Fleas, Caterpillars and Cockroaches

A Summer School in Bio-inspired Robotics

***Abstract*— There is no doubt that the coming decades will see a continued increase in the application of robotics in our daily lives. It is vital that we encourage more young people to pursue careers in STEM fields and in particular, robotics. Universities can play their part by running events that allow participants to explore the field of robotics through hands-on projects. In this paper our experiences in designing and running a bio-inspired robotics summer school for young women is described. The summer school was successful and we have made the teaching and learning materials available for others to use.**

Keywords—Engineering Education; Educational robots; STEM; Pre-college programs;

I. INTRODUCTION

Over the last few decades computers and digital technologies have revolutionised most aspects of daily life. Education and teaching practices have witnessed significant changes moving from the traditional lecture model, where students are recipients of the knowledge communicated by a teacher, to a more dynamic approach in which activities are structured in a way that allows students to construct their own knowledge [1]. This model of teaching and learning, known as constructivism, is becoming increasingly popular among Science Technology Engineering Mathematics (STEM) teachers and has been shown to lead students towards a better understanding of the subject matter with increased retention and improved performance during exams [2], [3]. Active learning experiences are also effective in encouraging students to integrate knowledge across different disciplines and this is particularly important for multidisciplinary subjects with growing popularity such as Robotics and Artificial Intelligence (AI) [4].

The last sixty years has seen continuing advances the field of Robotics and AI and experts predict that by 2025 autonomous machines will permeate many aspects of our lives. These changes will result in a parallel shift in the jobs market implying an increased demand for skilled engineers and programmers [5]. The purpose of engineering and robotics education is then to allow students to develop skills that will be necessary in their future careers. These skills go beyond "simple" technical knowledge and include, amongst other things, the ability to solve problems, perform critical thinking and implement solutions in an iterative process which is often known as the design cycle [6]. Educational robotics offers teachers the opportunity to develop and use learning activities targeted towards specific goals in design, mathematics, science, electronics and programming. Within the context of a robotics project, students are often encouraged to explore and test the limits of their knowledge in a proactive way. Additionally, the presence of physical outputs provides a tangible response to changes made during the various iterations of the design cycle [7], [8].

II. BACKGROUND

The importance of inspiring and educating a continuous stream of young engineers in the coming years cannot be underestimated. Tech Nation [9], reported that, in 2014, the digital technology economy in the UK accounted for 1.56 million jobs. Furthermore, the sector has a three times faster rate of job growth as compared with the rest of the UK economy.

It will be difficult enough to satisfy this increasing demand but it is widely acknowledged that the UK is already suffering a shortage of engineers with a suitable skillset and that this situation will continue to have a negative impact on the UK economy into the future [10]. Thus, engineering will have both the greatest recruitment needs and suffer, simultaneously, from the greatest skill shortages. Calls for action have been directed to universities, professional institutions and employers to inspire young generations to pursue careers in STEM [10]. In the field of engineering the problem is exacerbated further by the fact that very few girls and young women choose engineering as an option past the age of 18. Women are underrepresented at both undergraduate and graduate level. The reasons for this are discussed in [11] and range from: a lack of female role models in schools and families to a lack of concrete information about engineering careers.

It is worth considering why it might be difficult to ameliorate this situation in UK schools. Engineering and Computing are given little emphasis in the school curriculum. Computing, for example, is taught for one hour per week to children between 11 and 14. Computing has only been taught in most UK schools as a mandatory subject since 2014 [12] and this means that many teachers, who were trained to teach ICT, have had to teach themselves a new, very different skillset to deliver the new Computing curriculum. The main implication of this is that there are few teachers who have studied engineering, or more specifically computing, at degree level working in UK schools. Given that is the case, teachers may not feel confident to advise students about studying engineering after the age of 18 or what the potential job opportunities might be in any depth.

Potentially, there are opportunities to introduce robotics in Computing or Design and Technology lessons in schools. Elementary robotics is a fun and engaging way to teach computational thinking and topics relating to systems and control. The main barrier here is the lack of availability of a low-cost, portable robotics platform. Many schools will have a small number of robots but these can cost over £250 for each robot putting them way beyond the average classroom budget.

