PI SWARM SYSTEM

Reference Manual

Manual Version **0.91 Draft** - API Version **0.6** - PCB **1.2** - February 2014

This document contains information about the hardware and software for the Pi Swarm robotic platform.

Pi Swarm System

For PCB Version 1.1 & 1.2 and API Version 0.5

12th February 2014

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Introduction

The Pi Swarm System is an extension for the Pololu 3-Pi robot that enables the robot to feature as part of a fully autonomous swarm. At the core of the system is an MBED LPC1768 rapid-prototyping microcontroller board, which allows code to be easily created on any system with a USB-port and web-browser, without the need for any dedicated software or drivers. The MBED connects to a PCB designed in-house at YRL (www.york.ac.uk/robot-lab) that adds a number of sensors and actuators to augment those already present on the 3-Pi platform, allow for more complex interactions between robots to take place.

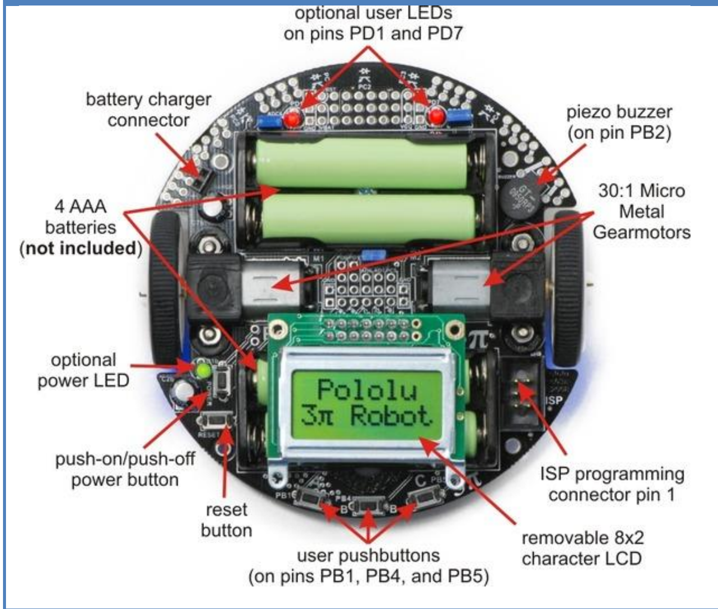
This document describes both the hardware that makes up the Pi Swarm System, and the basic API and software libraries that can be used in the MBED online compiler (and also exported for offline development using a variety of C++ programming tool-chains and IDEs). This version of the document is specifically for versions 1.1 and 1.2 of the Pi Swarm PCB and version 0.6 of the API and software libraries.

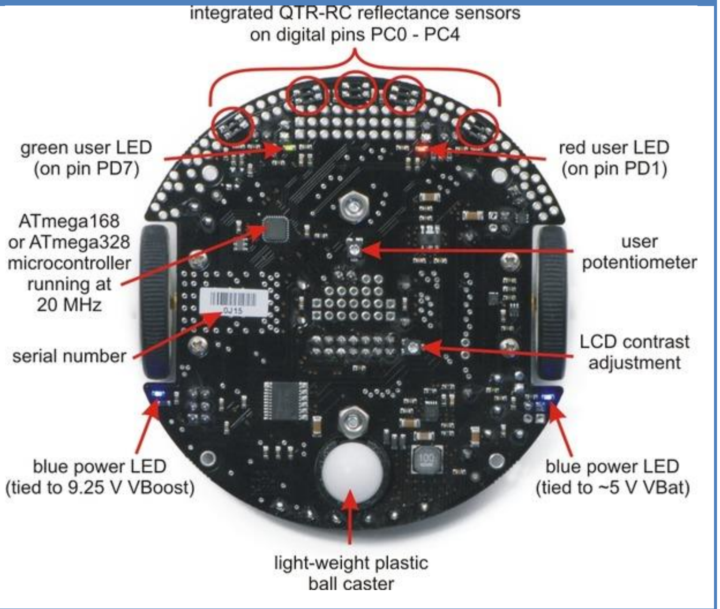
The Pololu 3-Pi Robot

The 3-Pi robot, manufactured by Pololu (www.pololu.com) is a circular mobile platform featuring two micro metal gear motors, five IR reflectance sensors, an 8x2 character LCD display, a buzzer and three user pushbuttons. It retails at around £80 and can be purchased at a number of UK-based robotics stores (such as www.active-robots.com), or direct from Pololu themselves. It is powered by a set of 4 AAA batteries (high-capacity Ni-MH recommended).

The peripherals and actuators are all connected to a C-programmable ATmega328 microcontroller, which operates at a 20MHz clock-speed and features 32KB of flash program memory, 2KB of RAM and 1KB of persistent EEPROM memory. The platform can be programmed using the GNU C/C++ compiler and Atmel Studio can be used as a development environment. However, for typical use with the Pi Swarm system, a generic firmware is used which reacts to messages sent over a serial-bus from the MBED board to operate all core functions of the robot. For more information on the 3-Pi, consult the User's Guide, Quick Start Guide and Sample Projects available on the Pololu website (http://www.pololu.com/product/975/resources).

Pololu 3-Pi Robot: Top View	Pololu 3-Pi Robot: Bottom View





The MBED LPC1768 Rapid Prototyping Board

The mbed LPC1768 is a small PCB designed to allow rapid prototyping for general microcontroller applications. It is based around the NXP1768, a 32-bit ARM® Cortex™-M3 microcontroller which operates at a 96MHz clock frequency and includes 32KB RAM and at least 512KB FLASH memory (1MB on newer boards) which appears as a USB-FLASH drive when connected to a computer. It is available to purchase from Farnell (uk.farnell.com) for roughly £40. It features a lot of interfaces and busses, including built in Ethernet, USB (host- and device-), CAN, SPI, I^2C, 6 channels of ADC, 6 channels of PWM output, a DAC and up to 26 GPIO pins [*certain pins are shared between interfaces so not all will be available at one time*]. Additionally on-board LEDs are connected to other GPIO pins on the microcontroller.

