The Pi Swarm: A Low-Cost Platform for Swarm Robotics Research and Education

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Abstract. The paper introduces the Pi Swarm robot, a platform developed to allow research and education in swarm robotics. Motivated by the goals of reducing costs and simplifying the tool-chain and programming knowledge needed to investigate swarming algorithms, we have developed a trackable, sensor-rich and expandable platform which needs only a computer with internet browser and no additional software to program. This paper details the design and use of the robot in a variety of settings, and we feel the platform makes for a viable, low-cost alternative for development of swarm robotic solutions.

Keywords: Swarm robotics, Tracking.

1 Introduction

Swarm robotics is a research field that allows for the study of complex swarm behaviours and emergent behaviours ("swarm-intelligence") as applied to robotic systems. Simple robotic platforms are ideal tools for teaching a wide range of engineering disciplines, encompassing digital electronics, control theory, signal processing, energy management and embedded programming; when the scope of the individual robot is expanded to allow communication and interaction with other similar robots, their potential value as a tool for education and research expands to allow investigation of swarm intelligence. What is required is a system which is flexible to multiple problems, robust to environmental changes and faults, and scalable enough to permit large swarms without impacting performance. However, such systems often come at a cost which is prohibitive to education and research, both in pure monetary terms, and also in the context of the time needed to learn how to use and program a system and general maintenance.

Historically, a number of platforms have been developed which attempt to allow swarm robotics research at a low unit cost, many of which have been highly popular amongst academic institutions for education and research. Unfortunately, such systems still often cost several-hundred GBP per unit; this can make their use for research, and especially as an educational tool, prohibitive, particularly in the context of a swarm of tens- to hundreds- of robots. Additionally, there is an inevitable compromise to be made in such systems between cost,

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processing capability and complexity of use. Those platforms which offer the lowest cost tend to use very limited microcontrollers; those which offer more processing capability have higher associated costs and often also challenging learning-curves to be able to program the devices.

The motivation for this research was to have a platform that could achieve a number of objectives: be able to sense and react to its environment, be able to communicate and interact as part of a swarm, be able to be accurately tracked by a infrared tracking camera system, and be able to be expanded at a future date to add additional capability. In addition to these basic requirements, to allow for the platform to be used by a wider variety of researchers and students with varying levels of programming experience and expertise, it was desirable for it to have a simple tool-chain and an easy and concise Application Programming Interface (API) to control all basic functions.

1.1 Alternative Swarm Robotic Platforms

Whilst there exist a wide variety of low-cost robotic platforms, only a limited number of these have been designed with swarm robotics in mind. Swarm systems generally need to be able to interact, so some form of communication, the ability to detect neighbours, and some method of identification are prerequisites. Also of significant importance is ease-of-use; the ease of (re-)programming and charging robots are factors which become increasingly important as the size of swarm increase. One of the largest obstacles is the cost of the whole system; this is particularly pressing in the educational field, where multiple swarms may be needed to support classes. Here we discuss a number of the more popular and relevant platforms which have been developed for swarm research.

The e-puck is one of the most widely used swarm robotic platforms, a small 2-wheeled stepper-motor driven robot developed at EPFL [10]. A significant benefit of being widely used in research is that is has accurate simulator models, including in Webots, V-REP and Player-Stage. The retail price of a e-puck is around £650[1]. To overcome the limited processing capabilities, an open-source Linux development board has been developed for the E-Puck [7]. Whilst this creates a powerful platform ideal for research, the overall cost and complexity of the tool-chain needed to program it present an obstacle to its use as a teaching platform.

The Khepera series of robots developed by K-Team are highly successful platforms that mix a reliable, sensor-rich base with a compact size and extensive simulator support. Whilst they have been promoted and used as a teaching platform [5], their high retail cost (in excess of £2000 for a single Khepera III model) prohibit their use for swarm research in many establishments.

The SWARM-BOT project developed fully autonomous platforms that had the ability to communicate and physically connect with other SWARM-BOTs to allow task completion that would not be possible with single robots, such as dragging heavy objects in rough terrain [4]. The electronic subsystem of the

[1] Price correct at time of writing: 840 CHF plus taxes from official retailers.

SWARM-BOT linked an ARM based main microcontroller running a lightweight Linux operating system to twelve auxiliary PIC microcontrollers which controlled the sensors and actuators [11].