Given this is the situation, the availability of opportunities to learn about robotics and engineering outside the core school curriculum is critically important. One such opportunity is the annual UK Robotics week, organized by the UK Robotics and Autonomous Systems (UKRAS) Network and launched in June 2016 with the aim of inspiring the next generation of scientists and engineers [13]. The main theme of UK Robotics week, at least for the activities aimed at schools, is bio-inspired robotics. This is a sensible choice because it gives students an opportunity to take what they know in a subject that they are familiar with, biology, and to learn why and how that knowledge might be useful in a domain that they are unfamiliar with, namely robotics. Moreover, biology is a popular subject with girls. The data for 2015 and 2016 shows that in the UK, about 8% of the girls taking 'A' levels study biology [14, 15], making it the most popular science for females.

We decided to run a bio-inspired robotics summer school as part of our contribution to the 2016 UK Robotics events. We felt that a summer school aimed at introducing female students to the multi-faceted world of robotics could help us breakdown some of the barriers, introducing participants to a field which is traditionally considered hard for everybody, but can be particularly inaccessible to female students. The theme of bio-inspired robotics offers a rich seam of interesting problems and research, attractive to those who have an interest in the application of biological sciences.

III. Objectives of the Summer School

Our high-level objectives were threefold:

1. To engage participants in an exploration of engineering scenarios, investigating how to develop solutions to real world problems.
2. To allow students to apply what they know in Biology and Mathematics to a subject area that is new to them.
3. To showcase what real engineers who are working in the field of bio-inspired robotics are working on.

Above all, we wanted the Summer School to be a ‘hands on’ experience. In [16] the authors describe six Engineering Habits of Mind (EHoM): Systems thinking, Adapting, Problem finding, Creative problem solving, Visualising and Improving as shown in **Error! Reference source not found.**. These are a distillation of engineering behaviours that inform the discipline. EHoM can be used to teach students of any age about what engineering involves and how to move from a problem statement to a solution in an engineering domain. The approach is practical in nature and places a strong emphasis on learning by doing as a means of illustrating the journey from inception to completion in an engineering project. EHoM offers the advantages of leveraging the innate capabilities of the individual, such as the tendency to use physical and practical approaches to learning, and improving the vocational aspect of education. Thus the summer school was structured into three projects of increasing complexity.

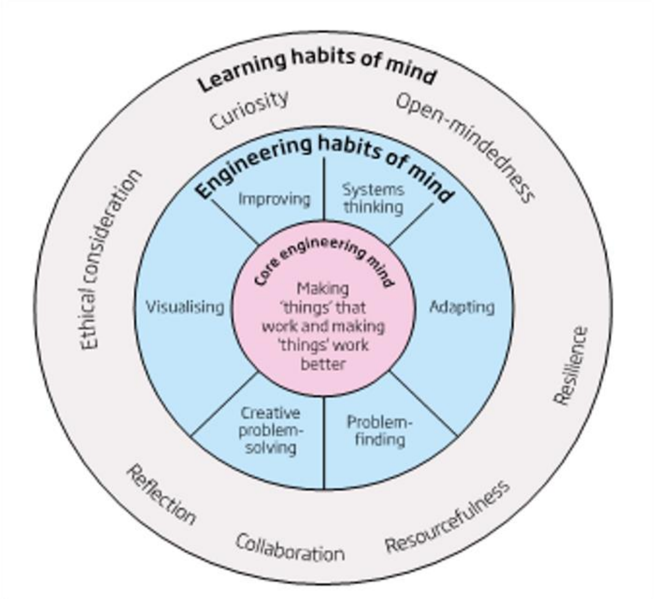

Fig. 1. Engineering Habits of Mind

As identified in [17], implementing any project-based learning activity with young students can be a difficult task. This is particularly true when time is limited and students are unfamiliar with technical aspects of the subject. The teaching team must provide enough scaffolding to enable students to accomplish their goals, at the same time the structure needs to present the students with an open ended problem and allow enough room for creativity and exploration. The inclusion of activities that are fun to do is crucial to the success of a learning experience. Make learning fun encourages independent enquiry, increases retention and motivates students to learn more [18]. It was for this reason that our robot building activities culminated in some kind of test or race to determine whose robot could jump or crawl towards a finishing line most quickly.

IV. Description of the Summer School

We followed a formal application process for the selection of attendees. The criteria used to assess applicant eligibility aimed to ensure that those who would benefit the most from the opportunity were allocated a place whilst also selecting a diverse group of individuals with different abilities, knowledge, skills and backgrounds. Primarily we used information about each student’s grades in STEM subjects, school attainment in general and the progression rates of the individual.