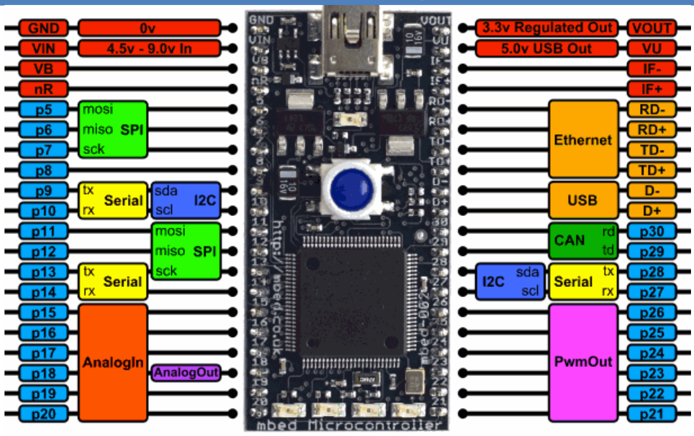
One of the key differences between the MBED and other similar microcontroller based prototyping boards is the availability of an online compiler at www.mbed.org. This compiler provides the toolchain and libraries necessary to quickly create C++ programs which can be compiler and installed onto the mbed. The bootstrap loader on the mbed board simply loads the most recent binary file that has been saved onto the FLASH memory upon reset, so the process of uploading new code to an mbed board is simple:

1. Navigate to www.mbed.org on a web browser, log in *(creating a new account if necessary)*, open the compiler, and create the code
2. Compile the code and download the compiled binary *(.bin)*
3. Connect the mbed board to the computer using a mini-USB – USB cable and save the *.bin* file in the flash drive folder
4. Press reset on the mbed board – the new code should now run

In addition to appearing as a flash drive on a connected computer, the mbed can also be setup as a virtual serial port (requires a driver to be installed in Windows but not needed for Linux). This makes it very easy to, for example, send debugging information back to a computer terminal using `printf` statements.

The mbed LPC1768 Rapid Prototyping Board

Pin-Out Diagram



The Pi Swarm Extension Board

The Pi Swarm Extension board connects to the 3-Pi base using the 14-pin peripheral connector, with a pair of additional 2-pin connectors allowing duplication of the reset switch and the recharging pins. It is secured in place using a set of 4 M2.5 bolts and spacers. The top of the board contains a socket for attaching the MBED and a number of sensors and actuators. On the underside of the board, a set of 8 IR optocouplers which act as proximity detectors are arranged around the edge. A socket allowing the connection of a separate ultrasonic range detector is present at the front.

PCB Versions

Version 1.1 and 1.2 of the Pi Swarm PCB include a staggered 4-pin connector on the underside which is designed to be used with a dedicated recharging board; this will be documented in future releases of this file. Differences between version 1.1 and 1.2 PCBs are minimal – the placing of certain connectors is shifted by less than a millimetre, certain holes are drilled slightly larger to facilitate construction, the silk-screen text is improved and two resistors are added for the full-size USB connector. These resistors are necessary to enable USB-host mode; should USB-device mode be needed these resistors would need to be removed.

The Pi Swarm boards are designed in **Eagle** PCB design software (version 6.5.0) as 2-layer boards. They have been designed to meet **EuroCircuits** (www.eurocircuits.com) design requirements for class 6 boards. In brief this means track widths of at least 6 mil (0.15mm) and drill sizes of at least 0.35mm. The board is ideally designed to be done in the standard pool on 1.55mm thick board, with optional black top and bottom soldermask (to match the 3-Pi PCB), HAL or selective AU plated finish and >2.0mm milling required for the display cut-out. The boards are a 95mm diameter circle. To reduce costs, there is only a silk-screen legend on the top layer of the board.

Hardware

The board is equipped with the following sensors and actuators:

- A set of 10 RGB LEDs arranged in a ring around the edge of the board. They are equally spaced 36˚ apart from each other. These LEDs can be enabled/disabled individually with the colour selected by setting three PWM values (the colour is the same for all the LEDs at one time).

- An additional high-power RGB LED in the middle of the board, facing up. This has independent colour control from the edge LEDs.
- A set of 8 IR-proximity detectors arrange around the edge on the underside of the board. These are spaced with a higher concentration at the front end of the robot, with sensors at ±15˚, ±45˚, ±90˚ and ±144˚.
- A MEMS 3-axis accelerometer (*ST Micro LIS332AX*)
- A MEMS yaw gyroscope (*ST Micro LY3200ALH*)
- A MEMS 3-axis magnetometer (*Freescale MAG3310FCR1*)
- A digital temperature (*MCP9701*) and ambient light sensor (*APDS-9005*)
- A 433MHz RF transceiver (*Alpha TRX-433*)
- A set of 5-DIL switches, for the setting of robot ID within the swarm. This allows a swarm of up to 31 robots (the ID 0 is to be reserved).
- A 5-way directional switch which may be used to trigger interrupts and control the robot
- A 64 kilobit EEPROM (*24AA64T*) *[PCB version 1.1 onwards]*

A plastic shim has been designed which should be attached beneath the board in normal use. The shim is laser-cut from 3mm Perspex, and provides protection to the optocouplers from collisions with other robots and walls etc. It also helps balance the weight of the platform, and creates the correct height above the 3-Pi to allow the use of 20mm PCB spacers.

Basic Design

To augment the number of peripherals which can be attached to the MBED, the Pi Swarm PCB makes use of a **PCA9505** I/O Expansion IC manufactured by NXP. This device connects to the I^2C interface of the MBED (pin 27 and 28), and also provides an interrupt output (connected to pin 29 of the MBED). The PCA9505 contains 40 general purpose Input/Output pins, arranged as 5 banks each with 8 I/Os.

MEMS Sensors

Gyroscope

The Pi Swarm board contains an analogue yaw gyroscope, a **LY3200ALH** manufactured by *ST Microelectronics*. This gyroscope produces an analogue voltage level based on the current YAW rotational velocity in the range ±2000˚ ps. The gyroscope output is directly connected to pin 16 on the MBED board, intended to be used as an analogue input.

The zero-rate output for the gyroscope is 1.5V, and its sensitivity is 0.67mV/˚ps. Thus a measured voltage of 1741mV would correspond to approximately one complete counter-clockwise rotation per second. The gyroscope is relatively stable to temperature and reliable, however a simple calibration routine to remove offset and error has been created in the API and it is recommended that this is run if the gyroscope is to be used; this means that care must be taken to make sure the Pi Swarm is kept stationary during boot-up.

Magnetometer

The *Freescale* **MAG3110** 3-axis digital magnetometer is connected to the I^2C interface of the MBED. It is capable of measuring magnetic fields with an output data rate of up to 80Hz. It has a full scale range of ±2000µT and a sensitivity of 0.1µT. The 7-bit address of the magnetometer is `0001110` *(0x1C in 8-bit hex format for MBED)* .

Accelerometer

The *ST Microelectronics* **LIS332AX** 3-axis analog-output accelerometer is attached to pin 19 (X-plane), 18 (Y-plane) and 17 (Z-plane) of the MBED board, configured as analogue inputs. The accelerometer produces an output voltage of 1.25V at zero G and has a sensitivity of 363mV/G over its acceleration range of ±2.0G. In typical use, on a flat surface, one would expect a 0G reading for the X and Y planes (1.25V) and approximately -1G on the Z plane (887mV).

Infrared Proximity Sensors

The Pi Swarm robot contains a set of 8 transistor driven reflective optical sensors around the edge of the board on the underside. The optical component is a **TCRT1000** manufactured by *Vishay Semiconductor*, which combines a phototransistor and infrared emitter in a leaded package which blocks visible light. The phototransistors all feed into an *Analog Devices* **AD7997** 8-channel, 10-bit analogue to digital converter, which is connected to the I^2C interface of the MBED (pin 27 and 28). The 7-bit address of the ADC is `0100011` *(0x86 in 8-bit hex format for MBED)* .