The Jasmine is an extremely small (approximately 3cm cube), low cost (around 100 Euro for components) open-source robot designed for large scale swarm experiments. Communication of short messages between robots uses infrared [6]. The low-cost and small size make it an attractive prospect for research into lightweight distributed swarm intelligence algorithms on larger swarms, but with this comes limited processing power on an ATMega168 microcontroller and a lack of high-level communication or environmental sensors. Such a compact size also limits the effectiveness of tracking systems, due to the resolution required to discriminate between such small robots.

The K-Team developed Kilobot is a widely used, low cost platform designed to be scalable up to hundreds and even thousands of platforms. It uses vibrating legs to allow directed motion. Many aspects of the platform, such as the ability to perform mass-reprogramming and large scale charging, make it well suited to large swarms. Rubenstein et al claim a raw parts cost of $14 USD for each platform [12], however the retail cost for 10 assembled robots is in excess of £1000 in the UK at the time of writing [2].

The r-one robot, created at Rice University, was developed with very similar goals to the Pi-Swarm robot: a platform that is low-cost, scalable and with a simple to use development environment to make it more accessible to students and outreach. It manages to include a wide array of sensors and high-speed communication system onto an accurate two-wheeled platform. The cost of parts for the robot are approximately $250 [8].

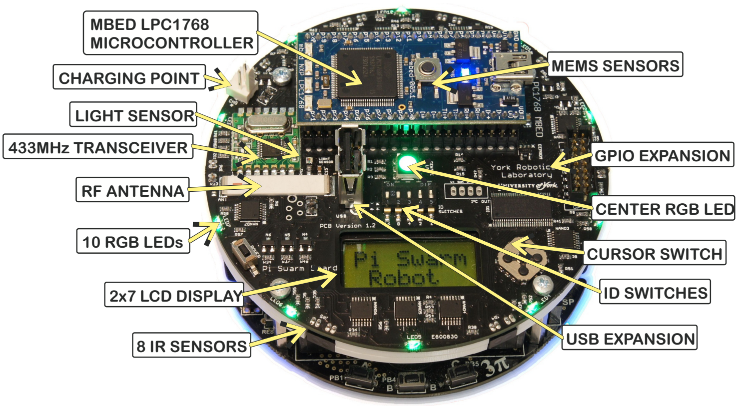


Fig. 1. The Pi Swarm robot annotated with the core features

[2] Prices taken from official UK distributor, Rahal Technology, `www.rahalco.co.uk`, at time of writing.

1.2 The 3-Pi and m3-Pi Platforms

Whilst researching possible platforms that would fit the teaching and research requirements for a new swarm system, it was observed that there exist a number of low-cost robotic platforms already developed which are designed for educational use, without explicitly being part of a swarm based system. One of these platforms, the Pololu 3-Pi, had a lot of desirable characteristics: a simple 2-wheeled design with a circular chassis is a proven platform for development of swarms, allowing simple motion, on-the-spot turning and minimising problems that can occur when robots collide or get very close to each other. The 3-Pi is widely available at a low-cost (approximately £70) and with the use of base-mounted infrared proximity sensors, designed to excel at line-following and maze-solving competitions [1].

The power source, 4xAAA Ni-Mh cells, is low in cost, readily available and easy to charge, and whilst not providing as high a charge density as Li-Ion type batteries, is generally safer. The built-in display is a useful addition not found on many other platforms, allowing debug information or user options to be shown as text on an individual robot. A set of five simple, but effective, infrared sensors on the base of the platform allow line-following tasks to be completed accurately, which provides an excellent introduction into control systems programming. The limiting factors of the basic 3-Pi platform as a swarm robotics platform are its limited processing capability, based around a ATmega328 microcontroller with 2KB of RAM and 32MB of FLASH memory, its lack of communication systems, a lack of proximity sensing and the use of standard geared motors, without wheel-encoders or stepping-motor capability, which limits the accuracy to which position can be estimated. However, it was observed that many of these potential issues could be overcome with the development of an expansion board, and given the low basic cost of the platform this could prove a very cost-effective solution.

