Exercise Bike Power Production – STEM Workshop

Specification *Version 3+*

1. Introduction

The purpose of this STEM workshop is to teach both children and adults of all ages the difficulties in producing electrical power in amounts sufficient to be useful for both household appliances and industrial machines. This project is intended to be a demonstrable example of how difficult it is for humans to generate enough electricity to power even the smallest of appliances. The main point of the workshop will be to represent the amount of power supplied by power generation sources such as Wind Turbines and Natural Gas Turbines in terms of Quantity of Exercise Bikes to bring home to the audience the scale of the demand, though it could focus on more green energy sources as that is effectively what the proposed Exercise Bike Generator design is. I feel the proposed design will be a success as not only will it give the target audience an in-depth knowledge of how much energy is needed to power everyday appliances, but it will also incorporate a competitive element in that riders could compete against one another to produce the most energy within a given time – a good way to make exercise fun!

The proposed design differs from earlier propositions in that it will be implemented with minimal technical consultancy from personnel external to my group, as well as the projected cost of the project being far lower than previously estimated. These improvements will serve in making the proposed design more viable than past iterations of the specification.

1.1 Project Outline

The project aims have not changed significantly. However, the plan of action and implementation in this version of the proposal will be slightly different. As the Demonstrator will be using moving parts to generate electricity, and especially as it will be used by members of the public, precautions must be taken to ensure the unit adheres to all applicable H&S guidelines. Also, as components *may* be sourced from a project code that is different to the ISIS Accelerator Controls' project code, extra care needs to be taken in the calculation of the forecasted costs associated with the project.

OBJECTIVE: The goal of this project is to show interactively how power is generated. The amount of power produced will be enough to charge a phone or a power bank, or to turn on low power household lights. Hopefully this will illustrate the difficulty in producing electricity in significant quantities to drive really power-hungry devices, from kettles and washing machines all the way up to our particle accelerator. The energy demand of these devices will be portrayed in terms of the number of units like the proposed Exercise Bike design, likely meaning that several hundred such Bikes might be needed. As such, the portrayal shall be made **graphically**.

EXECUTION: Humans are inherently bad at powering household devices, which will make the point even more clear of the difficulty in power production. As the project is primarily aimed at young children, it is reasonable to assume the power output will be low, which will reinforce the point.

The design will consist of the same exercise bikes purchased on behalf of STFC's PE (*Mar 2017*), but will deviate from other proposed designs in that the internal wheels will turn a **brushed DC motor which will act as a dynamo**, thereby generating electricity. The pedals of the bike are attached to a wheel that drives a belt – this belt delivers power to a heavy flywheel inside the bike (*Approx. 20Kg*). As the gear ratio is about 1:6, the flywheel could spin at around 1000rpm. The DC motor will engage with this flywheel by means of contact between a small wheel mounted on the shaft of the motor and the outside of the flywheel (*a rubber sheet will be placed on the flywheel to increase grip*). The DC motor will be attached to the frame of the exercise bike by a right-angled metal bracket. This bracket will likely be off-the-shelf with holes drilled, as the mounting points of the DC Motor are in a specific location, and the exercise bike frame has no good mounting point locations. As the DC motor is brushed, it has fixed magnet locations, meaning that electricity generated can be used straight away.

To show the information, the regulated and unregulated output will be connected to a microcontroller to log all data. It might be easiest to use an Arduino given the wealth of online support – not much exists for the micro:bit. This data could either be shown on an LCD like before, or I could write an app for a tablet or a laptop – the display could show the data while it is being charged! This could show how much power is being produced, as well as what device is taking what power.

MATERIALS: As the project is aimed towards children, though cost and variability should be noted, it is likely that the project will consist of the exercise bikes (*which have already been bought*). Depending on the bike, the project implementation could be varied to suit primary school children up to adults.

In addition to the bikes, a DC motor will be needed for each bike – as the expected power produced should not exceed 500 watts, the DC motors will be inexpensive; less than £50 each. The project may require some holes to be drilled in the chassis and the Motor mounting bracket, but this should be covered by site staff. The bracket itself will be a cheap right-angled piece of metal, costing no more than £5. The rubber sheet surrounding the flywheel will be inexpensive too, costing no more than around £10. The circuitry will likely be the most expensive part of the project, but this can be mitigated if the measurement devices used (*laptops etc.*) are STFC owned.

QUALITY: Opting for cheaper in place of quality would be disappointing, and could lack respectability at the conclusion of the project; as a project representing STFC, a rusty, worn-out experiment could send the wrong message about what we do. Likewise, any modification to the shell of the exercise bike might not be able to be replicated bike-to-bike. All of the mechanical aspects of the proposed design should be enclosed fully within the shell of the bike.

ADDITIONAL: As said before, the only other components either can be found around RAL or are small electrical equipment, like LCDs, Microcontrollers etc.

MAINTAINENCE: This project will be easy to maintain – the likelihood of electrical failure is low, and could be made to be easily replaceable in event of catastrophic failure. The only foreseeable maintenance concern would probably lie within the bikes themselves. As they incorporate mechanical moving parts, the wheels and mechanisms may require greasing from time to time.

COST: I don’t have the information as to how much the exercise bikes cost, but as these are unlikely to be put into full-scale production, it is equally unlikely the bikes will need to be bought again, and so their cost can be ignored for now. Besides that, the total cost might reach the early hundreds of pounds (*GBP*), but a more accurate cost estimation will be made in the Gantt Chart.

H & S: Health and Safety regulations will be adhered to during all moments of manufacturing process. When designing, the bikes will be tested for rigidity, strength and balance. Every effort will be made to ensure that people cannot be injured while using the apparatus. If necessary, mats could be placed around the bike in the event of a fall.

IMPACT: By far the biggest advantage over previous proposals is the fact that it actively engages with the audience – they can see all stages of the operation, which can in turn be showcased and discussed.

1.2 Design constraints

The volume of space inside the exercise bike is low, and so mounting anything inside could be difficult, meaning the bracket and motor assembly will need to be as small as possible. The small internal volume may also lead to the build-up of heat – the DC motor will likely get hot and within an enclose environment this could be a problem. Although the wheel attached to the pedals in ribbed, giving some sort of air circulation, it might be necessary to install a fan that taps off the power generated to ensure that the Motor does not overheat. Another problem might arise in the communication between the bike and monitoring equipment – at time of writing I am unsure of communication protocols between a laptop-computer and an Arduino (or Micro:bit). The issues raised above can be summarised thus:

- The DC Motor will need to be mounted such that it has good contact with the flywheel but does not impinge on the shell of the exercise bike.
- The Bracket holding the DC Motor to the chassis of the bike will need to be such that it is strong enough to hold the Motor in position, but not too big as to impinge on the shell of the exercise bike.
- The Motor must not get too hot, and so the air temperature within the shell should be kept reasonable.
- The shell of the exercise bike must not be modified too much – only the chassis of the bike should be modified.
- The electronics for communications must be designed for easy interface with other systems while being robust enough to withstand the workshop environment.
- The project must be constructed to the high quality demanded by STFC while being as cheap as possible to construct and maintain.

2. Technical Requirements

As stated above, the process of power generation is from the mechanical work of legs being transferred to kinetic energy of the flywheel, thereby spinning the DC Motor. The electrical power produced by the Motor will induce a current to flow in the attached device, thereby charging it up or powering it for its intended use. For clarity, the block diagram of the proposed design is shown below (*Fig. 1*).

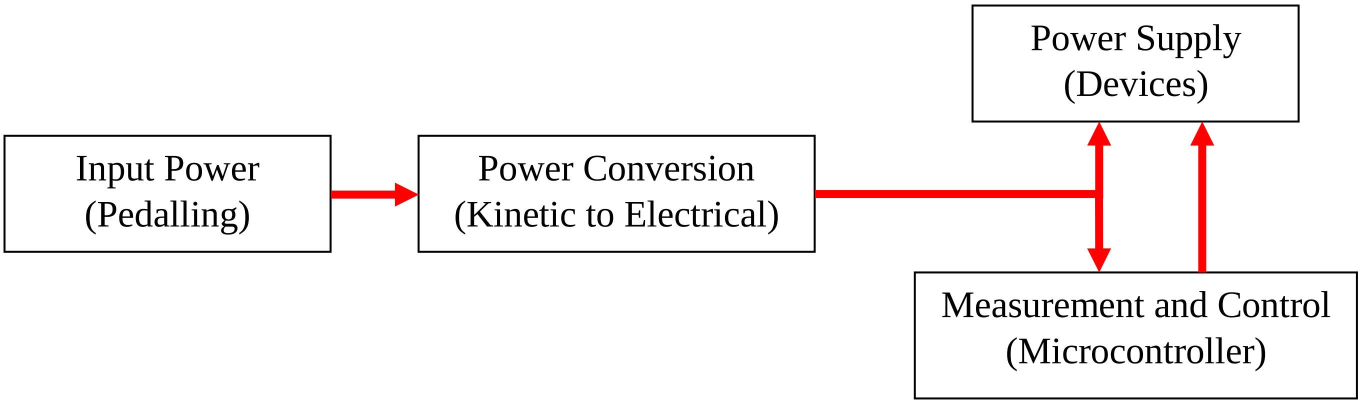

Fig. 1 **The proposed system is split entirely into mechanical and electrical parts, where the only interface between the two is at the DC Motor. The power generated by the Motor feeds directly to the attached devices, as well as the measurement and control systems. These will include the Microcontroller (Arduino or Micro:bit) which will monitor power generation, but this stage could also link to external equipment like laptops, tablets or projectors**

As the proposed design has both mechanical and electronic elements, the system development will need to keep both aspects in mind at all stages. This is because a suitable Motor must be chosen to withstand mechanical stresses such as over-torque, and the burn-out of the motor from over-revving. Likewise, suitable electronic components should be chosen to protect against over-voltage if the power-output of the motor exceeds safe levels, but should also be chosen with ease of use for both programming, testing, implementation and use in the workshop.

2.1 Technical Requirements – Mechanical

The main issues anticipated in the mechanical implementation arise from the possibility of the forces of the Demonstrator during use exceeding the design limits of e.g. the exercise bike frame, and from inaccuracies of measurement and assembly that could lead to loss of efficiency between the transfer stages.

As the exercise bike has been tested to enable users up to 100Kg to use the equipment, it can be assumed that the equipment has undergone extensive testing in all other regions, like friction between moving and stationary parts, and life expectancy of the rotary elements etc. The remaining precautions to be observed lie primarily in the choice of the Motor and the design of the attachment to the bracket. As the bike has no gears, it is not possible to protect against over-revving of the flywheel. Some assumptions will therefore have to be made in the choice of the Motor, taking this limitation into account:

- As the gearing is quite high, the user will not be able to spin the pedals any faster than 3 revolutions a second (*180 rpm*).
- As the gearing between the Pedals Wheel and the Flywheel is somewhere between 1:5 and 1:7, the ratio shall be called 1:6.
- Depending on the size of the wheel on the motor, the gear ratio will increase further. Because of the lack of space inside the shell, the upper bound for Motor wheel is somewhat limited to a maximum diameter of 5cm. Therefore the upper bound on circumference will be around 20cm. To allow errors and free movement in space, the proposed design will aim to use a Motor Wheel of circumference around 15cm. This will give a flywheel to Motor ratio of 1:4.
- With the above points in mind, the total ratio will be 1:24. Along with the first point, of a maximum angular frequency of 180 rpm, the upper limit for the Motor will be in the midst of 4320 rpm.
- As the requirements of the project call for a Motor that can charge devices such as Mobile phones, power banks etc. as well as household items like lightbulbs, the Motor should ideally be 12V. Therefore, the Motor must give a voltage output between around 7V and 12V, while being able to withstand a maximum rpm of more than 125% of the assumed angular frequency upper bound (5400 rpm).