Each of the optocouplers also contains a 950nm infrared emitter. These are driven by a dedicated power supply stage, which draws directly from the battery supply on the 3-Pi (to increase the current availability). The emitters are enabled in sets of 4 – those facing forwards form set 1, and those facing to the side and backwards form set 2. Set 1 is connected to GPIO Pin 12 of the MBED, and set 2 to pin 13. A logic high value will enable the emitters. It is intended that the emitters are only enabled for short pulses last at most a few milliseconds at a time, as they draw significant current (approximately 50mA per emitter). To reduce idle power consumption it is possible to turn the power supply stage for the emitters into a sleep state; its enable pin is connected to `IO2/6` **PCA9505** I/O Expansion IC.

Temperature and Light Sensors

Two other analogue sensors are placed close to the MBED on the Pi Swarm board. The temperature sensor, a *Microchip* **MCP9701T**, is a linear active analog thermistor. This provides an output of 400mV at 0˚C and ±19.5mV from this value for each ˚C difference, within the operating limits. The sensor is connected to AnalogIn pin 20 of the MBED.

An ambient light sensor, the *Avago* **APDS-9005**, faces upwards on the Pi Swarm PCB. It can be found approximately 5mm below pin 21 of the MBED, between the RF board, aerial and USB expansion connector. This is connected to AnalogIn pin 15 of the MBED, and provides a voltage proportional to the lux of light hitting the sensor. The sensor produces 1V, close to its peak value, at approximately 1000 Lux of light.

RF Transceiver

The primary system for communication between Pi Swarm robots and remotely to a computer terminal is using a 433MHz FM transceiver system, based on the low cost **Alpha-TRX433S** module by *RF Solutions*. The transceiver module connects to the MBED using the SPI interface and provides up to 115.2kbps data rate. A chip antenna is mounted on the PCB just below the transceiver module, which provides a typical range of several meters at the higher data rates and substantially further still if data rates are lowered.

The transceiver module itself supports the sending of simple short-word packets. To enhance usability, the software API includes a simple communications stack which implements basic error-checking using CRC codes, and a simple instruction protocol, allowing various control messages to be sent between devices. The protocol includes the ability to broadcast messages (similar to UDP) to all listening robots, or to target individual device and form a reliable, acknowledged link (similar to TCP/IP, although much more basic in scope).

USB Header

A USB type-A socket is positioned below the MBED board on the Pi Swarm PCB. The basic API does not include any support for USB devices, although a number of such libraries have already been written by others for use with the MBED, including support for USB BlueTooth dongles, Human-Interface Devices *[keyboards, mice and joysticks etc]* and flash-memory drives. It is likely that a BlueTooth dongle could be used to provide an additional communication network between robot-robot and robot-computer, although BlueTooth does have limits on the number of supported connections so may not be suitable for larger swarms. In might in principle be possible to utilise an 802.11 Wi-Fi USB dongle, although it is likely that the processing and memory overhead needed to support such a system might be beyond the practical capability of the MBED.

ID Switch

A 5-position DIL switch is positioned just above the display window, which allows each robot in the swarm to be assigned its own unique ID. Whilst there are 32 different possible combinations, it is recommended that 0 is not used, as this is utilised by the communications stack as the broadcast-to-all ID and as the ID for the radio modem. As a result it is possible to create swarms up to 31 robots in size. In principle this could be expanded further by, for example, recording more significant bits in the on-board EEPROM, effectively allowing multiple sub-swarms of up to 31 robots each.

The ID switch is connected to pins `IO2/1` to `IO2/5` of the **PCA9505** I/O Expansion IC, which communicates with the MBED using the I^2C interface. In the standard API these pins are not set to trigger an interrupt, instead they are read during the startup phase of the software and store the ID value in a local variable.

Direction Switch

To the right of the display window is a 5-direction push button switch. The direction switches are connected to pins `IO1/2` to `IO1/6` of the **PCA9505** I/O Expansion IC. In the standard API these pins are set to trigger an interrupt, which is connected to pin 29 to of the MBED. A small delay is associated to provide a simple software debounce of the switch and prevent multiple routines being triggered. An alternative solution to reading the switch would be to periodically poll the switch IO pins on the expansion IC or pin 29 on the MBED.

EEPROM

A 64-kilobit (8KB) EEPROM, the *Microchip Technology* **24AA64**, is connected to the I^2C interface of the MBED. It is accessed using the 7-bit address `1010000` *(0xA0 in 8-bit hex format for MBED)*. The EEPROM chip itself is sorted into 32-byte pages, and can be instructed to do either byte write or page write operations; it should be noted that a page write operation is restricted to a single physical page and that if it extends beyond the 32nd byte of a page the data will wrap over to overwrite the start of the page. An API routine abstracts this limitation and allows longer messages to be written regardless of where in a page they begin. It is important to remember that any write operation to EEPROM is relatively slow. The API follows the datasheet guidelines and adds a 5ms delay after any write operation (byte- or page-) which ensures that the data is correctly written; be aware that writing several hundreds of bytes will take several milliseconds. It is intended that in future API release a part of the EEPROM (possibly the first 4KB) will be reserved for system use, for storing things such as calibration data for individual robots, and the remainder will be "user area". The API will abstract this information away but it does mean that the entire 8KB area may not be available to the controller code.

Outer RGB LEDs

The edge of the Pi Swarm PCB contains ten very small right-angled RGB LEDs, evenly spaced at 36˚ intervals and numbered from 0-9[1] clockwise around the PiSwarm starting from the 036˚ position. Each LED has its own enable pin connected to a GPIO pin on the **PCA9505** expansion IC, that lets the outer LEDs be individually enabled or disabled. All ten LEDs share three connections to the PWM outputs on the MBED which assigns the colour of the LED: one output controls the red value, one green and one blue. Note that this arrangement means that the enabled outer LEDs must all be the same colour at one instance in time; the effect of having multiple colours at once on different LEDs could be implemented by rapidly enabling and disabling the LEDs and changing the colours if needed.

Central RGB LED

The central user LED is an upwards-facing, high intensity RGB LED that sits right in the center of the Pi Swarm PCB. This is directly connected to the other three PWM outputs on the MBED and is thus totally independent from the outer LEDs.

[1] Note that these are numbered 0-9 in the API but 1-10 on the PCB silk-screen

3-Pi Sensors

The 3-Pi itself contains a set of 5 infrared proximity sensors on the underside of the front of the PCB, which are intended primarily to allow line following. These raw value from these sensors ranges from 0 to 2000. A relative value of a preset variable resistor on the underside of the PCB can be read, which may be of use in setting offsets for slight variation between 3-Pi bases. Note that there are actually 2 variable resistors; the one centrally between the wheels is the user preset, the one closer to the left wheel controls the contrast of the 7x2 display.