Applications were also weighted based on five additional criteria. Firstly, the student’s geographic location was used to determine the number of students going on to university in the locale. This weighting is known as Participation Of Local Areas (POLAR) [19] and is used to determine the allocation of funding in the UK to support widening participation initiatives. Secondly, postcode data was used as a measure of likely family income. We also awarded points to applicants based on whether they were the first generation in their family to consider pursuing higher education. Finally, a short personal statement and a small number of subject-specific questions were used to ensure that students were motivated to participate fully. At the end of the selection process, 20 girls between 16 and 17 years of age were invited and 18 actually attended.

The summer school was structured around four strands of activity:

- Short lectures in which the foundations of knowledge and skills necessary for the workshop activities were presented by a member of the teaching staff,
- A discussion about some of the ethical issues arising from the creation and use of robots,
- Practical sessions in which participants built robots and wrote software for the robots,
- Talks given by guest speakers who are working in the field of bio-inspired robotics.

The lecture content was straightforward but we were careful to ensure that sufficient context for the practical activities was provided. Considering that no previous programming experience was required, few assumptions were made about participants' existing skillset beyond familiarity with the concepts taught in the UK for 'A' level Mathematics.

We included a discussion in which we encouraged students to think about some of the broader implications surrounding the use of robots. Topics included: the potential rise in unemployment caused by robots in the workplace, the rights of robots and determining legal responsibility for the actions of driverless cars.

The inclusion of guest speakers was important as it gave the participants a broader view of the practical application of some of the concepts and skills learned in school and enabled them to understand the summer school in the context of real world research. To illustrate this, Michelle Reeve brought George, her robotic spider. Michelle is investigating how spiders adapt their gait to leg loss, and how this can might applied to legged robots [20]. Likewise, Richard Bomphrey spoke about his research which sits at the interface of biology and engineering. Richard discussed several examples of studies in which he has used high speed video cameras to film free-flying and tethered insects and birds as a means of understanding and then modelling the mechanics involved [21]. Muna Elmi and Vijay Pawar presented their work on investigating touch sensation in the Caenorhabditis Elegans worm in the UCL TouchLab [22].

The robotics tasks involved robots with different types of locomotion: one jumped, one crawled like a caterpillar and the final robot had six legs for crawling like a cockroach. There was a logical progression in the physical complexity of the robots from the jumping robot, which was a prototype made from cardboard and elastic bands, to the cockroach which had six motor-driven legs. At the start of the summer school we wanted the students to have some experience of the early stages of the engineering lifecycle. The jumping robot exercise was really all about engaging in design and prototyping.

The caterpillar and cockroach robots were built from low-cost, off-the-shelf components that we purchased, such as the motors and the microprocessor, and parts that were 3D printed or laser cut from acrylic sheets. The summer school participants were asked to assemble the parts with nuts and bolts and to connect the electronic components together using jumper wires.

From the outset, consideration was given to the microprocessor, sensors and programming language to use. We wanted to use a board that would be familiar to students and low-cost. Ideally, it should be cheap enough for a young person to buy and available in schools. We chose the BBC Micro:bit [23] because it has an accelerometer, buttons and radio interface embedded on the board; these are of immediate use in robotics projects. The device was launched this year and, at the time of writing, costs £12. In 2016 The BBC gave away 1 million devices to UK secondary schools [23], which means that most pupils will have the opportunity to use a Micro:bit in the classroom in the near future. At the time we ran the summer school, the device could be programmed using C++, MicroPython and JavaScript, however the MicroPython and JavaScript Application Programming Interfaces (APIs) were not yet complete. For example: the MicroPython API had no radio library and the JavaScript API did not allow users to add their own custom blocks. It was for this reason that we opted for C++ with a simple text editor and the mbed yotta toolchain. Although C++ is not ideal for a complete beginner, we do have a significant amount of experience in teaching school children to code using sensors with C++ and the Engduino. The Engduino was designed and developed at UCL and is a forerunner, in its design, of the Micro:bit [24]. Next year we intend to use JavaScript with the Microsoft's block-based Integrated Development Environment as it now has all the features we require.

By constructing our own robots and using a low-cost microprocessor we were able to keep the costs of the summer school as low as possible. For us, this meant that we were able to achieve our goal of having the students work in pairs using their own robot. A bill-of-materials for each robot is given on our web pages [25]. We have not given costs for the 3D printing or laser cutting as engineering departments in universities often have this equipment that can be used at no cost.

At the outset of the week we ran a short, hands on coding activity so that students could explore some of the features of the Micro:bit board and familiarise themselves with the cycle of writing, deploying, testing and debugging code written in C++. In the following sub-sections the practical activities are described in more detail covering what we wanted the students to learn, the scaffolding for the activity and the way in which it was taught.