Pololu themselves have developed an expansion board, the m3-Pi, for the 3-Pi robot which includes a socket for a MBED LPC1768 rapid prototyping board. The MBED is a small 40-pin module based around an ARM Cortex-M3 microcontroller. One of the core features of the MBED board is it is designed for use with a special set of online compiler tools, which allow for the development of programs from any machine with an internet connection and compatible browser; this eliminates the need for purchasing and installing a specific tool chain [3]. The use of the MBED microcontroller adds a significant boost in raw processing power over the ATmega328 microcontroller on the 3-Pi and provides a wide array of IO expansion buses. Whilst the m3-Pi in itself offers little additional hardware to the base robot, it was observed that it would be possible to add a number of sensors and actuators suited to swarm robotics to the basic PCB, and this forms the basis of the Pi-Swarm system.

[3] Projects created in the online tools can also be exported to a number of different tool-chains designed for ARM microcontrollers, such as Keil μVision, IAR Systems and GCC if desired.

2 Hardware Design

The basic Pi-Swarm robot, as shown in Figure 1, comprises a standard 3-Pi base, onto which a custom PCB: the “Pi Swarm Extension Board”, is attached. It is this PCB that contains most of the sensors and actuators that convert the platform from a standard robot into one specifically engineered with swarm robotics as the core function. The total components costs for the Pi Swarm Extension Board are under £45 [4]. The PCB costs around £10 to manufacture; connecting hardware and plastic parts cost approximately £5 and a MBED board costs £38, bringing the total parts cost for a robot to around £165.

2.1 Pi Swarm Extension Board

The Pi Swarm Extension board is a 95mm diameter circular PCB, which connects to the 3-Pi base using a 14-pin 0.1” pitch dual row 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 4xM2.5 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. The Pi Swarm boards are designed in Eagle PCB design software as 2-layer boards. The board is equipped with the following sensors:

Sensor	**Description**
Infrared (IR)	A set of 8 IR-proximity detectors on the underside of the board, placed at $\pm15°, \pm45°, \pm90°$ and $\pm144°$. The optical component is a TCRT1000 manufactured by Vishay Semiconductor, which combines a phototransistor and infrared emitter. The phototransistors all feed into an Analog Devices AD7997 8-channel, 10-bit analogue to digital converter.
Accelerometer	A MEMS 3-axis accelerometer (ST Micro LIS332AX), which produces an output voltage of 1.25V at zero G and has a sensitivity of 363mV/G over its acceleration range of $\pm$2.0G.
Magnetometer	A MEMS 3-axis magnetometer (Freescale MAG3310FCR1), capable of measuring magnetic fields with an output data rate of up to 80Hz. It has a full scale range of $\pm2000\mu$T and a sensitivity of 0.1μT.
Gyroscope	A MEMS 3-axis accelerometer (ST Micro LIS332AX), which produces an output voltage of 1.25V at zero G and has a sensitivity of 363mV/G over its acceleration range of $\pm$2.0G.
Temperature	A linear digital temperature (MCP9701) which provides an output of 400mV at 0°C and $\pm$19.5mV from this value for each 0°C difference, within the operating limits.
Light	An ambient light sensor (APDS-9005), facing upwards on the expansion PCB. The sensor produces an analogue output of 1V at its peak value, at approximately 1000 Lux of light.

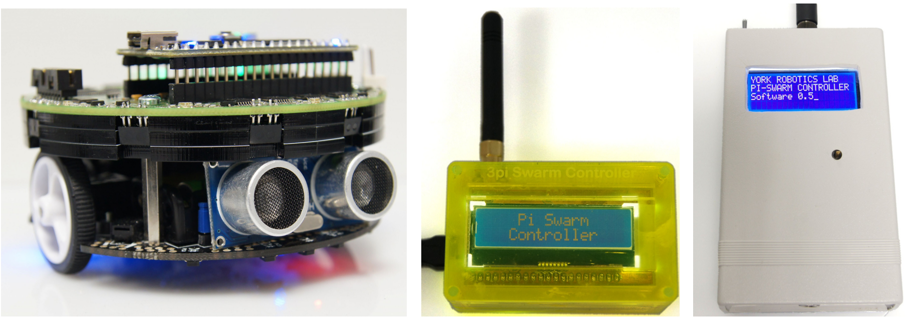
[4] The component are based on purchasing components for 20 boards, and are sourced from major UK component retails, Farnell and RS Electronics.