3-Pi Actuators

The primary actuators on the 3-Pi are the pair a motors which drive the platform. At the lowest level, a floating point value ranging from -1.0 to 1.0 is sent to the 3-Pi microcontroller to set the relative motor output. Other actuators on the 3-Pi include the 7x2 LCD display, which can be written to using standard C `printf` commands, and two user LEDs on the bottom of the Pi Swarm. There is a buzzer which can convert a ASCII string into conventional notes; examples and a description about using the buzzer can be found in `piswarm.h`.

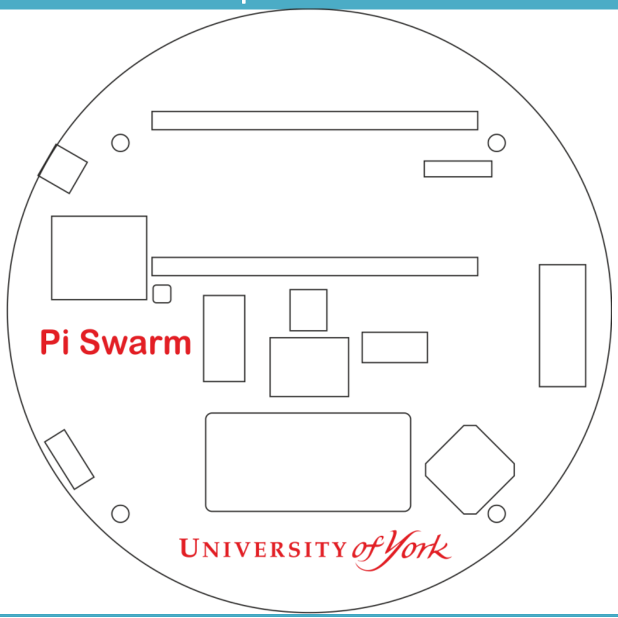
Construction

The Pi Swarm PCB contains three sets of connectors which link it to the 3-Pi base. The main connector is a 2x7 pin, 0.1” pitch connector, that contains the serial link from the MBED to the *ATmega* microcontroller on the 3-Pi. This connector also contains the power supply and ground lines. Two other 2-pin connectors link to the charge connector and to the power switch, allowing these to be routed up to the Pi Swarm board. Spacers are used to hold to Pi Swarm board firmly in place.

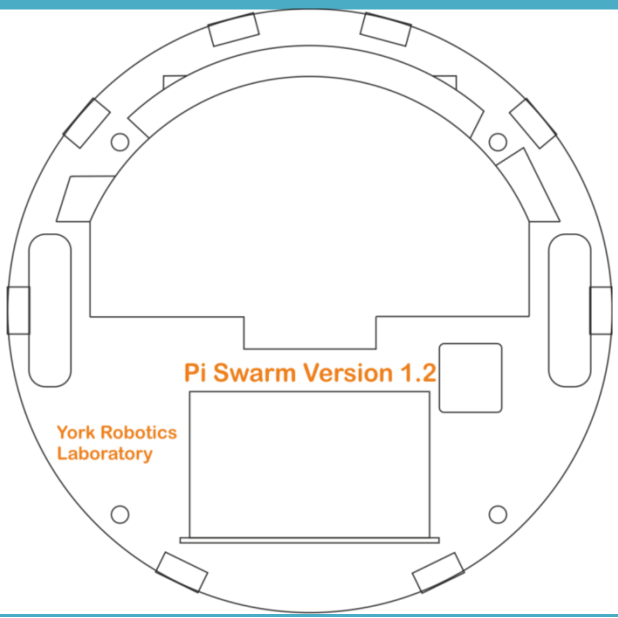
As supplied a 3-Pi base does not contain sockets for these connectors. A suitable 2x7 socket [*similar to that soldered on the base to connect the display*]and a pair of 2x1 sockets need to be soldered to the 3-Pi base. The Pi Swarm is drilled to accept M2.5 threads; the 3-Pi as supplied has M2 holes. As M2.5 hardware is stronger and far easier to source, a minor modification to the holes on the 3-Pi base to enlarge them to M2.5 is recommended – this can be done with a round needle file or, with care, a suitable drill.

A pair of plastic shims have been designed to be sandwiched below and above the Pi Swarm PCB, which give protection to the IR sensors and the surface components. These are designed to be laser-cut on 3mm Perspex. Extreme care should be taken when mounting the Pi Swarm board to the 3-Pi as it is easy to mis-mate the connectors, which can in certain combinations cause short circuits which have the potential to damage both the 3-Pi and the Pi Swarm board, regardless of power being turned on.

