 20 – Locomotive Top projection

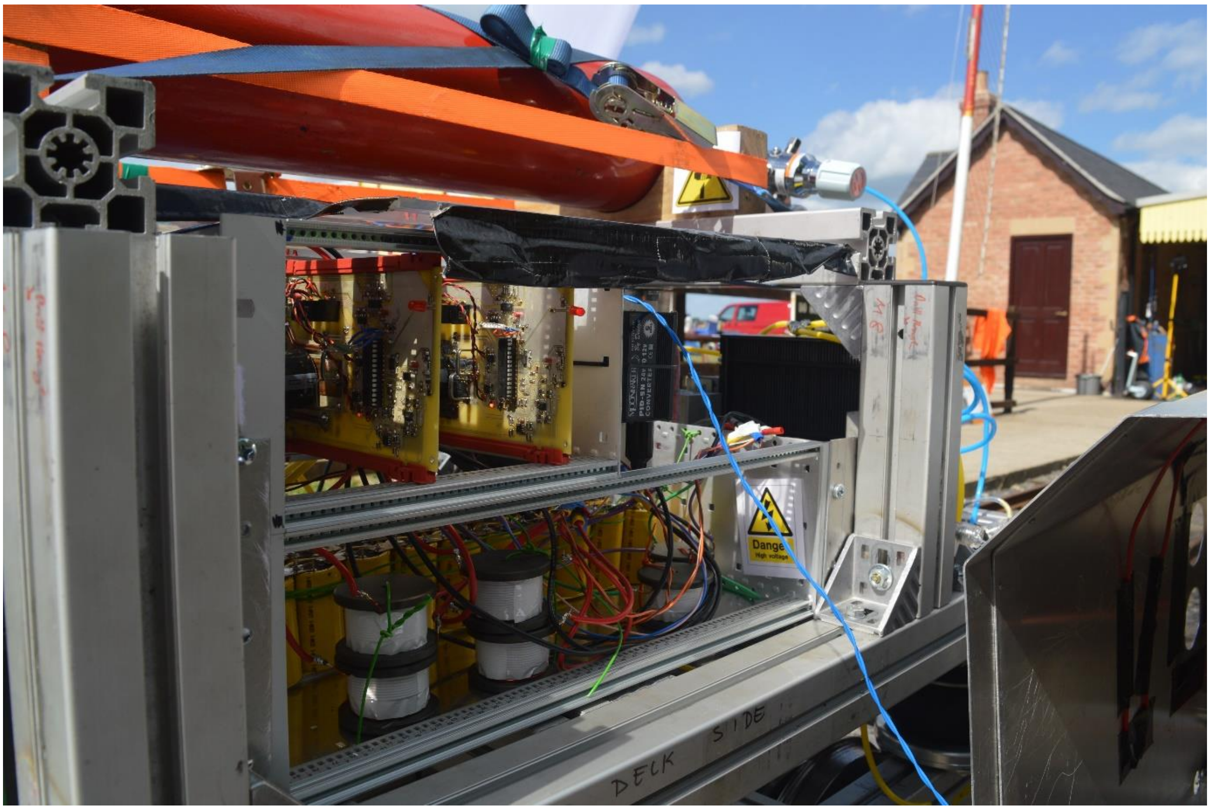

Figure 21 11- Super Capacitor bank and Converter Sections

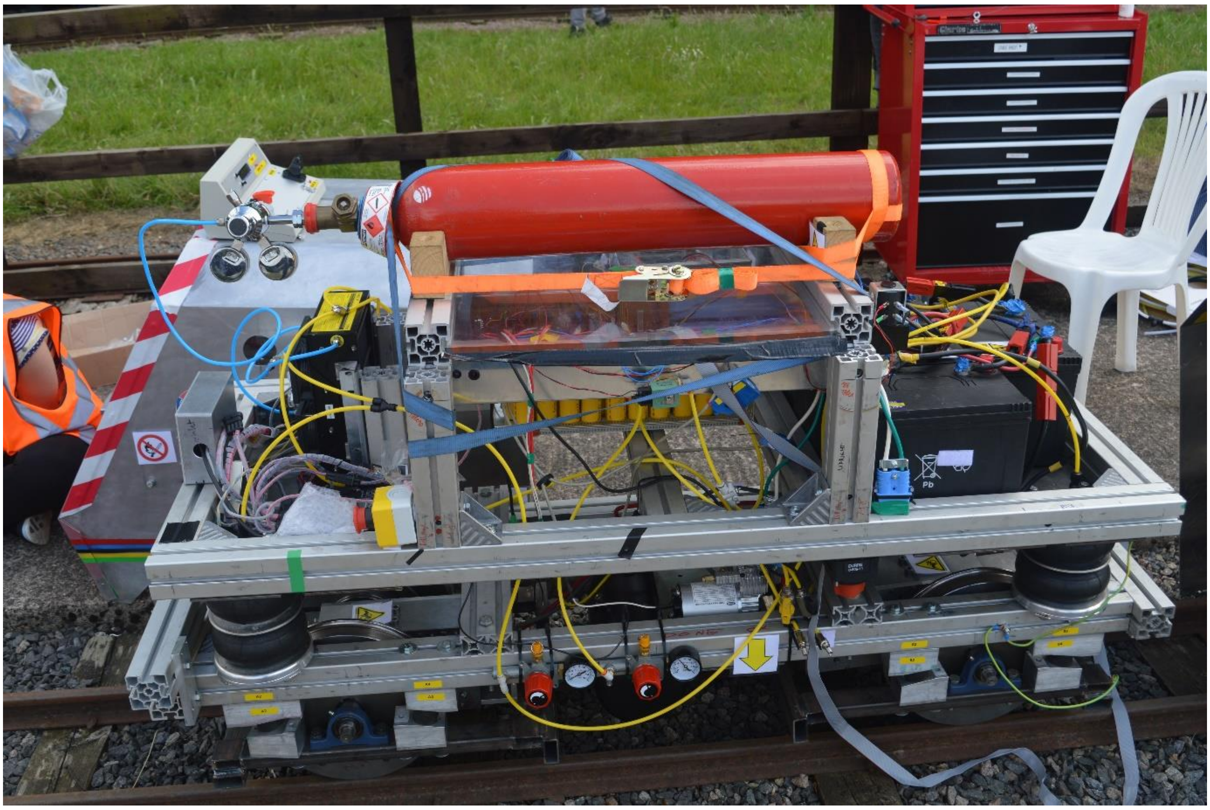

Figure 22 - Internal Side view of a locomotive

Figure 23 - Hydrogen Locomotive in motion