A number of additional hardware components are included, which allow for communication, visual feedback, user input and data storage:

Component	Description
RF Transceiver	A self-contained 433MHz RF transceiver (Alpha TRX-433) module forms the primary communication system for the Pi Swarms and provides up to 115.2kbps data rate. A chip antenna is mounted on the PCB providing a typical range of 10 meters at the higher data rates.
Outer LEDs	A set of 10 RGB LEDs equally spaced 36° apart in a ring around the edge of the board. These LEDs can be enabled/disabled individually with the colour selected by setting three PWM values.
Center LED	A high-power RGB LED in the middle of the board, facing up. This has independent colour control from the edge LEDs.
ID Switch	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).
Cursor	A 5-way directional switch which may be used to trigger interrupts and control the robot
EEPROM	A 64 kilobit EEPROM (24AA64T) provides non-volatile storage on the Pi Swarm, which can be used to storage calibration values. Additional FLASH memory storage is available on the MBED board.

2.2 Additional Hardware

To increase 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, and contains 40 general purpose Input/Output pins. Of these, 24 are used by the Pi Swarm hardware, and the remaining 16 are available on a 2mm pitch expansion port on the top of the PCB for connecting additional hardware.



(a) HC-SR04 ultrasonic module **(b)** PC Radio Modem **(c)** Hand-held Controller

Fig. 2. Additional hardware for the Pi Swarm robot

A set of plastic shims have been designed which are attached beneath the expansion board in normal use. The shims are laser-cut from 3mm Perspex, and provide protection to the optocouplers from collisions with obstacles. They also help balance the weight of the platform, provide an opaque layer to allow robots to detect other robots, and set the correct height above the 3-Pi to allow the use of 20mm PCB spacers. An additional plastic disc has been designed to attach above the expansion board, which allows unique patterns of reflective tracking balls to be fixed to the robot.

A connector on the underside of the expansion board allows a low-cost HC-SR04 ultrasonic sensor to be attached, facing to the front of the robot. This sensor module is a self-contained unit which can detect and range obstacles which are approximately 10cm to 100cm in front of the sensor. Originally developed for the Arduino range of controllers, it is widely available for less than £2. A Pi Swarm robot with the ultrasonic sensor attached can be seen in Figure 2a.

Whilst communication is primarily handled using the 433MHz transceivers, other communication systems are possible. A USB connector is included on the board and libraries are available for the MBED to use a number of low cost BlueTooth dongles; it should be noted that BlueTooth protocols can impose restrictions on swarm size. Additionally, the infrared sensors can be programmed to send and receive simple messages from adjacent robots.

2.3 Radio Modem

To facilitiate communication between the robot swarm and external sources, two different systems have been developed. The first is a simple radio-modem, shown in Figure 2b, which combines the Alpha-TRX433 transceiver with an MBED board and a 2-line LCD display. The MBED board can be connected to a computer using a standard mini-USB cable, and contains the hardware and drivers to allow it to act as a serial-USB interface. Using this, messages can be sent to-and-from the computer to the MBED, and in turn to the swarm of robots using the 433MHz transceiver.

Additional, a stand-alone handheld controller has been developed, as can be seen in Figure 2c, which includes a multi-directional controller switch and software to allow the remote control of one or many robots simultaneously. A special debug routine has been added to robot firmware to allow the controllers to remotely read the values of the robot's sensors, and control the various actuators. The use of MBEDs in the controllers simplifies code development and the addition of extra sensor inputs.

2.4 Tracking the Robots

A specially designed plastic disc to facilitate the use of a tracking camera system has been designed and tested. The tracking hat is laser cut from 3mm Perspex sheet, and contains 21 regularly spaced 3mm diameter holes arranged in a grid. Short M3 machine screws can bolted through these holes to provide secure mounting points for placing reflective Scotchlite balls for use with the

OptiTrack commercial tracking camera system. A set of distinct patterns of different placements for between 4 and 6 balls on each hat has been created using an evolutionary algorithm based on NSGA-II [3]; these placements ensure that all the patterns are maximally unique in both translation and rotation. More information on the tracking system, the algorithm to evolve patterns and its use in practice can be found in Millard et al [9].