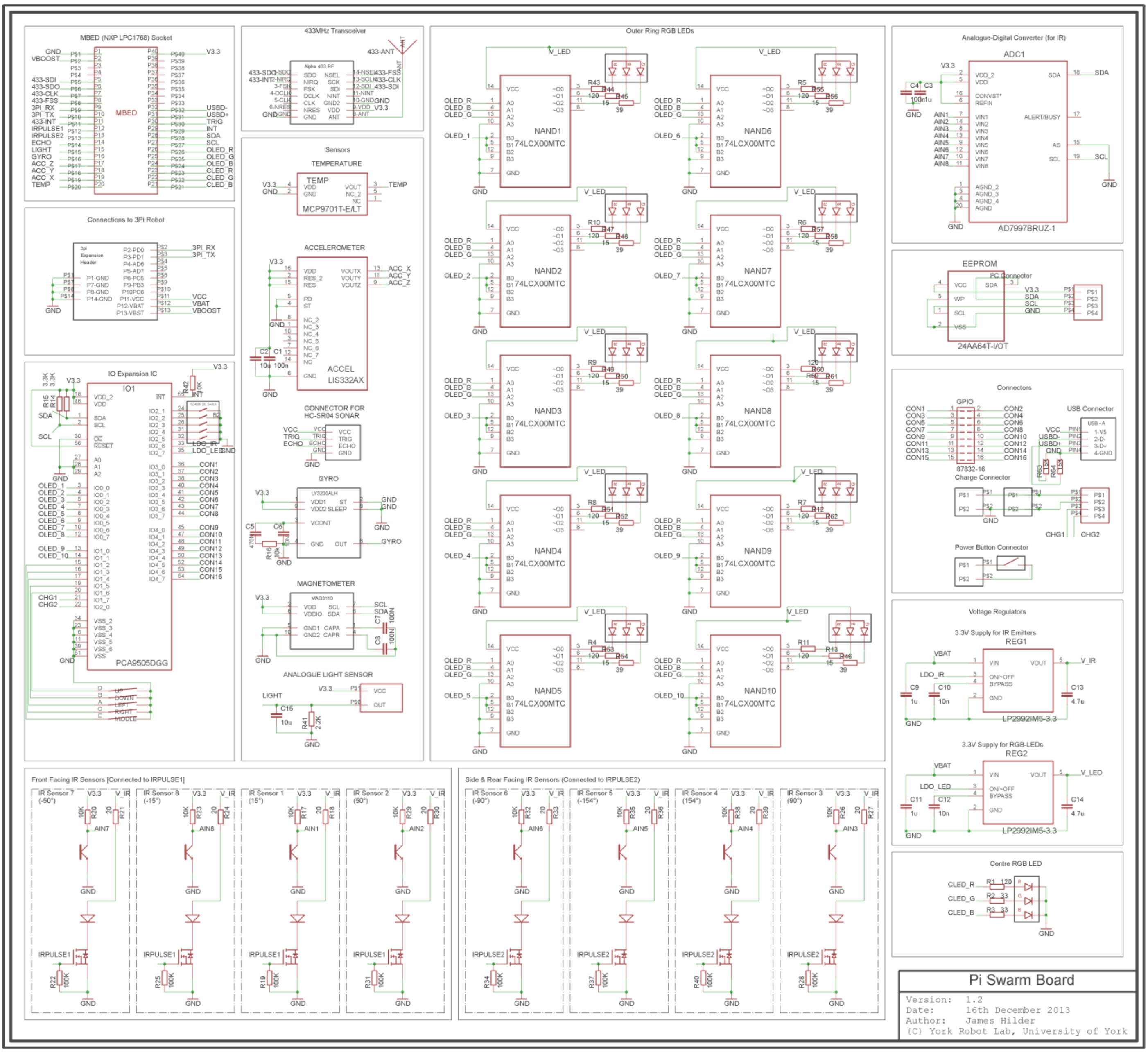
Top Plastic Shim



Bottom Plastic Shim

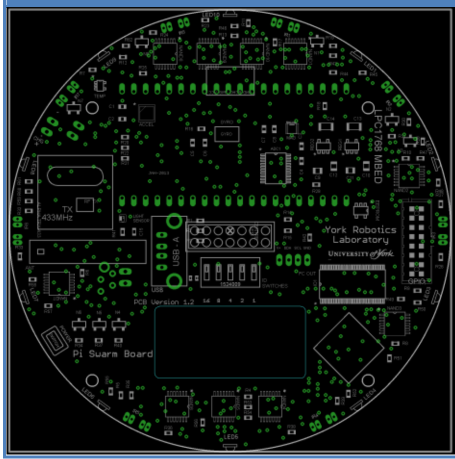


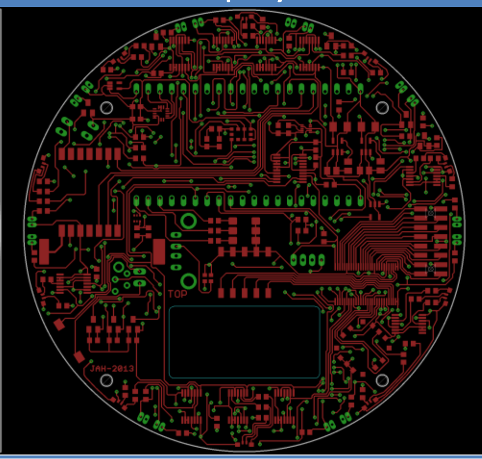
Schematic

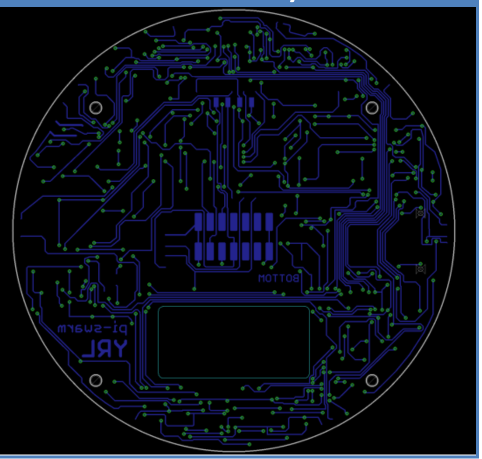


PCB Design

Silk Screen	Top Layer	Bottom Layer







Components

Parts-list for Pi Swarm Extension Board Version 1.2

Parts	Farnell	Quantity	Unit Price	Total Price	Value	Manufacturer
3PI_HEADER	9689605	1	£0.98	£0.98	1241050-7	TE Connectivity
ACCEL	1838527	1	£1.78	£1.78	LIS332AX	STMicro
ADC1	1078305	1	£4.61	£4.61	AD7997BRUZ-1	Analog Devices
ALPHA433	1718689	1	£4.97	£4.97	ALPHA-TRX433S	RF Solutions
ANTENNA	2148530	1	£1.24	£1.24	ANTENNA	Johanson Technology
C1,C4,C7,C8	1759037	4	£0.01	£0.04	100n	Multicomp
C2,C15	2309028	2	£0.16	£0.32	10u	TDK
C3	1759399	1	£0.01	£0.01	1u	Multicomp
C5	1759396	1	£0.02	£0.02	470n	Multicomp
C6	1759003	1	£0.01	£0.01	10n	Multicomp
C9,C11	1658211	2	£0.35	£0.70	1u	AVX
C10,C12	1759246	2	£0.02	£0.04	10n	Multicomp
C13,C14	1754181	1	£0.15	£0.15	4.7u	Vishay
CENTRE_LED	1855543	1	£0.62	£0.62	CLP6C-FKG	Cree
CHG_IN,POWER_CON	1022245	2	£0.10	£0.20	2-PIN-CONNECTOR	Harwin
CHG_OUT	1841369	1	£0.41	£0.41	2-PIN-CONNECTOR	Wurth
EEPROM	2101260	1	£0.56	£0.56	24AA64T-I/OT IC 64KB	Microchip
GPIO_CON	1756949	1	£1.53	£1.53	87832-1620	Molex
GYRO	1838547	1	£5.98	£5.98	LY3200ALH	STMicro
I2C_CONN	9492437	1	£0.13	£0.13	B4B-PH-K-S	JST
IO1	2212087	1	£2.54	£2.54	PCA9505DGG	NXP
IR1-IR8	1470064	8	£0.76	£6.08	TCRT1000	Vishay
LED1-LED10	2335788	10	£0.39	£3.90	KPFA-3010RGBC-11	Kingbright
LIGHTSENSOR	1548110	1	£0.65	£0.65	APDS-9005	Avago
MAGNETO	2080492	1	£1.13	£1.13	MAG3310FCR1	Freescale
MBED-CON	1593469	2	£1.17	£2.34	2212S-20SG-85	Multicomp
N1-N8	9102710	8	£0.26	£2.08	IRLML2402PBF	International Rectifier
NAND1-NAND10	1607738	10	£0.13	£1.30	74LCX00MTC	Fairchild
R1	9238379	1	£0.01	£0.01	120	Yageo
R2,R3	2331705	2	£0.01	£0.02	33	TE Connectivity
R4-R13	1738888	10	£0.03	£0.30	50	Vishay
R14,15,19,22,25,28,31,34,37,40	2073350	10	£0.01	£0.10	100K	Multicomp
R16,17,20,23,26,29,32,35,38	2073356	9	£0.01	£0.09	10k	Multicomp
R18,21,24,27,30,33,36,39,41	2331703	8	£0.01	£0.08	22	TE
R41	1652868	1	£0.05	£0.05	2.2K	Vishay
REG1,REG2	1469141	2	£0.71	£1.42	LP2992IM5-3.3	Texas Instruments
SONAR_CON	2084263	1	£0.79	£0.79	BG300-04-A-L-A	Global
SWITCH1	1703878	1	£0.22	£0.22	FSMSM	TE Connectivity
SWITCH2	1316988	1	£0.60	£0.60	MCTT5-V	Multicomp
SWITCH3	1524009	1	£0.52	£0.52	MCEMR-05-T	Multicomp
TEMP	1084622	1	£0.24	£0.24	MCP9701T-E/LT	Microchip
USB_CONNECTOR	1654064	1	£0.80	£0.80	1734366-1	TE Connectivity