Acknowledgement *– The motor will not be under any load (apart from the rotation of the internal magnets), and so its maximum torque can be disregarded; it is assumed that the shaft can turn under no load without damaging the gearbox.*

The wheel that attaches to the shaft of the motor needs not be very grippy, as the friction between the wheel and the Flywheel should be sufficient for it to turn properly. As the power output of the motor is expected to be quite low (*around 20 watts*), the spinning resistance of the Motor is likely to be low too. As Power is derived from Angular Frequency and Torque (*Math. 1*), the expected Torque can be calculated.

$$P = \omega T, where\ \omega\ is\ Angular\ Frequency\ in\ rpm\ and\ T\ is\ Torque\ in\ Nm^{-1}$$

With an expected upper bound of Power at 20 watts, the total torque is around 4 mN/m. This amount of torque is insignificant, especially if the bracket is strong enough to counteract the twisting force. The wheel could therefore be as simple as a wheel found on a model car, but should have some sort of grip to protect against uncertainties (*Fig. 2*).

Fig. 2 **The above is not necessarily the final proposed motor nor wheel, though does serve as an indication as to how the final design will most likely look. The Flywheel will have some adhesive applied to the outside to assist with friction between the Motor Wheel and the Flywheel, but this may well be unnecessary if the friction between the two wheels is already high enough**

The bracket that is proposed to hold the Motor to the frame of the exercise bike must be strong enough to hold the Motor in free space, but not too bulky such that it impedes the shell of the bike. Also, it must not flex when torque is applied to the Motor (*the force of twisting of the magnets inside the Motor will cause an equal twisting force on the bracket*). A higher Motor Torque will result in more power produced, too much torque could flex the bracket out of position such that the wheel of the Motor scrapes the Flywheel rather than turning against it. With this in mind, the following assumptions can be made:

- The bracket will need to be constructed of metal rather than wood or plastic, most likely steel.
- The easiest interface between the Motor Wheel and the Flywheel is parallel to the Flywheel axle. However, the axle of the flywheel protrudes from the frame of the exercise bike, and so the bracket would need a segment cut out of it so that the remaining pieces could attach to the frame either side of the axle mount – the result would resemble a fork (*Fig. 3*). The bracket will therefore be mounted beneath the axle mount. Although there will be less room between the Motor and the base of the bike, the bracket would now be a right-angled piece of metal (*Fig. 4*).
- To make the mounting holes easier to drill, the bracket will be no thicker than 2mm.

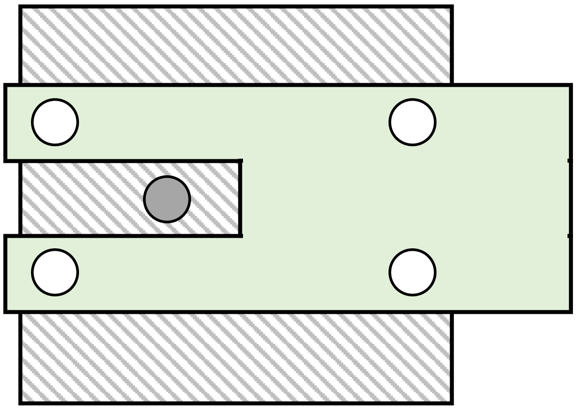

Fig. 3 **This is the discarded solution. The metal bracket would most likely need to cut to fit – it's unlikely that a bracket like this would exist off-the-shelf. In each Figure, the *white* holes represent the mounting holes, the *grey* hole represents the Axle of the Flywheel, the *green* area represents the bracket and the *grey hatched* area represents the bike frame**

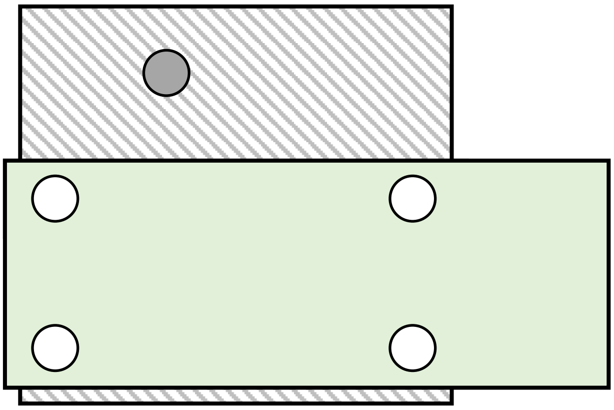

Fig. 4 **This is the preferred solution. As the bracket is mounted lower, it does not need to be cut into a specific shape. A bracket like this is much more likely to exist on the open market as it is, and so is much better suited to the design specification**

With the technical requirements discussed in detail, the final proposed assembly is shown below (*Fig. 5*)

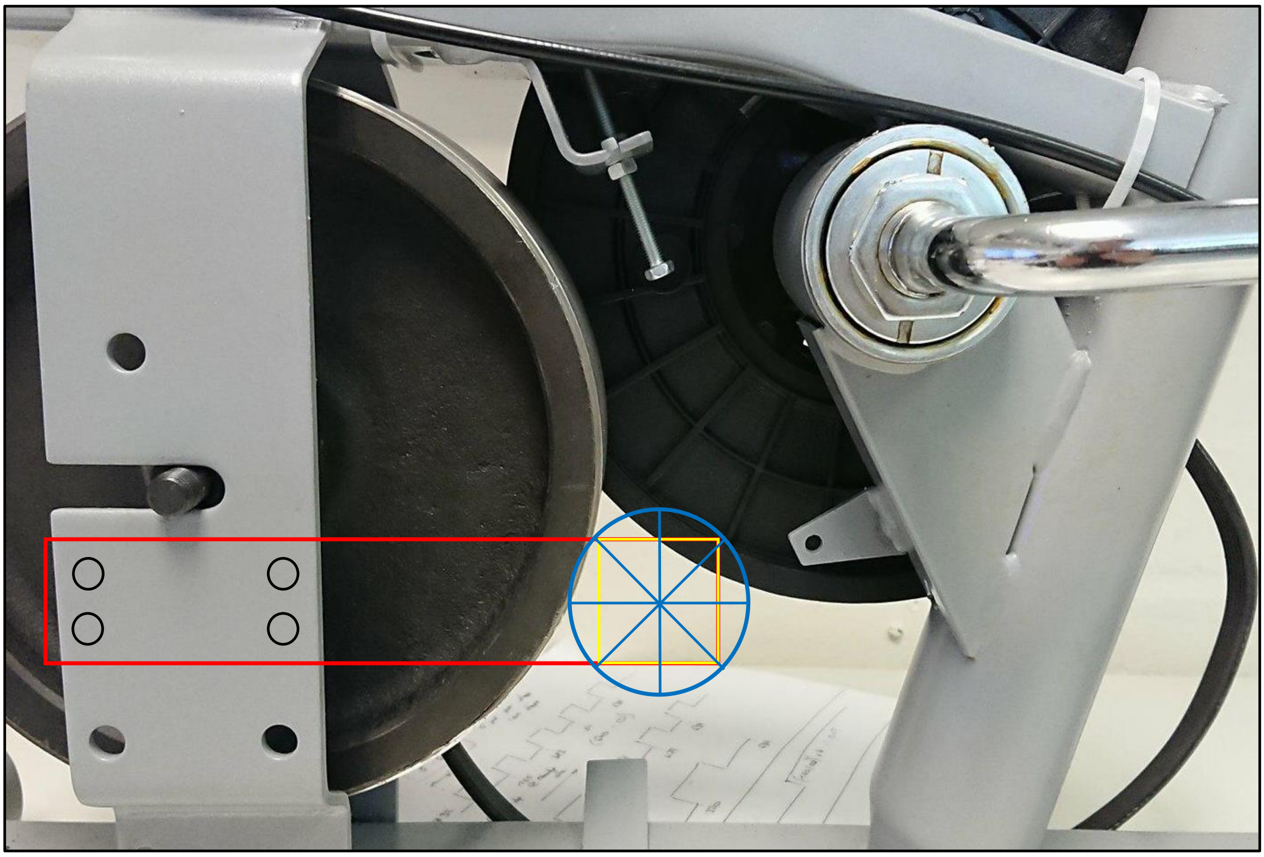

Fig. 5 **The *red* section is the bracket, the *yellow* section is the Motor housing, and the *blue* section is the Motor Wheel. This is a very simplistic representation, however it has not yet been decided which motor would be best for the proposed design, so the above shows where everything would be in relation to the bike**

2.2 Technical Requirements – General Electronics

The main points regarding the electrical/electronic side of the proposed design lie in the amount of power that can be extracted from the Motor, how the equipment is powered, where the equipment is located, and how the data is presented. *Though I haven't quite decided yet how the data will be presented, so long as I can get the data to a microcontroller, anything will be possible.*

Given that the Motor will not be 100% efficient, it will be assumed that it has an average efficiency of 80% maximum; "*It depends on the size and the precision of construction, but 80% is easily achievable…*" [1]., and so calculations for output power will be based on this efficiency. If it is also assumed that a reasonable sustainable output power (*before inefficiencies*) could be around 200W, **the resultant output power from the Motor would be around 160W** (*this would vary with how hot the Motor gets*). The only way to accurately predict what kind of power could be expected from the proposed design is to acquired and test a motor. Only then would the efficiency rating be known instead of assumed. ***Note; the actual output power would depend on the motor – a cheap motor costing around £25 might produce 20W, whereas a very expensive motor costing around £250 might produce 200W (a higher power motor would no doubt incur higher magnetic resistance, and so the gearing would be adjusted to take this into account). The motor chosen, ergo the power output would ultimately depend on budget constraints.***

The bikes came with a UI that displays basic exercise information, including Elapsed Time, Speed, Distance, Calories Burned, and Pulse from the volts-free sensors on the handles (*Fig. 6*). Though it would be good to relay this information into the microcontroller, the information is not accessible; these data go into a small microcontroller on the UI's PCB which is protected from view by epoxy resin. The data is transmitted to an LCD on the front of the reader, however, and so it would be possible to extract this data while it was en-route to the LCD, and send it to the master microcontroller – the data lines on the PCB suggest that the data connection is made by 8-bit parallel signals (*Fig. 7*). This would mean that only the information described on the LCD would be measured; Pressing the "Mode" Button would sample a new data set, and the data that was just being measured would not be measured anymore. Some of the data presented on the UI is now redundant, given that the Flywheel spins a Physical Motor;

- Time could be calculated by measuring the voltage generated – so long as the output is above 0V, the Motor is spinning.
- Distance and speed could also be measured in this way – the relation between the voltage output and rpm of the Motor would be known, and so the faster the spin of the Motor, the higher the voltage.