2.5 Battery Life

A drawback of the use of the MBED board is it requires a relatively high current draw and does not provide easy access to the lower power states of its Cortex microcontroller, as can be seen in the table below showing the average power consumption when using a 5V bench power supply. When using high-capacity 1000mAH cells, a battery life of around 2 hours can be expected for most tasks with intermittent motor use.

Device	**Power**	**Description**
3-Pi	400mW	Robot switched on but idle
MBED	800mW	MBED board only in idle loop
Pi Swarm	1700mW	Complete Pi Swarm in idle loop
Pi Swarm	2450mW	Performing obstacle avoidance, motors at 25% power, all LEDs blinking
Pi Swarm	2650mW	Performing obstacle avoidance, motors at 50% power
Pi Swarm	11500mW	Motors stalled at 100% power

3 Software Design

One of the core principles for the Pi Swarm is that it should be easy for someone with limited programming experience in embedded and robotic systems to program. To achieve this, an API has been written which simplifies the process of interacting with all of the sensors and actuators. This is implemented as a published C++ library that can be imported into a new project in the online MBED compiler. The programmer is given a shell *"Hello World"* program which performs all the code necessary to set up the expansion board, start communication with the 3-Pi base and initialise the RF communication stack.

3.1 Communication Stack

The API includes a communication stack for use with the 433MHz RF transceiver which simplifies many of the core communication tasks. A 4-byte header encodes the sender and target IDs, an identifying flag for the message and a set of predefined functions. These functions include operations which allow for most of the sensors and actuators on the robot to be read and set by the external sender. The stack also allows for user-defined functions to be augmented to the pre-defined ones, so more complex interactions can be implemented if desired. Messages can be defined as broadcast, meaning they are to be handled by all members of the swarm, and a TDMA-system based on the robot ID is used to minimise the risk of collisions in acknowledgements and replies. For brevity the API and communication stack is not discussed in detail here, the reader is referred to the manual available online for more in-depth details [5].

3.2 Simulation

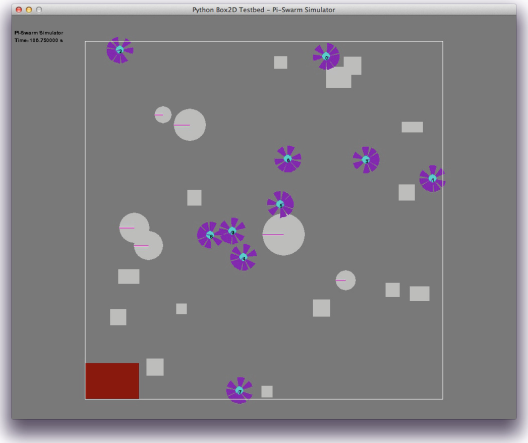


Fig. 3. Pi-Swarm simulator with robots as blue circles with an ID number and IR sensor cones shown in purple. Obstacles are shown in white.

The Pi-Swarm simulator is a 2D top-down environment being developed in Python. It uses **pygame** for graphics and **pyBox2D** as a physics engine [6]. The simulated Pi-Swarms use a simplified model of the physical hardware, they are shown as light blue circles in Figure 3 with a unique ID number and a centre line indicating their heading. The robots move using two wheels on the perimeter of the robot body. A small force is applied at each time-step to represent the motor drive in the direction of movement (either forwards or backwards).

The environment is a square arena with obstacles placed at random locations. The Pi-swarms use 8 IR sensors, at the same positions as the physical robots, to perform obstacle avoidance and navigate the arena. The sensors' fields of view are represented as cones surrounding the robots. When running the robots draw 0.33C from their battery, based on an average use case for the real Pi-Swarm robots. They recharge at a rate of 0.5C in power areas on the ground (bottom left of Figure 3).

[5] Manual and videos available at `www.york.ac.uk/robot-lab/piswarm`

[6] See `http://pygame.org` and `http://code.google.com/p/pybox2d`

4 Case Studies

Despite the short-development time, the Pi Swarm platforms have already been used successfully in a number of taught-courses, research projects and outreach demonstrations. Some examples are outlined below; example videos of some of these projects are available for viewing online [5].

4.1 Maze-Solving Tasks

As an introduction to the Pi Swarm platform and embedded programming, students were required to solve a number of tasks using the platform. These included line-following, making the robots solve a small walled-maze, and locating the warmest or brightest zone within an arena using the on-board sensors and an optimisation algorithm. Some students were starting this task with very limited programming experience and managed to successfully complete all the tasks in 3 x 3-hour laboratory sessions.