A. Flea

Fig. 2. Bio-mimetic flea

This was a short, introductory activity taking up about half a day. The participants were asked to make a jumping insect - a flea from cardboard, rubber bands and pins. The primary objective was to introduce the students to prototyping, giving them some hands on experience of the engineering process. Students were given a brief and some hints and were able to watch a video clip of the cardboard flea. The activity was based on a design by Ian Goode [9].

B. Caterpillar

Fig. 3. Caterpillar robot

The second practical activity, lasting about a day and a half, involved constructing a caterpillar from the Micro:bit, three servo motors and the body units. The mechanical design of the robot was taken from [10].

The learning objectives were:

- To consider how the insect moves and to think about how servo motors could be moved in phase to simulate the motion.
- To learn about how servo motors work, where one might encounter them in daily life and the way in which they are controlled using Pulse Width Modulation (PWM).
- To learn about Central Pattern Generators (CPG) and how to simulate a CPG with a series of sine waves to make an oscillator.

A servo motor library was written so that the students had to do less low-level coding. Once the participants had built the robots from the parts provided, they had to write code to synchronise the movement of the motors so that the movement of body units moved simulated a crawling motion. Initially, students were given a template for a program to rotate one servo motor on a button press. From there, they were required to progress through a given set of stages up to the point at which they could drive several motors smoothly through 180 degree rotation. Students who wanted to progress further could use a sine wave to mimic movement driven by a CPG. The final stage of the activity was a caterpillar race which was intended to be fun but also allowed pairs of students to compare their approach to that of the other teams.

C. Cockroach

In the final activity, the summer school students built a roach-like legged robot. The robot was designed to support the students' learning from simple to more complex tasks and had interchangeable wheels and legs. The learning objectives were:

- To learn how to use a continuous rotation servo motor.
- To understand how to move a wheeled robot by controlling the motors.
- To make a controller capable of bi-directional communication for the robot using simple wireless communication and another Micro:bit.
- To use the motors to create a gait with a legged robot using either 2, 4 or 6 legs.
- To use a Hall sensor to determine the position of the wheels or legs.

Initially the focus of the lesson was to set up simple radio communications with two Micro:bits. Students learned to write an event-driven program to send datagrams containing information about the combination of buttons pressed on the controller. We gave them annotated code examples to help them to do this. At the receiving end, they had to write code to make the robot respond appropriately depending on the message received. Finally, they had to show that they could implement bi-directional communication by sending the temperature back from the robot to the controller.

The first tasks that the students had to complete with the motors involved learning how to calibrate the movement and control the speed. They had to show that they could use two motors on a four wheeled robot to start, stop, speed up, slow down and move forwards, backwards, left and right according to the message received from the controller. The students had to design the wheel motion by moving the motors.

Once students were comfortable controlling robot movement with two powered wheels, we asked them to use four motors and subsequently the wheels were progressively substituted with legs. As shown in Figure 3, the cockroach robot legs were modelled as wheels moving around an asymmetric centre in order to give a crawling motion.

Fig. 1. Robot with interchangeable wheels and legs

The students had to think about how they could model a crawling gait with the motors. They were shown video clips illustrating gait in animals showing that pairs of legs move at the same time and that there are points in a stride when pairs of legs are still.

The final task involved controlling the leg motion using the data from a Hall sensor and a magnet. In fact, none of our attendees completed this as we ran out of time. We are confident that next year, as we will using the JavaScript API, some students will progress to this point.

V. EVALUATION

The participants were between 16 and 17 years of age. We asked all of them to complete a short questionnaire to determine their views, attitudes and perceptions. The main aims were to evaluate levels of satisfaction and the impact that the experience had, firstly, on their perceived abilities and, secondly, on their motivation to pursue a degree in engineering. A combination of closed and open-ended questions were used to improve response and question flow. The open-ended questions gave the respondents the opportunity to reply in their own words, revealing the aspects of the summer school that were most important to them.

The first questions were designed to set the tone and ease the respondent into the questionnaire by asking about their reasons for attendance, prior knowledge and participation in similar programs. The remaining questions focused on the most significant benefits and the challenges, the knowledge and skills acquired and the most enjoyable aspects. Students' intentions in relation to degree / career pathways were also explored together with the likelihood of future participation in related activities and suggestions for improvement.