The data lines are 8-bit parallel, and so it would be simple to solder 8 cables to each line, and send them to the master microcontroller where they could be used in other measurements. For example, the number of calories could be measured for the duration of the cycle, and then the efficiency of converting the chemical energy of calories into electrical energy could be calculated.

Fig. 6 **Pressing the Mode Button steps through each data set. I would like to make as few modifications as possible to this unit, as the space within the unit is quite tight, and so it would be very difficult to fit additional circuitry in here. The Master Microcontroller and it's circuitry would be better suited in another box somewhere else**

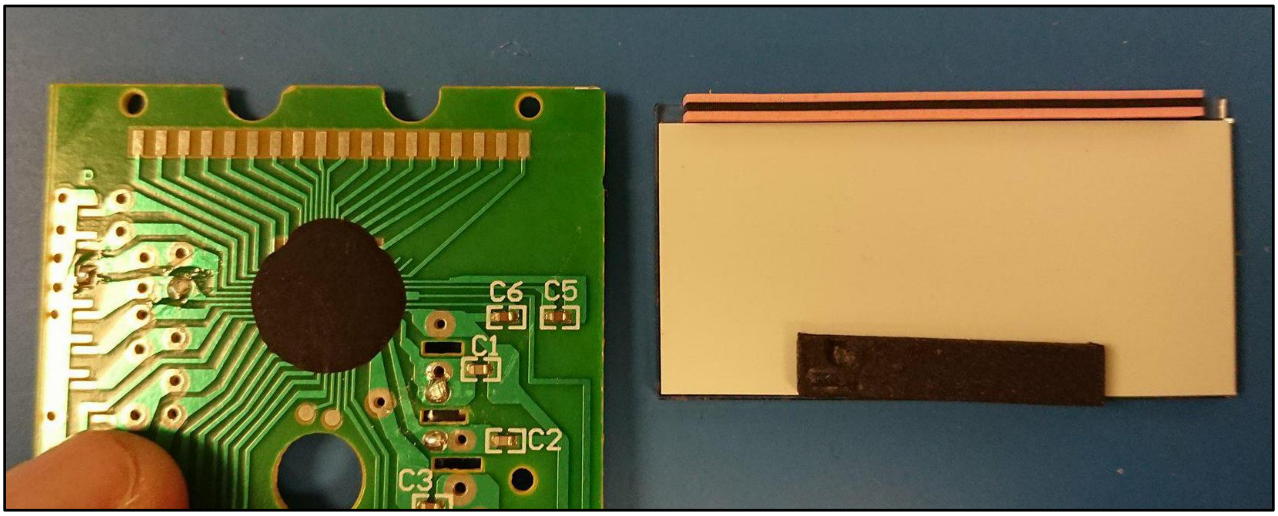

Fig. 7 **The data is probably transmitted to the LCD as an 8-bit signal. The other connections would likely be: 4 for Power, 2 for the Backlight, 3 for Enable Signals, and 1 Spare**

The Bike UI (*shown in Figure 6*) uses AAA batteries to power the LCD and other supporting systems. As the Master Microcontroller will likely be located far away from this unit, it would be sensible to keep the AAA batteries as the UI power supply, so that it can continue to function independently. On a similar note, the Master Microcontroller will need a constant power supply to function. Though the exercise bike does have rudimentary electrical storage (*the Flywheel keeps spinning for a few seconds after the rider has stopped pedalling thereby turning the Motor and generating electricity*), the Microcontroller would need to be running for the duration of the workshop. In this case, it would be better to power the Microcontroller by a set of batteries; these could be AAA, AA or 9V PP3 (*Table 1*) (*there are other battery types that would likely have a better capacity in mAh, but would likely be more expensive*). If the batteries were rechargeable, they could be recharged by the bike Motor – as the Microcontroller would draw so little current to operate, the Power drain on the Motor needed to charge the batteries would be negligible, but could be done so intermittently as to not waste current on fully-charged batteries.

Battery Type	Nominal Voltage (*V*)	Capacity (*mAh*)
AAA [2].	1.5	~550
AA [3].	1.5	~1330
9V PP3 [4].	9	~375

Table 1 **The AA battery has the best capacity of the 3 battery types. All rechargeable batteries have a lifespan of around 500 recharges, so this battery type would only need to be recharged once in the workshop, and then be unconnected from the recharge supply. Also, their voltages can be increased by placing the batteries in series – two AAs would have a combined voltage of 3V, but still keep the same capacity as if it were on its own**

Acknowledgement *– The capacities for the batteries in Table 1 were sourced from Wikipedia [2, 3, 4] and the mean of the capacities were of the rechargeable battery types were taken – though these may differ in real life, the AA is still the superior battery type across the board.*

The Microcontroller selection for use as the master device is subject to the following requirements:

- Power Demand – a Microcontroller requiring only a low-current power supply is mandatory for this project, as it is required to operate from AA batteries.
- I/O Ports – The Microcontroller will probably require a large number of ports. If the data is transmitted to a Mobile Phone(s) or a Laptop(s), the majority of the UI would be shown on that external device, meaning the microcontroller would not need so many ports. It might be useful to represent some data locally to the rider however, on an LCD or/and some LEDs, so at least 2 for LEDs, and those same 2 pins for the LCD for I2C.
- Connectivity – The Microcontroller needs a minimum of USB connectivity to be able to communicate to external devices. Bluetooth, WiFi or similar would be a bonus.
- Ease of Use – The Microcontroller needs to be easy to use and understand. If this project were to be taken up or maintained by personnel not sufficiently familiar with Electronics, the Microcontroller must have a wealth of online support to assist with necessary work.
- Relevance – As the proposed solution is meant for a STEM workshop, it would be irrelevant to use a Microcontroller that is not actively used by the Public Engagement group of STFC. An FPGA or an STMicroelectronics device would be the best chip to use for this purpose, but a BBC Micro:bit or Arduino Uno/Mega would be more in-line with what the target audience were familiar with.

With the above points in mind, the selection can be narrowed down to 3 possible choices:

- Raspberry Pi Zero W
- Arduino Uno
- BBC Micro:bit

2.2.1 Raspberry Pi (Zero W)

The Raspberry Pi (Zero W) is the newest iteration of the low-power line of Raspberry Pis, being released in Feb 2017 (*Fig. 8*). The main attractive features of the Zero W include 802.11n Wireless communications as well as Bluetooth 4.1 (*as well as low-power Bluetooth*). The Zero W also contains 17 GPIOs, meaning that an LCD and chain of LEDs can easily be attached without worry of running out of ports – more peripherals could be added without having to rethink design choices. The major advantage that the Zero W holds over the Arduino Uno and BBC Micro:bit is the price; with a start price of £11.66 per unit (*as of **01/06/2018** – from Pimoroni Website*), other Microcontrollers of similar power and performance will struggle to beat the device on cost effectiveness. The Zero W has 4 mounting holes on at each corner, making it very easy to mount to a PCB or housing.

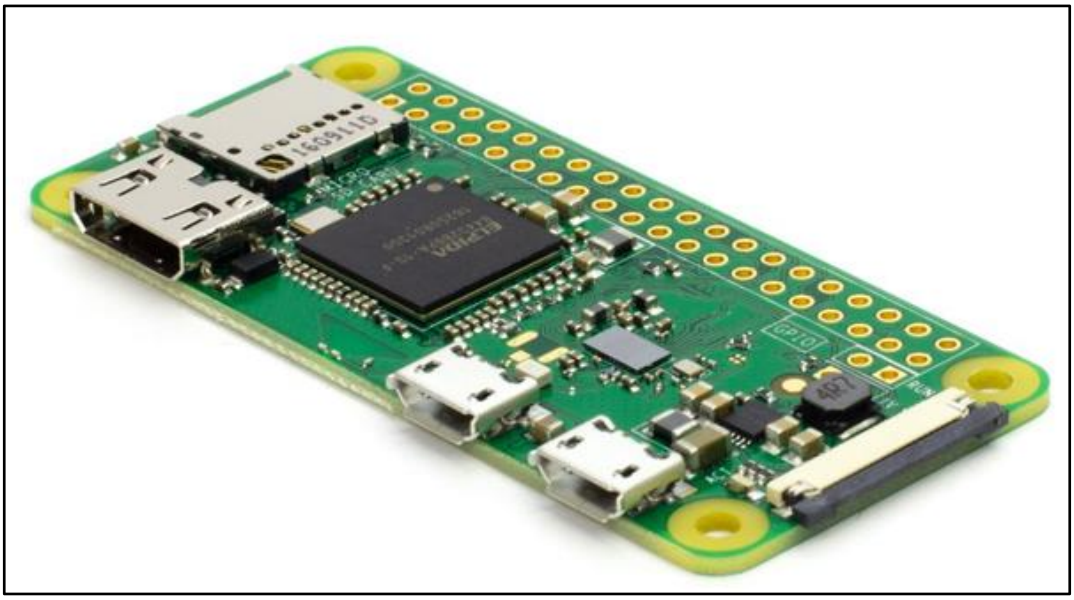

Fig. 8 **Raspberry Pi Zero W. Note that the Zero W requires a Micro SD card with an Image loaded to work. Micro SD cards are inexpensive, and means the Zero W can work independently from a PC tether**

2.2.2 Arduino Uno

The Arduino Uno has been the mainstay of hobbyists for the past decade as it is a very easy tool to use and build projects around. Now on the 3rd revision (*Fig. 9*), the Uno offers a vast suite of connectivity options, including 14 Digital I/O pins, 6 of which can be programmed to provide PWM Output (*which could be useful for controlling LEDs*). As the Uno is well known in the engineering community, there's a very wide range of online documentation and assistance meaning that maintenance and repairs could be done easily by anyone of any technical ability. The major disadvantage that the Uno (*and for that matter, all boards that are offered by Arduino*) is two-fold; the basic Uno board is expensive, at £22 (*as of **01/06/2018** – from Pimoroni Website*), and the Uno has no on-board communication modules. These can be bought extra as shields that plug directly into the I/Os as a shield, but these are expensive too – the WiFi shield is 69 Euros BEFORE tax and shipping (*as of **01/06/2018** – from Arduino Website*). The Uno does however have mounting holes built into the PCB, making it easy to connect to a box, or similar containment housing.