4.2 Block-Counting Tasks

As a taught module assessment, single Pi Swarm robots were programmed to autonomously navigate a number of walled-courses. On one side of the wall a number of black lines were painted; the robots were to count the number of lines, then automatically switch to a line-following task when the walls ended. The task was designed to test the students ability to implement effective PID controllers and make use of the various sensors and actuators on the platform to provide feedback from the counting task.

4.3 Creative Demonstrations

Students were assigned the task of performing a creative task over two minutes with multiple robots. This resulted in a diverse set of work, examples of which can be viewed on the website. Some students made use of the lights and high speed of the robots to produce creative synchronised dances; others created novel examples of human-robot interaction with playable games, including a version of the popular "Angry Birds" game in which one robot behaved as the bird, with trajectory and power determined by hand-actions behind the IR sensors, and others as the pigs (the targets for the bird).

4.4 Implementation of a Swarm Taxis Algorithm

A implementation of Bjerknes' ω algorithm, which demonstrates behaviours of aggregation and taxis towards a beacon [2], was implemented on the Pi Swarms. The goal was to replicate prior examples of the algorithm implemented on the e-puck robots. The algorithm was implement using only the IR sensors, which uses signal processing to descriminate between self-, other robots and an IR beacon. The algorithm lets an individual to predict the average heading of the swarm based on the strength of IR signals received, which allows the taxis behaviour to emerge.

5 Future Work

The Pi Swarm platform is still in active development, with new features planned to improve the robots reliability, ease of use and longevity. Some of the current work in progress and future plans are discussed here.

5.1 Scalability

The Pi Swarm has been designed for small swarms of up to 32 robots, based on the budget available and size of arena we currently have, and the limitation of the tracking system that is being used. Whilst the hardware ID switch and the TDMA protocol used in the communication system are limited to 5-bits, these limitations could be adapted with minimal efforts for larger swarms. As observed by Kornienko et al [6], RF-based communication can be problematic when scaled to large numbers. Also, the practicalities of reprogramming and charging become an issue; a system to allow dynamic reprogramming of multiple robots would be a useful solution if scaling to larger swarms was desired.

5.2 Dynamic Recharging

Currently in development is a system to allow the platform to recharge whilst it is in use. The system works by collecting power from the base of the arena, on which a chequerboard arrangement of copper pads allows wide regions of power distribution. The power is rectified by a small daughterboard sandwiched between the two main PCBs which contains a small charging IC, allowing the batteries to be charged whilst the robot is still drawing power. The current prototype model for the recharging PCB and components costs approximately £15.

5.3 Improved Base

One of the most biggest limitations of the platform is the lack of feedback about wheel positions; many similar platforms employ the use of either wheel-encoders or stepper motors which allow turning angles to be more accurately known. The 3-Pi base does use a stable, regulated supply for power to the motors, which allows a good level of repeatability of turns, but this relies on smooth, flat surfaces to avoid wheel slip. With careful arena design it is possible to use the magnetometer or either infrared system to provide feedback on the robots approximate heading; this has been successfully achieved in experiments using a programmable infrared beacon at one end of a 2.5m square arena. However, it is planned to investigate a redesign of the base-portion of the robot (the 3-Pi) with the use of stepper motors to improve its ability to move controlled distances and turns on multiple terrains. Replacing the 3-Pi base will also allow a redesign of the power source; replacing the AAA cells with a combination of a Lithium Polymer battery and low internal resistance supercapicitor will allow for a longer running time and the ability to rapidly recharge the platform.

6 Conclusions

This paper has discussed the design and implementation of a low-cost platform, designed for the teaching and research of swarm-robotics, built on an existing commercial base and easy to use rapid-prototype board. As with all designs, there are limitations and trade-offs the occur between versatility and scalability of the platform and cost; the authors believe, however, that the broad array of sensors and actuators provided coupled with the simplicity of the programming interface of the MBED and the API written for the platform make it a unique prospect for teaching and research. Further information about the Pi Swarm, including the reference manual, schematics, software API and demonstration videos can be found at `www.york.ac.uk/robot-lab/piswarm`.

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