Participants' answers were analysed using Grounded Theory [26]. Students' motivation for participating in the course were varied. The most common reason given for their application was an interest in the field of robotics. Two of the students reported a specific interest in bio-inspired robotics, while the others had a more general curiosity about the topic. Another participant stated that the summer school was recommended to her by a teacher and yet another was keen on learning about design strategies. None of the participants had any previous experience in robotics or with C++ as a programming language although 20% reported some experience of coding. Sixty percent of students reported participating in general STEM or engineering activities in the past.

Eighty percent of the participants said they had previous experience with more general STEM related extracurricular activities, but no previous experience in coding. Based on this, we were not surprised to find that over 70% of students declared that the biggest challenge they encountered was the coding. On the other hand, students stated that their ability to write basic C++ code was one of the biggest benefits they obtained from participating to the summer school. Other skills that the participants felt they had developed were learning about coding in general, problem solving abilities, critical thinking, familiarity with the iterative design process, teamwork skills and the ability to perform independent enquiry.

Students reported that the practical robot building sessions were the most engaging part of the summer school. When they were asked about the activity they enjoyed the most, 80% of participants described the process of building and programming the caterpillar as it allowed them to explore different options in order to find their optimized movement pattern. The presence of a final competition was also very well received as it encouraged the "*perfect level of competition between teams and camaraderie among teammates*". Other students also enjoyed the opportunity to interact with researchers working in the field.

Overall the summer school received extremely positive feedback and all participants stated that they would recommend the experience to a friend. When asked about how likely they were to attend similar programmes and activities in the future, 40% of students rated the possibility as extremely likely and 60% as very likely. The ultimate goal of our summer school was to motivate young students to pursue a career in STEM, for this reason we were very pleased to discover that 80% of participants described it as extremely likely that they would apply to study Computer Science or Engineering at degree level. Lastly, we asked all participants to suggest possible improvements for in future editions of the summer school. The majority of respondents advocated for the inclusion of a larger number of external speakers. However, it was also mentioned that talks given from external speakers should be made as engaging as possible by the inclusion of demos and interactive activities.

VI. LESSONS LEARNED

The Robotics Summer School for girls was, in the end, a successful and engaging experience for both educators and participants. Throughout our journey we learned few lessons, sometimes the hard way, which we would like to share as we believe that they could be valuable for those people delivering similar activities, especially those who might be organising an outreach program for the first time.

A. *Assemble a competent and motivated team*

There are several reasons why this is important. Firstly, one of the main aims of any outreach activity is to motivate young students to pursue a particular career, or course of studies. As noted in [27], a demotivated instructor can have a detrimental effect on participants' motivation. Secondly, most university staff or students involved in the organisation and delivery of outreach events do so on a voluntary basis. If the person is not enthusiastic about the project, it might become increasingly hard to keep working on it when more pressing commitments come along. Thirdly, outreach events, particularly on the first run through, often require adjustments on the fly necessitating a team of people who are able to respond quickly to unexpected events.

B. *Budget carefully for equipment and people*

The two main budgetary expenditures were costs for support staff and equipment. In a course for programming and robotics novices we recommend a ratio of 1:6, maximum 1:8. Students are likely to need 1-to-1 support at some points and significant delays might lead to feelings of frustration or cause them to lose interest. Overstocking some of the equipment is also a good idea as there will be component failures.

C. *Set rewarding intermediate goals*

It is key that participants remain motivated and engaged and it is important that they feel they have accomplished something even if they do not reach the end of a particular project. For example, none of our teams were able to generate a caterpillar movement that followed a sinusoidal pattern with a constant phase shift; however, all teams were able to write code to move the servos in series. This was viewed by participants as a considerable accomplishment in itself and guaranteed them the ability to enter the robot race at the end of the activity. The students felt proud of their achievements and of their new-found ability to write code of increasing complexity.

D. *Prepare the material according to participants' abilities*

Our primary objective was to inspire students and show them what engineering really is, rather than instruct them on basic programming principles. This means that students must write code to achieve their immediate goals without using complex programming syntax. We recommend using a block-based programming language, if possible and writing libraries that will allow students to accomplish the goals without needing to use complex data structures or programming constructs.

VII. CONCLUSION

In the near future, the fields of Engineering and Computer science will witness both an increased demand and a shortage in the availability of skilled graduates. In this paper we presented a bio-inspired robotics summer school, targeted at young female students, that was organised by the Department of Computer Science, UCL. The summer school was structured using a learn-by-doing approach to provide students with a more engaging and active learning experience. The practical activities helped students to improve their programing skills and to develop some of the EHoM that constitute the core of any engineering discipline. The summer school was successful in increasing student motivation to pursue an Engineering or Computer science degree in their future studies.

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