Fig. 9 **Arduino Uno Rev 3. Though the Uno lacks on-board Bluetooth and Wi-Fi modules, the placement of the I/Os makes it very easy to connect to PCBs below or above the Uno. The main advantage of the Uno lies in its massive online support making projects easy to**

2.2.3 BBC Micro:bit

The Micro:bit is a Microcontroller (*Fig. 10*) with the specific intention of encouraging programming to children of all ages (*though primarily aimed at children around year 7*). The Micro:bit, as it has designed to be used as simply as possible, has a very easy programming interface, meaning that getting projects to work is very straight-forward for people of all technical abilities. The Micro:bit has a major advantage over the Arduino range of devices in that is has on-board Bluetooth capabilities (*although not WiFi connectivity like the Zero W*), while still having a large number of I/Os – 18 Digital IOs, of which 6 can be Analogue inputs. The Micro:bit also supports off-board communication protocols, including I2C and SPI, meaning that it can be easily interfaced with any kind of control circuitry that may need to be used in the design of the proposed system. One slight downside of the device is that the IOs use edge connections – these are rectangular surface-mounted contacts that allow crocodile clips to be connected to the PCB, rather than 2.54mm headers. This slight design flaw means that the edge connector breakout board accessory must be purchased to allow standard header connectivity. Though this increases the overall price slightly, the total price is still very affordable **-** £21 (*as of **01/06/2018** – from Pimoroni Website*). The edge connector breakout board has the added benefit that it includes mounting holes that allow the entire unit to be mounted to a housing or box. The edge connector can connect to the Micro:bit either way round, so the buttons and 5x5 LED Matrix on the Micro:bit can face outwards and be used if necessary.

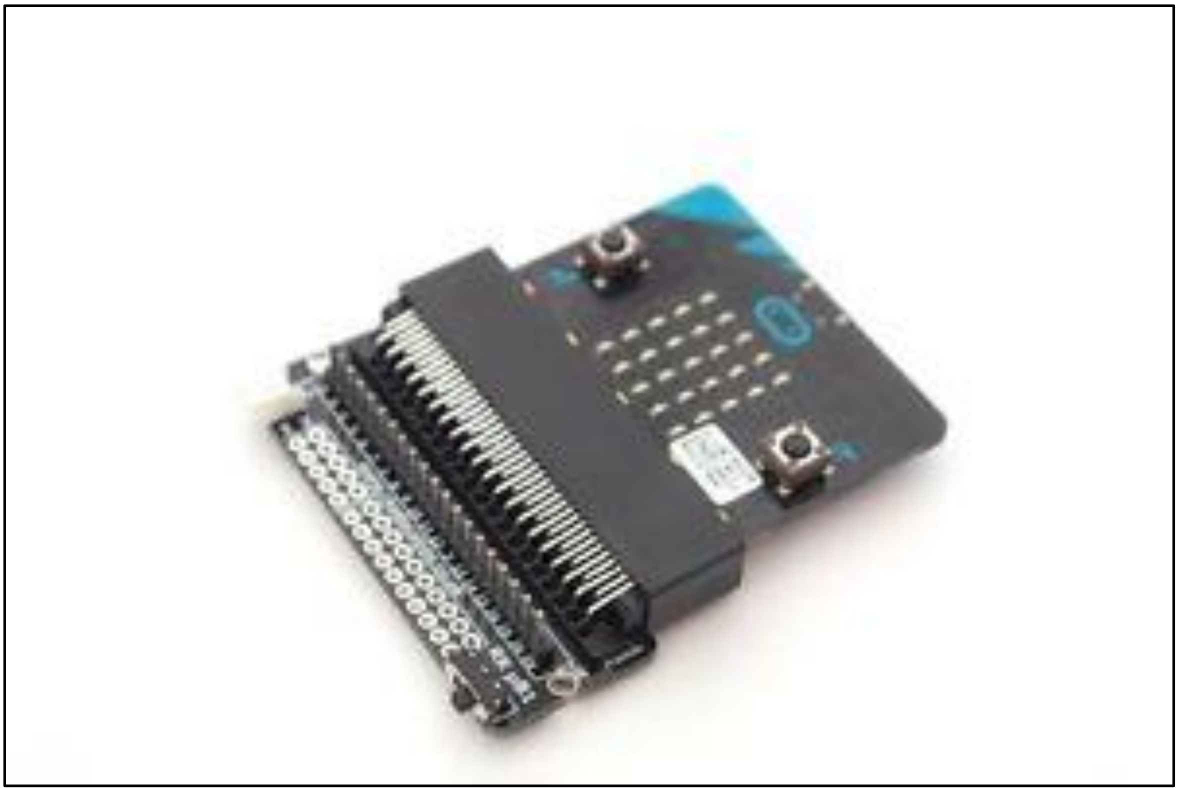

Fig. 10 **BBC Micro:bit. The inclusion of two user-defined push buttons on the device makes switching between options on a device such as an LCD very useful. Also, the on-board Bluetooth controller will allow the Micro:bit to communicate with external devices such as Mobile phones or Laptops**

2.2.4 Summary of Options

Each of the choices presented above suit their audience strongly, however, their strengths and weaknesses become apparent when considering their inclusion in an application such as the Exercise Bike Generator demonstrator. Though cost is a key consideration, the determining factor in the decision of which controller to use should lie in its suitability for the application and how it will engage with the target audience. Below (*Table 2*) shows each of the proposed controllers' strengths and weaknesses, and how they compare with one another in the specified fields.

Having considered all the specified options as shown for each microcontroller, the BBC Micro:bit will be chosen as the Master Microcontroller for this project.

	Raspberry Pi Zero W	Arduino Uno	BBC Micro:bit
Bluetooth Connectivity	✓	×	✓
WiFi Connectivity	✓	×	×
I/O Ports	17	14	18
Operating Voltage	5V	5V	3V
Current Draw (*in standard operation*)	100mA – 350mA max	80mA – 500mA max	120mA max
Cost per Unit	~ £12	~ £22	~ £21 (*with breakout*)
Ease of Use (*Relatively*)	Hard	Medium	Easy
Impact on Audience	Low	Medium	High

Table 2 **Bluetooth and Wi-Fi connectivity is important for communicating with external devices, with a high number of I/Os enables the device to communicate with circuitry required for the system to function. A low current draw is useful, as it allows the proposed design to operate for as long as possible between charges of the battery. The Impact and Ease of Use fields have been designed in line with audience interaction, and how it will be received by the targeted people**

2.3 Technical Requirements – Power Electronics

The primary role of the Microcontroller is to measure the power generated by the Motor and relay it to an external device, like a phone or a laptop where it can be displayed to the user or logged into a database, or the data can be shown locally on a device such as an LCD for use in conjunction with powering of attached devices like phones, power banks or other household appliances. To measure the power, the voltage and current must be read; the Power can then be calculated from the equation, P = IV. For each device connected to the power supply line, the current draw will differ, depending on the device that is connected. For example, a low-end mobile phone may require 500mA at 5V, meaning a 2.5W dependency, however, a high-end iPhone may require 1000mA at 5V, meaning 10W will be dissipated instead. To know what is being drawn by what, the current flowing in each device must be measured. As the proposed design has 4 output ports for charging, the system will require at least 4 current measuring circuits – one for each device.

As the connected devices for charging are likely to be driven via USB ports (*Devices such as Mobile Phones. Larger devices such as laptops are too ambitious as their power supplies are highly complex and require a very large amount of power, much more than the proposed design could possibly generate, and often at higher voltages*), the output voltage will be within the range of 4.75V to 5.25V. This can be measured simultaneously across all the devices if they are connected in parallel – the voltage across each device will be 5V, but the current will split depending on what device is connected. This segment of the circuit will consist of 4 ports to connect devices, a potential divider to measure the voltage across these devices, and a branch leading off to charge the AA batteries supplying the Microcontroller. Each of these components will have a current monitor to measure how much current is drawn in each section, apart from the potential divider which will be designed to draw as little current as possible (*Fig. 11*).

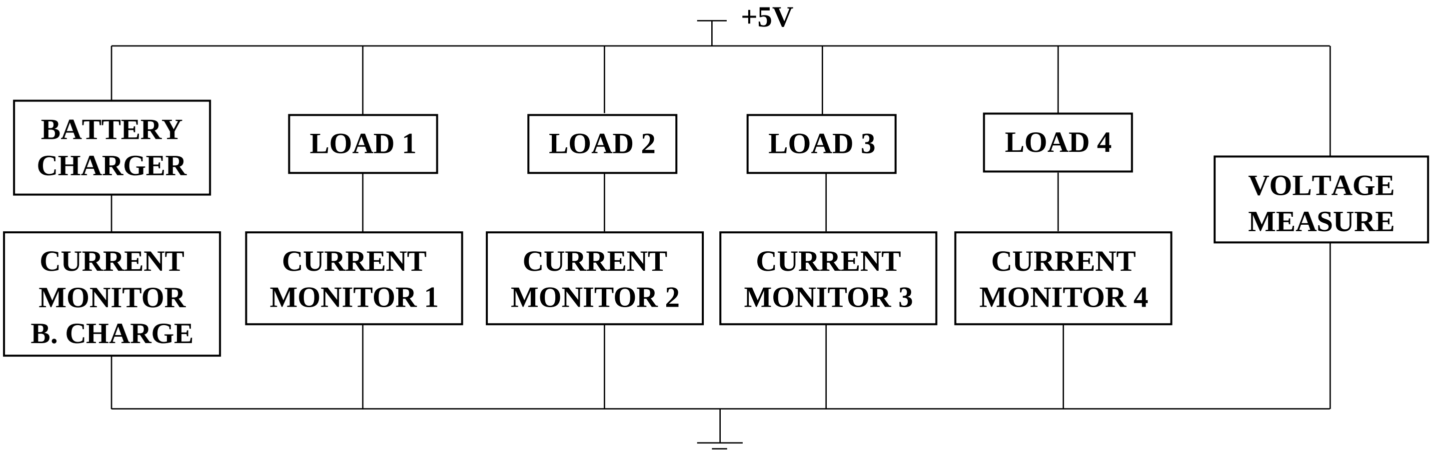

Fig. 11 **Each LOAD will likely be a USB Type-A Port charging a mobile phone or something similar – these will require 5V and around 500mA. Each current monitor will draw only a few mA and so will have little impact on circuit efficiency**

As one intended purpose of the proposed design is to measure efficiency (*or rather, inefficiency*) in the generation chain, the current will be measured in several other points in the circuit. The circuit will require a DC/DC Converter to change the voltage of the DC Motor (*most likely to be a* ***maximum of +12V***) to the intended circuit voltage of +5V. Therefore, a current monitor will be located before and after the converter to monitor the current in each stage. Additionally, another potential divider will be located before the converter to measure the actual voltage being produced by the Motor. This will allow the Microcontroller to measure the realistic efficiency of the converter, as oppose to the efficiency stated on the datasheet which will no doubt be inaccurate.

As stated above, the charger circuit could be used to charge the batteries used to power the Microcontroller circuit. As the some of the power would be wasted when the batteries were fully charged (*and the connected devices would suffer a drop in current as some would now be re-directed to the Microcontroller circuit*), the connection between the charger circuit and the Microcontroller will be made with a switch and relay. The benefit of using a relay rather than a mechanical switch is that the connection can be made electronically, removing the user from directly making the connection, thereby promoting user safety. Also, as the connection is made with an electro-magnet, several connections can be made at the same time, allowing a user-feedback system to denote that the connection has been made successfully without drawing current from the power supply line (*Fig. 12, 13*).