Using the Pi Swarm

The power switch, located on the edge left of the display, is used to turn on and turn off the Pi Swarm. When no MBED board is attached, this will power up the default firmware on the 3-Pi base, which will load the 3-Pi demo/test code after approximately 5 seconds. This demo and test code can be used to check that the 3-Pi is working properly, test the motors, monitor the battery level and check the line-following sensors. None of the hardware features on the Pi Swarm expansion board can be tested with this software. To navigate between functions the user-buttons on the 3-Pi (and not the Pi Swarm expansion) must be used.

Charging

The charging connector, located on the left-hand edge next to the MBED, allows the batteries to be recharged without having to remove them. To do this, a battery charger specifically designed to charge 4 external Ni-Mh AAA cells must be used, and must be fitted with the suitable connector (a 0.1" pitch, 2 pin, locking plug, such as *Farnell* code 1841370). A high-quality, fully programmable battery charger such as a Tenergy TB6AC is ideal for this.

It is strongly recommended that the Pi Swarm is switch off during charging. Depending on the batteries used, it is recommended that an absolute maximum charge rate of 0.5C is used, that a timer is used to ensure that the charger is switched off after 2 hours (or adjusted time based on charge rate). Alternatively, most Ni-Mh will happily accept a trickle charging at 0.05C or less indefinitely without damage; check the datasheet of the batteries used to see if this is the case.

Software

The Pi Swarm robot has an MBED C++ library that provides the API routines and internal functions to allow all of the main Pi Swarm (and 3-Pi) sensors and actuators to be controlled. The user functions from the API itself are described in detail in the following section. The Pi Swarm Library comprises 6 key files: `piswarm.cpp`, `communications.cpp` and `alpha433.cpp` along with their respective header files. The main API functions can be found in `piswarm.cpp` with additional user functions related to RF transceiver communication stack in `communications.cpp`.

Communications

This section describes the setup and use of the **Alpha 433** FM transceiver on the Pi Swarm board and the use of the simple message handling and communications stack written for use with the transceiver. Other communications interfaces, such as the use of BlueTooth dongles, Ethernet or IR communication are all potentially possible but beyond the scope of this document; www.mbed.org would be a good starting point for research into possible options here.

In the Pi Swarm API there two methods of handling the RF transceiver. For complete flexibility, the user can use methods which simply use the transceiver as a communication channel; the user can write and receive string messages from this channel and handle them as they wish. However, to improve reusability and compatability between code, it is recommended to use the simple communication stack that has been implemented. The stack also provides a library of 16 commands and 16 information requests that can be automatically handled by the robot without requiring additional code to be written.

Communications Hardware

The Alpha RF transceiver is a low-cost standalone module for communication on the 433MHz FM band. The 433MHz band allows low-power, license free communication; it is often used for applications such as garage door openers and remote car keys. It is far removed from modern wireless communication systems such as 802.11x and BlueTooth, but is suitable for allowing short messages (a few bytes) to be sent between connected devices at a modest data rate. The transceiver is easily identifiable on the Pi Swarm PCB, being a standalone small green PCB to the left of the MBED. Directly below the transceiver is the white chip-antenna for the RF system.

Communications Software

There are two pairs of files that handle communication in the Pi Swarm. "`alpha433.cpp`" and "`alpha433.h`" are essentially the driver code for the transceiver. The low level functions required to initialise the RF transceiver, set the transmission mode, and send and receive short packets of data are included in these files. To reduce the likelihood of processing a corrupt packet, a parity checksum byte is appended to the end of every send message; any packet received with an incorrect final byte is rejected.

"`communications.cpp`" and "`communications.h`" contain the simple communication stack written for use with the Pi Swarms. The communication stack is enabled by defining the flag "`USE_COMMUNICATION_STACK`" as 1 in the code. When the communication stack is in use, any message received which passes the simple checksum test is sent to the `processRadioData()` function in `communications.cpp`. Note that if the communication stack is not being used, the message is instead sent to the `processRawRFData()` in the user's code (*normally in main.cpp*); the user would need to add code to handle the message appropriately here.

The communication stack provides a strict format to the structure of messages. Every message is a minimum of 4 bytes long (excluding the checksum byte). The structure of these 4 bytes in shown in the table below:

Byte	Function	Range	Notes
0	Sender	`00010000 – 00011111` *(32 – 63)*	The sender is the ID of the sending robot (1-31), or 0 if sent

			from a modem. 32 is added to the value.
1	Target	00010000 – 00011111 *(32 – 63)*	The target is the ID of the intended recipient robot (1-31), or 0 if it is a broadcast message sent to all. 32 is added to the value.
2	Message ID	00000000 – 11111111 *(0 – 255)*	The message ID is a 1-byte identifier set by the original sender of the command. A response to a command or request will share the original ID of that request.
3	Command	See next table	

When a message is received, the `decodeMessage()` function checks that it is valid message by ensuring a sender and target bytes are within the correct range. It then determines if it is a target recipient of the message, by checking if the target ID matches its own or the message is a broadcast message (target set to 0 *+32*). If the message is not for this robot, it does no further processing.

Bit	Definition	Notes
7	**is_response**	The `is_response` bit determines if the message is a response to a previous message (1) or is a new message (0).
6	**request_response or success**	The `request_response` bit determines if the sender is anticipating a response to the new message (1) or not (0). When the message is a response, this bit instead records whether the request or command issued in the prior message was successfully completed.
5	**is_user**	The `is_user` flag determines if the message is user defined (1) or predefined by the communication stack (0).
4	**is_command**	The `is_command` flag determines if the message is a command (1) or a request (0). Commands can be disabled in code, resulting in all command messages being rejected. Conversely requests are always handled.
3-0	**Function**	The 4-bit (0-15) identifier for the required function. The communication stack provides a set of 16 basic commands and 16 requests for controlling the robots via RF.