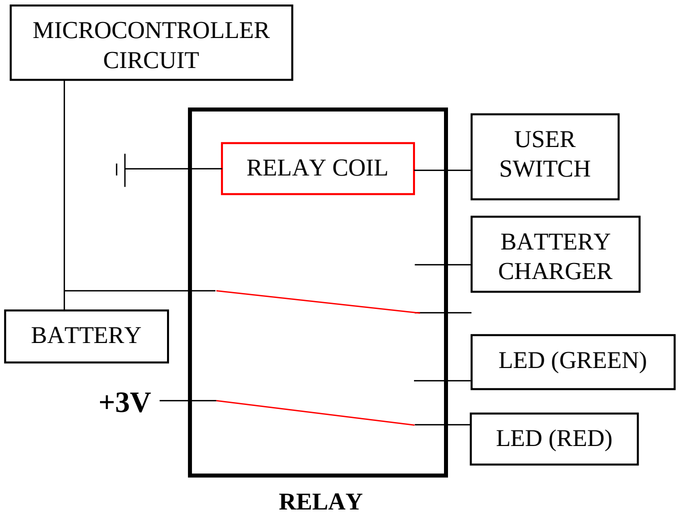

Fig. 12 **When the Relay is off and the switch is in the off position, the Battery Charger will be disconnected, and an LED will shine red to show that it is disconnected. The Microcontroller circuit will run off the Battery**

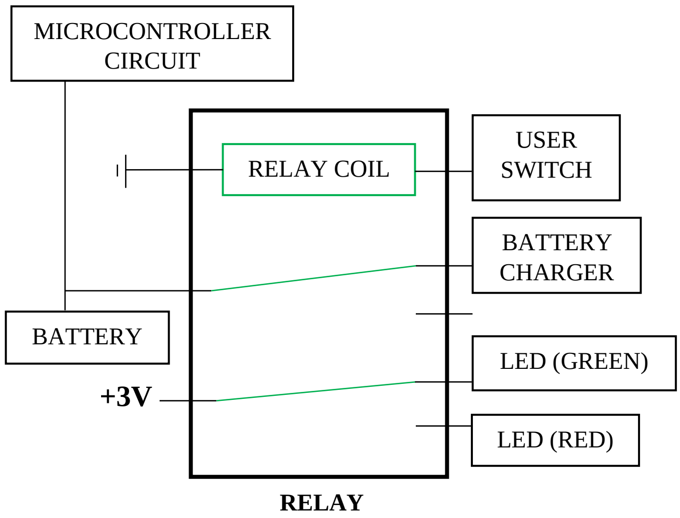

Fig. 13 **When the Relay is on and the switch is in the on position, the Battery Charger will be connected, and an LED will shine green to show that it is connected. The Microcontroller circuit will run off both the Battery and the Battery Charger – the resultant excess current will charge the Battery**

All of these components will draw some current, though the total current draw will be as low as possible, so as to ensure the maximum possible power is available for the devices connected. If it is assumed the DC/DC converters and LDOs (*Low Drop Out Voltage Regulators*), have a fairly good efficiency (*in the range of 80 – 90% efficiency, particularly at these voltages*), the main losses, other than in the motor, will be power converted to waste heat, primarily in the resistors of the current monitors and potential dividers, microcontroller (and in the person doing the pedalling!). Minimisation of these losses will be a priority while designing these circuits. The losses in potential dividers can be reduced by having very large resistances, as current (*and power*) decreases as resistance increases (*Math. 2*).

$$I = \frac{V}{R}, where\ V = Voltage\ Drop\ across\ the\ Resistor$$

The losses in Current Monitors can be reduced by having very small resistances, as voltage drop decreases as resistance decreases (*Math 3*). One note however, surface-mount resistors with very low resistances often have low power ratings (*< 50mW*). As resistors heat up from power dissipation, their voltage drop increases, and so the power dissipation increases also. This can be protected against by using resistors with extremely low starting resistances (*hence dissipation ~ 0mΩ*).

$$V = IR, where\ V = Voltage\ Drop\ across\ the\ Resistor$$

With the above requirements in mind, the final power circuit can be designed, and the approximate circuit is shown below (*Fig. 14*). ***Note; each measurement stage and each device charging stage connect to an ADC to measure their output signal. These signals feed to the Microcontroller and are relayed to a laptop and LCD to show important circuit information.***

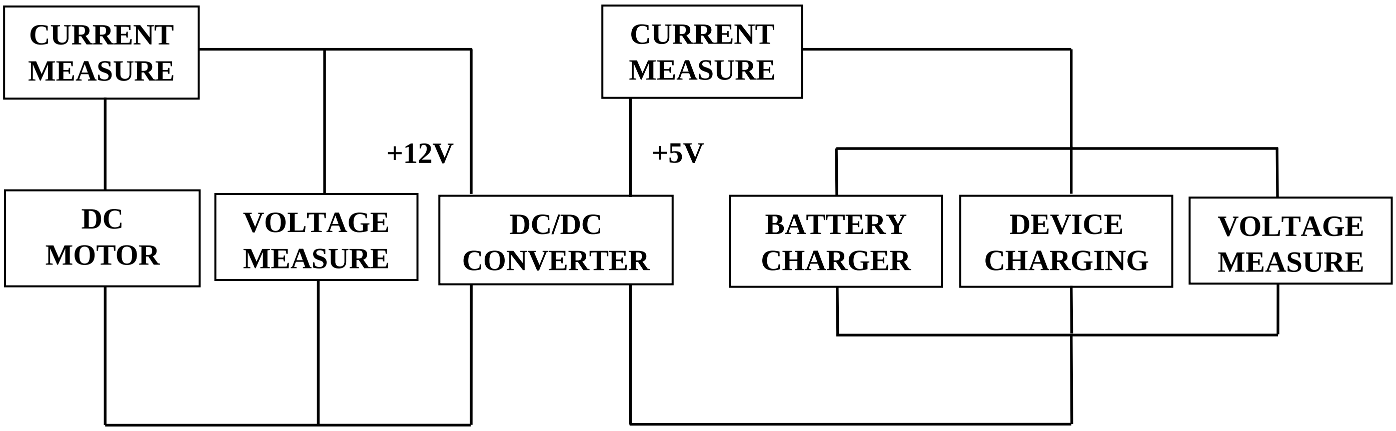

Fig. 14 **The voltage in the DC Motor stage is +12V, while the voltage in the Devices stage is +5V. The Devices in the +5V stage will only draw what current is required, and so overcurrent will not be an issue**

2.4 Technical Requirements – System Electronics

The circuit for the Microcontroller is very straight forward in its design, as the role of the Microcontroller in the proposed design is to monitor the current and voltage levels of the Power Circuit, and to display these data in meaningful readouts, be it LCDs and LEDs to graphical UIs on Mobile Phones and Laptops. The inputs and outputs of the Microcontroller are;

- The ADC measuring the voltage and current levels in the Power Circuit,
- An LCD to show Power Circuit Device power consumption, Power Circuit efficiencies, and Microcontroller circuit current draw,
- An I2C module controlling LEDs and the LCD to provide instant power feedback to the rider (*more on this in a moment*),
- The Push-Button located on the Micro:bit to switch between menus on the LCD,
- The Bluetooth wireless output to provide real-time data to a Mobile Phone or similar interface.

The Micro:bit operates on 3V, and so the components chosen to be used in the Microcontroller circuit will also run off 3V. Additionally, as AA batteries work at 1.5V, 4 batteries will be used – two pairs of batteries in serial connected in parallel will give a 3V output at 2660mAh – more than enough to run the system for a whole workshop without need of recharge.

The LCD will be ***at least*** a 16x2 display, and will be positioned between the two sets of Device Charging outputs of the Power Circuit – this will enable the user to switch between a set of menus that will show the power consumption of the top two outputs, and then the bottom two outputs. If the Outputs for charging devices are indeed USB Type-A Ports, the setup will look similar to that below (*Fig. 15*).

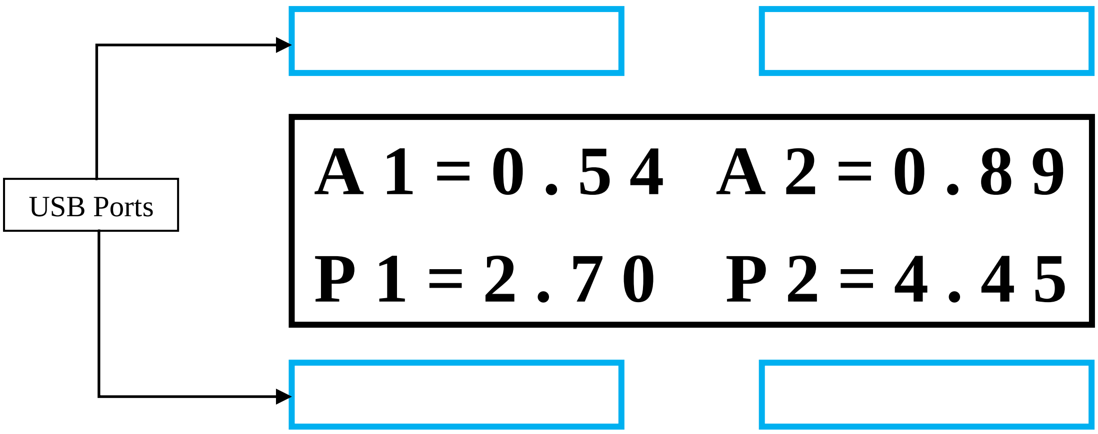

Fig. 15 **As the LCD is only 16 characters wide, the data that can be shown is limited. "A1" could stand for "Current used by Device 1", while "P1" could mean "Power consumed by Device 1". Pressing the Push-Button on-board the Micro:bit could switch the readout to show consumptions of Devices 3 and 4, while further presses could show total circuit efficiency etc. If an I2C LCD is used instead, the LCD could have a display size of up to 40x4, meaning much more information could be shown –** ***see below***

Device 1 => I = 0.54mA ___ P = 2.70W

Device 2 => I = 0.89mA ___ P = 4.45W

Device 3 => I = 0.00mA ___ P = 0.00W

Device 4 => I = 0.72mA ___ P = 3.95W

The LCD Could be positioned at 45 degrees so the viewer would not need to bend over to read the display. The above is an example of what could be written on a 40x4 LCD

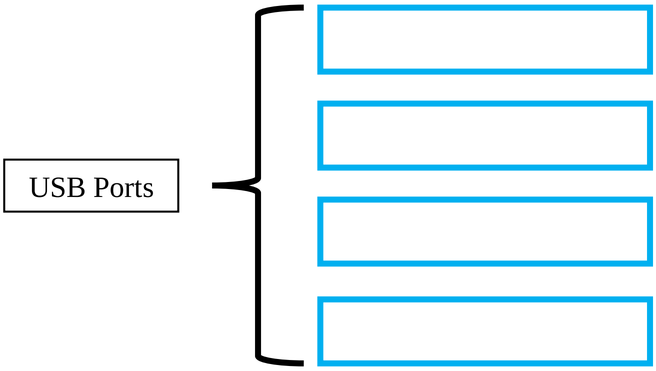

Fig. 15.1 **As the LCD is now controlled by I2C instead of GPIOs, the display size can be increased up to 40x4. The benefit is immediately clear – all 4 USB port consumption data can be shown simultaneously, and be shown descriptively rather as oppose to abstractively like Figure 15. This is the preferred implementation for the proposed design.**

As stated before, the bike UI could be tapped to provide useful feedback to the user while riding the bike. While already showing total distance, time, speed etc., the data that is stored in the internal microcontroller on the UI could be used to calculate useful data in the Micro:bit. The data on the bike UI is presented on an LCD, which is sent from the microcontroller by an 8-bit data line. These 8-bits could be serialised into an analogue signal, sampled in an ADC and given a reference voltage level (*Fig. 16*). If this were to be done with the speed, the optimal power and torque curve of the motor could be calculated, and the rider could track exactly what speed they must pedal to get the optimal power out of the system.

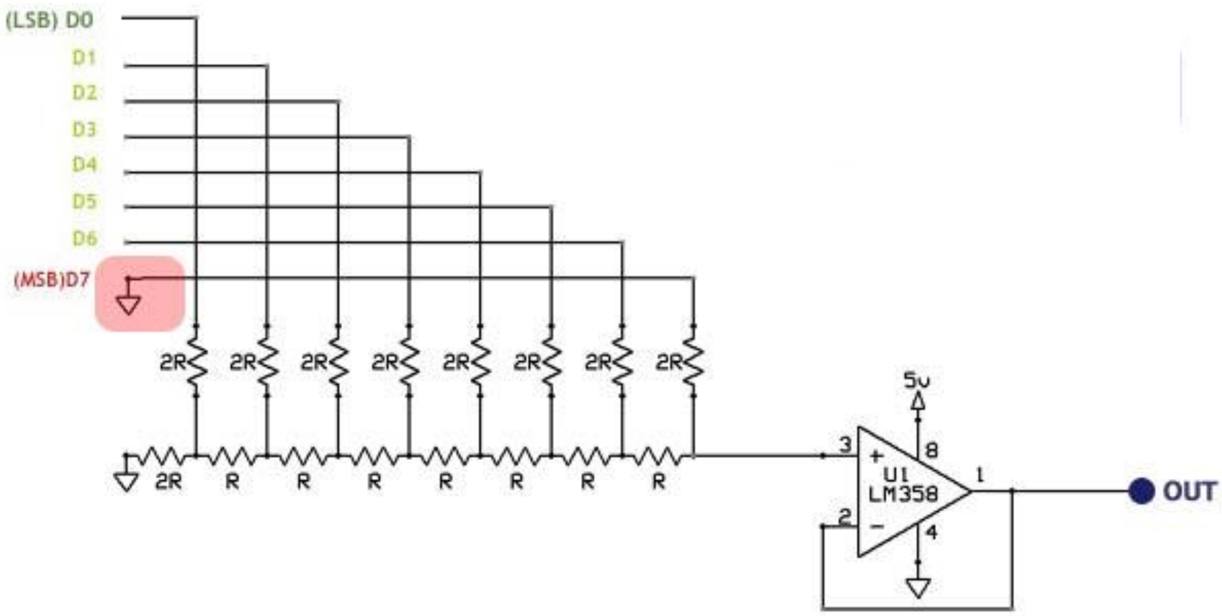

Fig. 16 **Though the above is an approximation of the intended circuit, it shows that the signal can be easily changed into a single-ended signal. As the ADC has many input lines available, "OUT" could be sampled by one of the inputs, and processed by the Micro:bit**

Once this speed data had been processed, the Micro:bit could calculate the optimal power output of the DC Motor, and at what speed the motor should spin to get this output. This would be done by sampling the current and voltage outputs of the +12V stage of the Power Circuit, and tracking where they rose, peaked and fell. This data could be shown by;

- Showing the data in a menu in the LCD. This would mean the LCD had to be close to the rider so they could see it uninterrupted, which would mean the whole unit would need to be mounted on the handle bars. This wouldn't really be viable as there isn't anywhere to attach the system to the frame,
- Showing the data graphically on a projector image – the data would be parsed to a laptop where the laptop could run a script and show the data in a much clearly labelled format. This could be difficult as the Bluetooth may not be able to send data quickly enough for this to be effective,
- Showing the data as a power band on a chain of LEDs mounted to the handle bars. This option might not be the simplest, but would certainly be the most effective, as the user would receive instant feedback with a refresh rate of tens of times a second. This LED chain could show red LEDs when in bad power, yellow in average and green in good power. It could also show when the rider was approaching the Motor's maximum spin speed, alerting them to slow down as soon as possible. This display would be similar to a Formula 1 steering wheel readout for when to change gear, and could be mounted in the same sort of way (*Fig. 17*).

Fig. 17 **The LED readout could begin as yellow and transition to green for optimal power output. The LEDs could shine red when approaching the maximum speed of the Motor, providing good safety feedback. As this would likely be driven by the Micro:bit's on-board I2C, the refresh rate of the LEDs would be far more than its Bluetooth communication capabilities**

The LEDs will be controlled by the Micro:bit's I2C module – as there aren't enough I/Os on the Micro:bit to control up to 15 LEDs, an I2C IO Expander will be used. As the LEDs provide feedback to the rider, the IO Expander could be at the top by the handle bars, or at the bottom with the rest of the circuit, with only the LEDs at the top (*a PCB might not need to be made if only LEDs are at the top*). If the IO Expander sits at the bottom, a signal line will need to be routed up to the LEDs, as well as a power line, meaning 16 cables. However, if the IO Expander is at the top, the I2C lines would need to be routed up to the top, and a bigger PCB might need to be made to accommodate the additional circuitry. I2C is a short range communication protocol, and so clock delays may cause mismatches in data sent and received. ***The best solution would be to have the IO Expander at the bottom and route signals lines up, thereby possibly avoiding the need of an extra PCB to mount the LEDs.***

The Micro:bit has an on-board Bluetooth LE Module that allows it to communicate with external devices. These devices will likely be Mobile Phones, though it could also communicate with Laptops if they have Bluetooth capabilities. If they don't, they would still be able to communicate with the Micro:bit via the USB Micro port on the top of the Micro:bit. The data sent to the external device will likely include:

- 8-bit data recovered from the bike's own Microcontroller, though this is most likely to be speed data as this is most useful to the proposed system
- Current and Voltage measurements taken throughout both the Power Circuit and Microcontroller Circuit to track efficiency and losses associated with the system

When this data reaches the paired device, the data will be presented to the user or to an audience where they'll be able to view a selection of the data at their own discretion. This will likely be shown within an app; the app could include past data, and so the audience could compete against one another to produce the most power, and analyse the data at the conclusion of the event, where they could view total power, peak power, average efficiency etc. The data could also be presented graphically to both the rider and audience to give real-time feedback in a more accessible format.

As all the sections of the Microcontroller Circuit have been discussed in depth, the Circuit Map can be designed (*Fig. 18*).

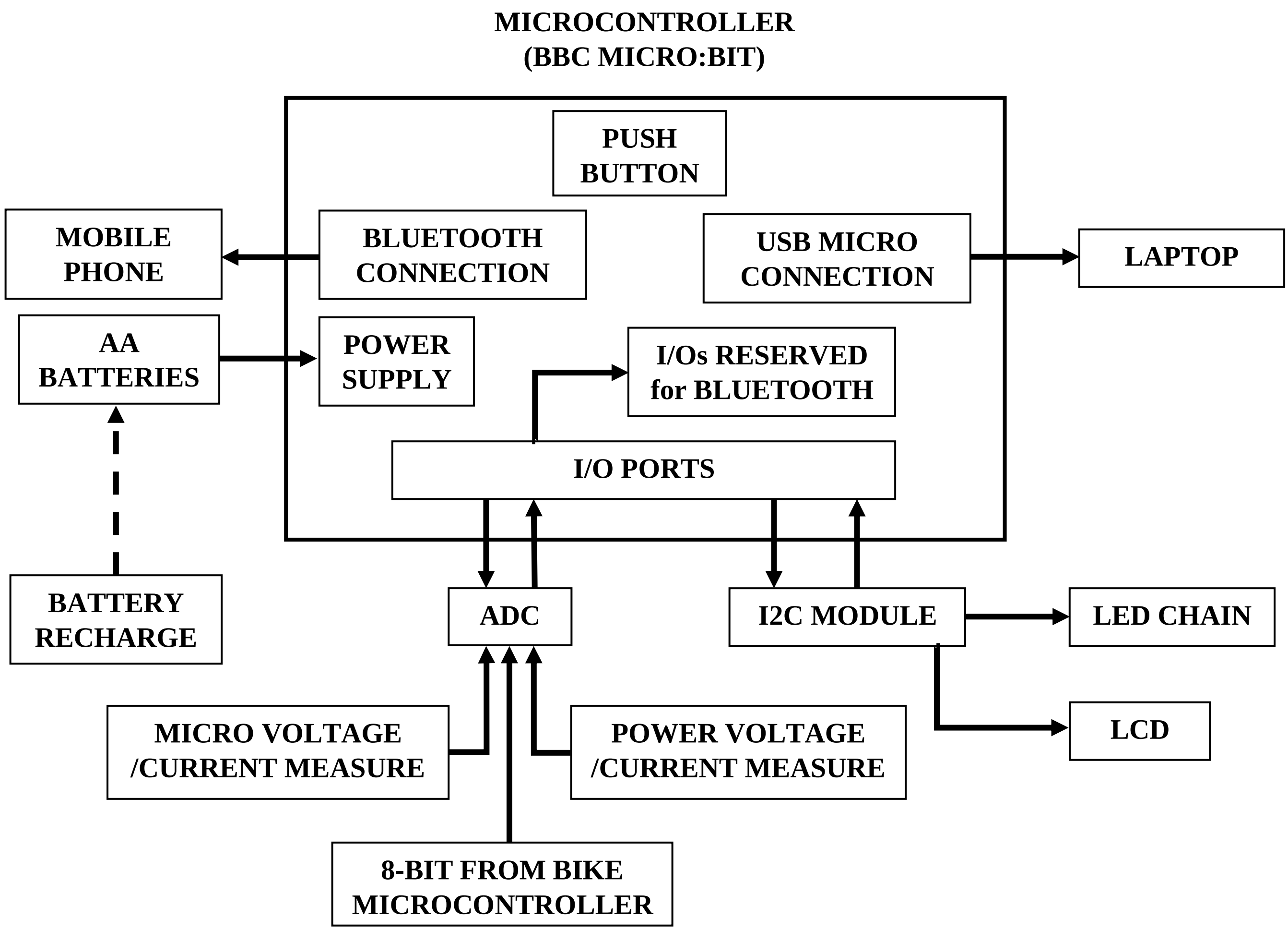

Fig. 18 **The components for connection have been chosen in such a way that the IO port usage is maximised without incurring challenges that are too difficult to overcome for a Micro:bit project. Though the circuit is complex, the Micro:bit is more than capable of driving the suite of components attached**

3. Proposed System Placement

Though the technical system has designed, the position of the system on the bike is yet to be established, or what the system enclosure will look like and where the ports, LCD, LEDs, Switches and Micro:bit will be located in the enclosure. Ergonomics must take precedent when designing this kind of enclosure, as the ease of the user interface will determine the success of the layout choice. With this in mind, it will be important to design the enclosure to be easy to use while somebody is riding the bike, as well as when they are not; meaning that it must be narrow enough to not impede cyclist's motion, while not being too narrow as to not be able insert devices easily or read the user interface. Also, it will be important to design the interface such that an observer is able to interact with the system while kneeling or crouching – the system is likely to be placed low to the ground, and so the user must not need to lie down or crane themselves to use the system.