There are a set of 15 predefined data request messages that can be sent using functions in `communications.cpp` that can be found in the list below. Upon the receipt of a response to one of these requests, the relevant data is stored in an array contained for all members of the swarm. A status flag changes state to indicate that the request has been successfully answered.

Request	Command	Function	Notes
0	0x80	**send_rf_request_null**	
1	0x81	**send_rf_request_left_motor_speed**	
2	0x82	**send_rf_request_right_motor_speed**	
3	0x83	**send_rf_request_button_state**	
4	0x84	**send_rf_request_led_colour**	
5	0x85	**send_rf_request_led_states**	
6	0x86	**send_rf_request_battery**	
7	0x87	**send_rf_request_light_sensor**	
8	0x88	**send_rf_request_accelerometer**	
9	0x89	**send_rf_request_gyroscope**	
10	0x8A	**send_rf_request_background_ir**	
11	0x8B	**send_rf_request_reflected_ir**	
12	0x8C	**send_rf_request_distance_ir**	
13	0x8D	**send_rf_request_line_following_ir**	
14	0x8E	**send_rf_request_uptime**	

Additionally there are 14 predefined commands. The notional difference between commands and requests is the commands will only be accepted if `RF_ALLOW_COMMANDS` is defined as 1. This allows remote control of the robot to be blocked if desired.

Request	Command	Function	Notes
0	0x90	send_rf_command_stop	
1	0x91	send_rf_command_forward	
2	0x92	send_rf_command_backward	
3	0x93	send_rf_command_left	
4	0x94	send_rf_command_right	
5	0x95	send_rf_command_left_motor	
6	0x96	send_rf_command_right_motor	
7	0x97	send_rf_command_oled_colour	
8	0x98	send_rf_command_cled_colour	
9	0x99	send_rf_command_oled_state	
10	0x9A	send_rf_command_cled_state	
11	0x9B	send_rf_command_set_oled	
12	0x9C	send_rf_command_play_tune	
13	0x9D	send_rf_command_sync_time	

Pi Swarm API

The following pages list all the main public functions from the core Pi Swarm API files (`piswarm.cpp` and `communications.cpp`). There are a number of functions which are explicitly for setup, not intended for use in user code, or legacy functions to maintain compatibility with m3-Pi code that are not included in the tables below.

piswarm.cpp

Outer LED Functions

Type	Name	Inputs	Description
int	get_oled_colour	(**void**)	Returns the current setting for the outer LED colour. Returned colour is stored as 24-bit positive integer (R<<16 + G<<8 + B). Used by communication stack.
char	get_oled_state	(**char** oled)	Returns the current enable state an individual LED. `oled` = LED to return enable state. Returns 0 for disabled, 1 for enabled
void	set_oled_colour	(**char** red, **char** green, **char** blue)	Set the colour of the outer LED. Values for red, green and blue range from 0 (off) to 255 (maximum).
void	set_oled	(**char** oled, **char** value)	Set the state of an individual LED. `oled` = LED to enable Value = 0 for disable, 1 for enable Use to change 1 LED without affecting others.
void	set_oleds	(**char** oled_x,...) *[x=0-9]*	Sets the state of all 10 LEDs. `oled_x` = 0 for disable, 1 for enable Use to change all 10 LEDs at once
void	turn_off_all_oleds	(**void**)	Sets all outer LEDs to disabled and turns off LED power supply.
void	set_oled_brightness	(**char** brightness)	Set the brightness (total period of PWM output increases as brightness decreases). Ranges from 0 (minimum) to 255 (maximum)
void	activate_oleds	(**void**)	Function responsible for sending updated outer LED enables to the GPIO expansion IC. Called automatically after `set_oleds` but not `set_oled`.

Center LED Functions

Type	Name	Inputs	Description
int	get_cled_colour	(**void**)	Returns the current setting for the center LED colour. Returned colour is stored as 24-bit positive integer (R<<16 + G<<8 + B). Used by communication stack.
char	get_cled_state	(**void**)	Returns the current enable state for the center LED. Returns 0 for disabled, 1 for enabled
void	set_cled_colour	(**char** red, **char** green, **char** blue)	Set the colour of the center LED. Values for red, green and blue range from 0 (off) to 255 (maximum).
void	enable_cled	(**char** enable)	Turn on or off the center LED. `enable=1` to turn on, `0` to turn off
void	set_cled_brightness	(**char** brightness)	Set the brightness (total period of PWM output increases as brightness decreases). Ranges from 0 (minimum) to 255 (maximum)

IR Sensor Functions

Type	Name	Inputs	Description
float	read_reflected_ir_distance	(**char** index)	Macro which estimates the distance to an obstacle from one of the IR sensors, defined by `index` (range 0-7). Function measures sensor value, then enables IR emitter and measures the value again. The value

			is converted to an approximate distance in millimetres, or 100.0 if no obstacle found. Since API 0.6 it is recommended to use `store_reflected_distances()` and `get_reflected_ir_distance()` unless only one or two IR distances are required, as this reduces the amount of time the IR emitters are active and improved efficiency.
float	`get_reflected_ir_distance`	(**char** index)	Introduced in API 0.6 Returns the stored value of reflected distance saved on the last call of either `read_reflected_ir_distance()` and `store_reflected_distances()`
unsigned short	`get_background_raw_ir_value`	(**char** index)	Introduced in API 0.6 Returns the stored value of the non-illuminated sensor based on last call of `store_background_raw_ir_values()`
unsigned short	`get_illuminated_raw_ir_value`	(**char** index)	Introduced in API 0.6 Returns the stored value of the illuminated sensor based on last call of `store_illuminated_raw_ir_values()`
void	`store_reflected_ir_distances`	(**void**)	Introduced in API 0.6 Stores the reflected distances for all 8 IR sensors [calls `store_background_raw_ir_values` then `store_illuminated_raw_ir_values` then `calculate_reflected_distance` for all results]
void	`store_background_raw_ir_values`	(**void**)	Introduced in API 0.6 Stores the raw ADC values for all 8 IR sensors without enabling IR emitters
void	`store_illuminated_raw_ir_values`	(**void**)	Introduced in API 0.6 Stores the raw ADC values for all 8 IR sensors with a 500us emitter pulse
float	`calculate_reflected_distance`	(**unsigned short** background_value, **unsigned short** illuminated_value)	Introduced in API 0.6 Converts a background and illuminated value into an approximate distance in mm (or 100.0 if no object detected) Used by `read_reflected_ir_distance()` and `store_reflected_ir_distances()`
unsigned short	`read_illuminated_raw_ir_value`	(**char** index)	Returns the illuminated raw sensor value for the IR sensor defined by `index` (range 0-7). Turns the relevant emitter on for 500us before sampling.
unsigned short	`read_adc_value`	(**char** index)	Returns the raw sensor value for the IR sensor defined by `index` (range 0-7).
void	`enable_ldo_outputs`	(**void**)	Function enables or disables the LDO voltage regulators which supply power to the outer LEDs and the IR photo emitters. In general this function is used internally, but it may be necessary to use when custom IR code is being written.