Because the enclosure is most likely to be a plastic or polycarbonate box (*metals such as Aluminium would require machining by a specialist*), the enclosure would be cuboid-shaped. The benefits of this material and shape are threefold:

- The material is plastic or a plastic variant, so it would be easy to cut, or at least, easier to cut than metal. This would allow the system to be entirely built within the lab without external assistance
- The enclosure is shaped like a cuboid, so the PCB for the electronics need not be a strange shape, but rectangular. This would save on costs for PCB production
- The enclosure would be easy to mount to the bike – it could either attach to the handle bar stand or the saddle stand by means of cable ties/grip ties, or be mounted directly to the shell of the mechanism by means of screws

From the perspective of security, specifically in transportation and interaction, it would be much better if the enclosure were to be fixed to the bike somehow, so it couldn't wobble or flap when a user was interacting with it. As stated above, there are two possible positions (*Fig. 19*):

1). It could be mounted to the handle bar (**1**) or saddle stand (**2**), or,

2). It could be mounted to the front (**3**) or rear (**4**) of the shell of the mechanism (*there's nowhere on the side for it to be mounted, as the enclosure would impeded the motion of the pedals*)

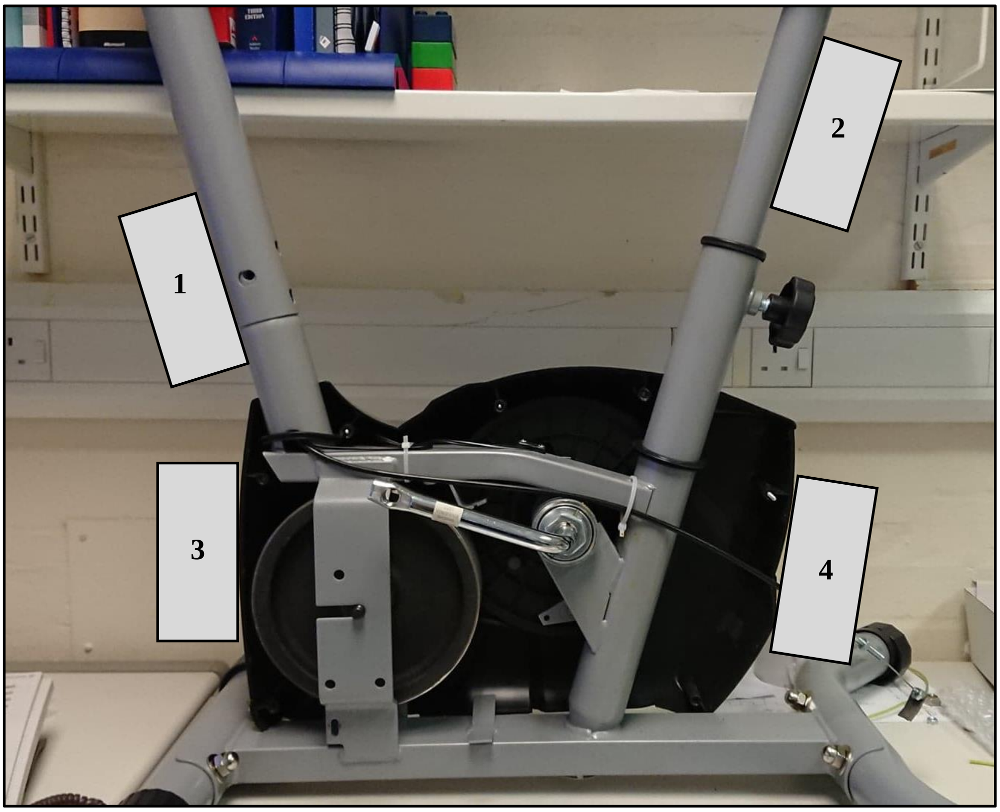

Fig. 19 **These are the only real connection points for the enclosure on the bike, as the handle bars simply don't have effective mounting points. The size of the boxes illustrated above are roughly the dimensions of what the box will be like in real life**

These placements are not without their flaws, though placing the enclosure in some places will be better than other places. These will be discussed below; their numerical assignments are identical to those given in *Fig. 18*.

(**1**). This will be the best position in terms of user comfort – as the enclosure is furthest from the floor (*on the front side at least*) it may not require kneeling in order to read the display, or to interact with the ports. It also has the benefit that the stand is slanted slightly away from the bike – if the LCD were to be mounted on top of the enclosure, the LCD could be placed flush with the side of the enclosure while still pointed at an angle towards the user. The downsides, however, are quite profound; as the system is presented to enable riders of any height to participate, the rider will inevitably need to change the seat height, thereby changing the action movement of their knees. If the enclosure were to be placed in position (**1**), the user's knees could very easily clip the edges of the enclosure, damaging the mounts or the box itself. Also, if the box were to be mounted with screws or bolts, additional holes would need to be drilled into the stand.

(**2**). This will remove the danger of knees bashing the enclosure, as no-one will cycle backwards. It will also have the benefit of being adjustable, and so the box could move up and down to enable audience of different posture requirements ease of use in viewing of the LCD and interaction of the ports. Although an advantage , this also brings a significant disadvantage – the saddle could not be any lower than about 20cm from the saddle adjustment wheel, as the enclosure would impede the movement of the saddle. Also, riders may feel uncomfortable having people crowd around behind them looking down while they are possibly standing up cycling to generate peak power. **On the basis of possible discomfort and/or harassment, this option is unviable.**

(**3**). The obvious benefit of this arrangement is that the box is far away from the rider, from both their legs and their body, and so this setup would give the rider the most comfort out of the selection (*the rider would also be able to see what the observer is doing, which would add comfort to the rider*). This option would also place everyone in a safer environment as everyone can see what everyone else is doing. Also, as the box is close to the ground, the USB cables charging Mobile Phones would be able to reach the ground – cables may be too short if the box were placed in option (**1**) or (**2**), unless they were long cables. The only difficulty would be in placing the LCD in such a position that would be easy to view; if the LCD were facing outwards, the pitch would be too low, and so observers would have to crouch very low to see the readout. If the LCD were facing upwards, the same problem may arise, though to a lesser extent. The LCD could be placed at an angle at the edge of the enclosure however, meaning people could view the display, possibly from standing up.

(**4**). This has the same advantages and disadvantages as option (**3**), in that it is placed far away from the rider's legs, and so there'll be little risk of contact with the box. Also, as the box is slanted slightly, the LCD could be placed flush with the top of the enclosure, making it easier to position. It also has the disadvantages of option (**2**), in that the rider could feel uncomfortable with people behind them looking down, particularly as the rider would not be able to see them.

From the options above, the most viable, agreeable and safest option would be option (**3**).

3.1 Proposed System Component Placement

The position of the USB Ports, LCD, switches and Micro:bit depends entirely on how the components will be placed for the circuit inside the enclosure. The best option by far would be to place the components on a PCB; a circuit on veroboard would be cheaper, as a PCB does not need to be made, but components could **only** be through-hole, and so the circuit would become enormous, and the components may only be able to be mounted on one side of the board – a veroboard circuit would be at least 3 times larger than a PCB circuit. It would also look unprofessional, given that veroboard is a hobbyist's approach, and the quality would be lacking in what would be expected from a project from STFC. That being said, a PCB need not be expensive – if the PCB were made to be 2-layered, and entirely designed and placed in-house, the only costs incurred would be production of the PCB, delivery and tax, which could be reduced by good PCB design. If the PCB were 2-layered, and approximately 80x100mm, the costs of 2 PCBs would be in the realm of £45 (*Fig. 20*).

As a rough estimate for location of component placement (*both on the PCB and how they protrude from the surface of the enclosure*), it is likely that the AA batteries would be placed at the bottom, the Micro:bit would be placed at the very top, the LCD would be at 45 degrees pointing up and outwards, and the USB ports would be arranged in a vertical line from top to bottom on the right hand side. The Power Circuit may need to be isolated from the rest of the circuit, and so would require a separate GND connection to the Microcontroller GND. As the PCB would be 2-layered, it would be best to have this isolated GND in a corner, as to have all the necessary components in one place. Also, as the LCD's connections would connect to the PCB via ribbon cable, it is likely that the connections to the PCB will be made on the right hand side (*as looking from the front*). These connections would require quite a lot of space, so the Microcontroller GND may as well be on the right, and the Power GND on the left. This is shown below (*Fig. 21*). ***Note; Fig. 20 shows the PCB layout – the enclosure will be bigger as the AA batteries will not go on the PCB.***

Fig. 20 **This is a price estimate from the Czech PCB producer *Printed.cz*. Even at the very best quality of PCB, the price is only around £45. This could be reduced to around £40 if the surface were not au-galvanic, and E-tests were not performed, though this would pose the risk of the boards not working properly. The PCBs produced at CERN are made by Printed.cz, so they're definitely a safe company!**