MEMS Sensor Functions

Type	Name	Inputs	Description
float	`read_gyro`	(**void**)	Returns the yaw (clockwise) rotation in degrees-per-second reported by the LY3200 gyroscope.
float	`read_accelerometer_x`	(**void**)	Returns the acceleration in the X plane reported by the LIS332 accelerometer. Returned value is in mg.
float	`read_accelerometer_y`	(**void**)	Returns the acceleration in the Y plane reported by the LIS332

			accelerometer. Returned value is in mg.
float	`read_accelerometer_z`	(**void**)	Returns the acceleration in the Z plane reported by the LIS332 accelerometer. Returned value is in mg.
char	`read_magnetometer`	(**void**)	Sends message to the magnetometer to read new values. Should be called before `get_magnetometer_*` when updated values are required
signed short	`get_magnetometer_x`	(**void**)	Returns the raw value for the X-plane magnetic field stored on the last call of `read_magnetometer`
signed short	`get_magnetometer_y`	(**void**)	Returns the raw value for the Y-plane magnetic field stored on the last call of `read_magnetometer`
signed short	`get_magnetometer_z`	(**void**)	Returns the raw value for the Z-plane magnetic field stored on the last call of `read_magnetometer`

Other Sensor Functions

Type	Name	Inputs	Description
float	`read_temperature`	(**void**)	Returns the temperature reported by the MCP9701 sensor in degrees centigrade.
float	`read_light_sensor`	(**void**)	Returns the adjusted value (0-100) for the ambient light sensor
void	`read_raw_sensors`	`(int * raw_ls_array)`	
float	`get_uptime`	`(void)`	Returns the uptime of the system (since initialisation) in seconds
float	`battery`	`(void)`	Returns the battery level in millivolts
float	`pot_voltage`	`(void)`	Returns the raw value for the variable resistor on the base of the platform. Ranges from 0 to 1024.
char	`get_id`	`(void)`	Returns the ID of platform (set by the DIL switches above the display). Range 0-31 *[0 reserved]*.
char	`get_switches`	`(void)`	Return the current stored state for direction switch(es) pressed *[1 = Center 2 = Right 4 = Left 8 = Down 16 = Up]*

Motor Functions

Type	Name	Inputs	Description
float	`get_left_motor`	(**void**)	Returns the target speed of the left motor (range -1.0 to 1.0)
float	`get_right_motor`	(**void**)	Returns the target speed of the right motor (range -1.0 to 1.0)
void	`left_motor`	(**float** speed)	Set the target speed of the left motor (range -1.0 to 1.0)
void	`right_motor`	(**float** speed)	Set the target speed of the right motor (range -1.0 to 1.0)
void	`forward`	(**float** speed)	Drive forward at the given speed (range -1.0 to 1.0)
void	`backward`	(**float** speed)	Drive backward at the given speed (range -1.0 to 1.0)
void	`left`	(**float** speed)	Turn on-the-speed left at the given speed (range -1.0 to 1.0)
void	`right`	(**float** speed)	Turn on-the-speed right at the given speed (range -1.0 to 1.0)
void	`stop`	(**void**)	Stop both motors

Sound Functions

Type	Name	Inputs	Description
void	`play_tune`	(**char** * tune, **int** length)	Play the `tune` of `length` characters on the 3-Pi buzzer.

Display Functions

Type	Name	Inputs	Description
int	`printf`	(**const char** * format, …)	Write data to the 8x2 LCD display on the 3-Pi starting at the current cursor position. Uses standard C printf input
void	`locate`	(**int** x, **int** y)	Locate the cursor on the 8x2 LCD to the stated position. (range x: 0 – 7, y: 0 – 1)
void	`cls`	(**void**)	Clears the 8x2 LCD display

EEPROM Functions

Type	Name	Inputs	Description
void	write_eeprom_byte	(**int** address, **char** data)	
void	write_eeprom_block	(**int** address, **char** length, **char** * data)	
char	read_eeprom_byte	(**int** address)	
char	read_next_eeprom_byte	(**void**)	

communication.cpp

Data Request Functions

Type	Name	Inputs	Description
void	send_rf_request_null	(**char** target)	
void	send_rf_request_left_motor_speed	(**char** target)	
void	send_rf_request_right_motor_speed	(**char** target)	
void	send_rf_request_button_state	(**char** target)	
void	send_rf_request_led_colour	(**char** target)	
void	send_rf_request_led_states	(**char** target)	
void	send_rf_request_accelerometer	(**char** target)	
void	send_rf_request_gyroscope	(**char** target)	
void	send_rf_request_background_ir	(**char** target)	
void	send_rf_request_reflected_ir	(**char** target)	
void	send_rf_request_distance_ir	(**char** target)	
void	send_rf_request_line_following_ir	(**char** target)	
void	send_rf_request_uptime	(**char** target)	

Remote Command Functions

Type	Name	Inputs	Description
void	send_rf_command_stop	(**char** target)	
void	send_rf_command_forward	(**char** target)	
void	send_rf_command_backward	(**char** target)	
void	send_rf_command_left	(**char** target)	
void	send_rf_command_right	(**char** target)	
void	send_rf_command_left_motor	(**char** target)	
void	send_rf_command_right_motor	(**char** target)	
void	send_rf_command_oled_colour	(**char** target)	
void	send_rf_command_cled_colour	(**char** target)	
void	send_rf_command_oled_state	(**char** target)	
void	send_rf_command_set_oled	(**char** target)	
void	send_rf_command_play_tune	(**char** target)	
void	send_rf_command_sync_time	(**char** target)	

Operational Notes

This section contains some early notes that have been observed with the use of basic demo code on the Pi Swarm robot.

Power Consumption

To test the power consumption in various states the Pi Swarm was attached to a high quality bench power supply with the batteries removed. The power supply provided a high-stability, regulated 5.0V output (a good representative output for 4 Ni-Mh cells approximately half-way through their discharge cycle) and displays the instantaneous current drawn.

State	Current Drawn (mA)	Notes
Idle Loop (MBED)	370	Typical idle loop; MBED not in low-power state.
Idle Loop (3-Pi only)	80	This result means the MBED + always on peripherals consume approximately 290mA.
MBED only (removed from board)	150	Thus the other peripherals are drawing approximately 140mA.
Obstacle avoidance	490	LEDs pulsing, motors at quarter-speed, zero friction
Obstacle avoidance	520	Motors at half speed
Obstacle avoidance: stalled	950	Motors at half speed, held in stall
Motors at full power: stalled	2300	Motors at full speed, held in stall