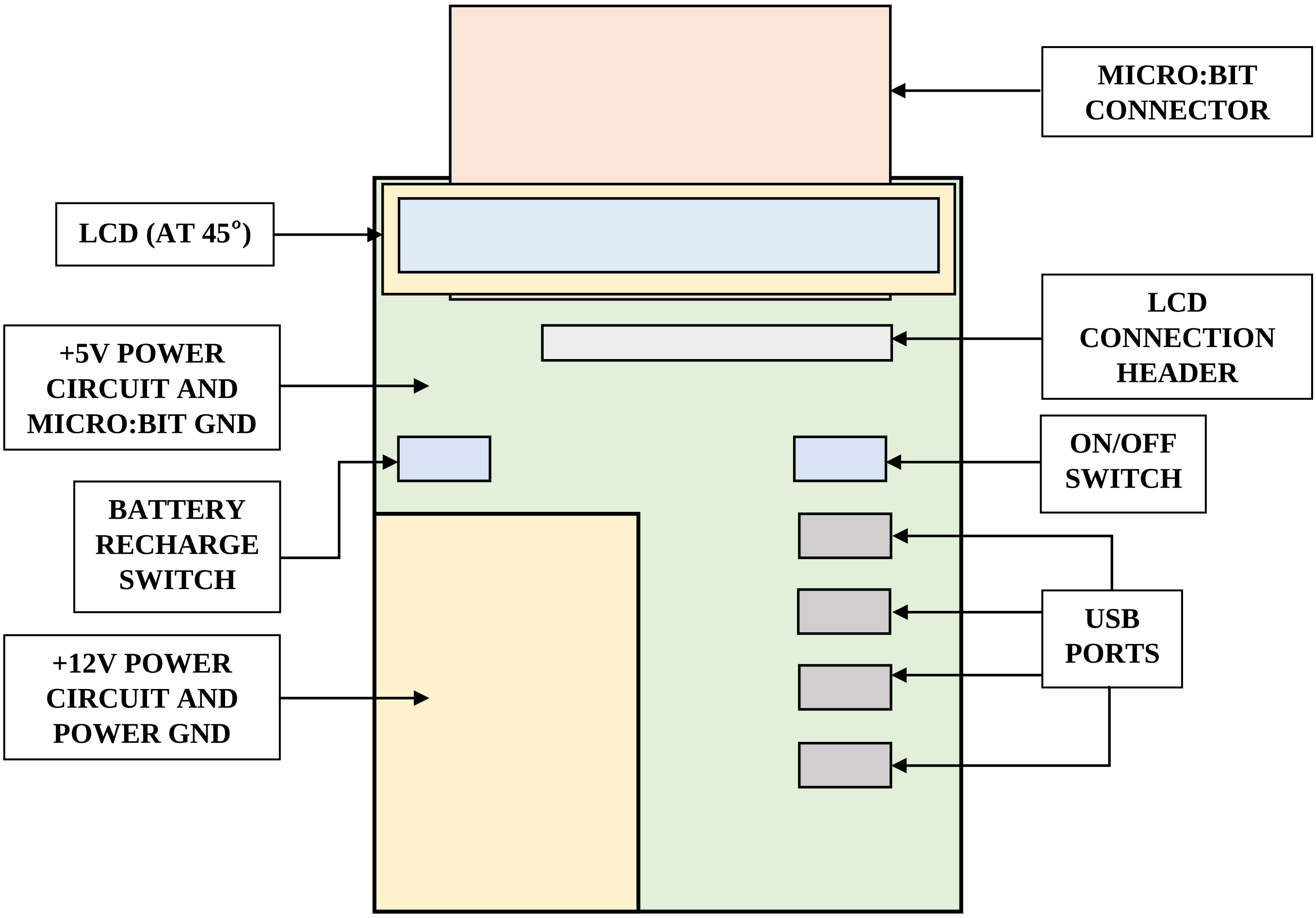

Fig. 21 **This is an approximate layout for the PCB. The actual PCB could well be smaller than this, saving on production costs, though the above illustration doesn't contain the ICs and other components that will be required**

I've purposefully left this section vague, as the options for implementation are limitless – as the data acquired by the Micro:bit will be sent to a device like a Mobile Phone or Laptop, the data will most likely be presented in the form of an app or GUI. This could be written in Python for a computer or Java for a Mobile Phone (*I don't want to get too deeply involved with writing apps, as there are so many different versions of Android and iOS available, that making an app to present this data and be compatible correctly across all devices could easily become a project in itself*). A possible GUI for a laptop could be a representation of a power or torque curve, and whereabouts the rider is currently producing their power on that curve, based on the power data that is being sent over the Bluetooth Connection (*or micro USB line*) (*Fig. 22*). It could also be used in talks to show the efficiency, power, current and voltage data to a large audience, especially if the laptop were connected to a projector. Though the data coming across would no doubt be slower than the LEDs or LCD, even average data would be useful. The GUI could also show a leader board of who has produced the most power during the activity, or the total power that has been produced collectively – the possibilities really are endless. Additionally, as this would be written for one of STFC's own Laptops, the cost for doing so would effectively be nil, as all the equipment is already owned. The only cost would come out of working hours (*for the purpose of this project, time and working hours are ignored in terms of cost*).

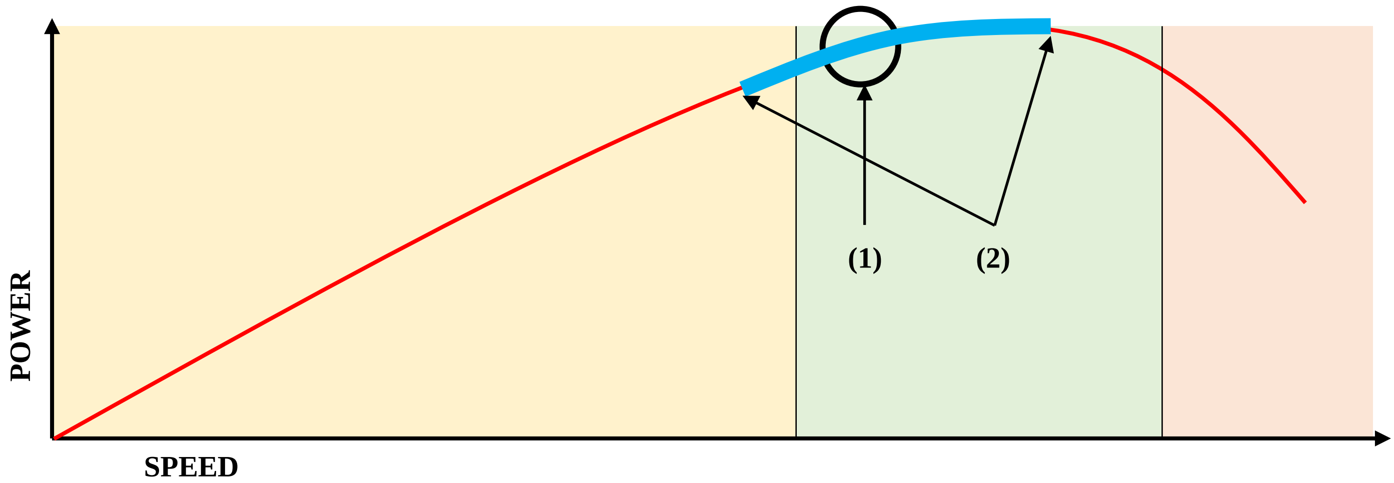

Fig. 22 **The above is a representation of what could be presented on a Laptop – this shows a power curve; the DC Motor likely follows a similar characteristic. An indicator (1) could show the rider and the audience where the current power output is, and where the optimal power output is. At the conclusion of the ride, the data could be collated and an average "sweep" could be shown to represent the power band produced over the course of the ride (2). Like the LEDs, the yellow region could represent low power, green represent good power, and red represent danger**

5. Final Specification based on Proposed Concepts

With the changes suggested above in mind, the following specification can be formed for the proposed design:

- The Proposed Design will make use of the exercise bikes purchased by the Public Engagement team in Mar 2017
- The Proposed Design will not have any moving parts outside of the plastic shell of the exercise bike, besides moving parts that were already there like the pedals and pedal arms.
- The Proposed Design will not make any unnecessary major changes to the exercise bike. The only changes that will be made are holes being drilled into the shell to hold the System Enclosure, holes being drilled into the frame to hold the DC Motor bracket (*inside the shell*), cables soldered to the 8-bit data line of the bike's Microcontroller to LCD link, and a hole for the motor to protrude from the shell by 1cm.
- The Proposed Design will use a DC Brushed Motor to produce electrical energy that will be used to charge devices plugged into USB Ports, and charge the Microcontroller circuit controlling the system.
- The Microcontroller used in the Proposed Design shall be a BBC Micro:bit.
- The Microcontroller will show collected data on an LCD and LEDs, and transmit the data to an External Device where the data shall be presented more in-depth.
- The Proposed Design will adhere to all codes of conduct, including safety, protection, and professionalism, and will be representative of only the highest standards, which should be expected from an STFC project.

[1]. Quora. 2016. What's the reasonable electrical efficiency that can be expected from a dynamo?. [ONLINE] Available at: https://www.quora.com/Whats-the-reasonable-electrical-efficiency-that-can-be-expected-from-a-dynamo. [Accessed 31 May 2018].

[2]. Wikipedia. 2018. AAA Battery. [ONLINE] Available at: https://en.wikipedia.org/wiki/AAA_battery. [Accessed 1 June 2018].

[3]. Wikipedia. 2018. AA Battery. [ONLINE] Available at: https://en.wikipedia.org/wiki/AA_battery. [Accessed 1 June 2018].

[4]. Wikipedia. 2018. Nine-volt battery. [ONLINE] Available at: https://en.wikipedia.org/wiki/Nine-volt_battery. [Accessed 1 June 2018].

The Data collected for the different Microcontrollers were taken from the Raspberry Pi, Arduino and BBC Websites.

When choosing the components, their technical datasheets were consulted to ensure that they were the correct component for the job – this will continue in the design phase, and each component will be thoroughly researched to find the optimal balance between cost and quality

A. Appendix – Approximate Bill of Materials

As no real design work has yet been carried out, it is impossible to say which components will be used and how much they will cost. However, it is more or less known which components will be used for each of the stages – current amplifiers will most likely be used for the current measurements, an ADC Chip will be used for the ADC stage, and a cheap, compact DC Motor will most likely be used as the Motor. As far as possible, each component will be listed below in as much detail as possible, but they are very likely to be changed if another component is found which is better and/or cheaper, and so this should only be taken as a rough estimate only. Also, as the Exercise Bikes have already been purchased (*and that I can't find how much they costed*), their price will be left out of the BoM. With this in mind, the initial BoM is below (*Table 3*).

Quantity	Part	Distributor	Distributor Part Number	Cost - Each (£)	Additional Information
2	BBC Micro:bit	Pimoroni	N/A	21	Price includes Breakout Board + VAT
2	PCB (Power and Micro)	Printed.cz	N/A	22.5	Doesn't include shipping
2	PCB (LEDs)	Printed.cz	N/A	18	Doesn't include shipping
2	Motor	RS	417-9633	25.30	Cost including VAT
2	Enclosure	Farnell	1635161	6.40	Cost including VAT
2	LCD	Farnell	2674135	11.88	Cost including VAT
2	I/O Expanders	Farnell	1439758	1.43	Cost including VAT
2 (lots of 15)	LEDs	Farnell	158113, 158114, 158115	3.10	9x Yellow, 3x Red, 3x Green
2 (lots of 4)	USB Port	Farnell	1696536	2.145	Cost including VAT
2	Relay	Farnell	1703727	2.27	Cost including VAT, 8A
2	ADC	Farnell	8455210	7.06	Cost including VAT
2 (lots of 2)	LDO	Farnell	1685484	3.80	Cost including VAT
2 (lots of 4)	Current Amp	Farnell	2842972	2.436	Cost including VAT
2 (lots of many)	General Components	varies	varies	~ 20	
				~ 150	

Table 3 **The initial BoM comes to around £150 per bike. This is a projection to include everything of significance – enclosures, PCBs, components and the Motor. The actual cost may be higher or lower, but this will not be known until the first schematic is produced. The "PCB (LEDs)" row is highlighted grey as it may not be needed**