Developing Extended Real and Virtual Robotics Enhancement Classes with Years 10–13

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Abstract There is growing evidence of the potential of educational robotics to enhance science, technology, engineering and mathematics education provided that they are deployed carefully. This paper describes a developmental research project between a university and a secondary school in the UK to develop extended robotics enhancement classes, mainly using LEGO MINDSTORMS robotic kits, and GeoGebra, which was used to animate virtual robots. Two styles of class were deployed: student-led project creations and facilitator-led challenges. The pedagogical principles underpinning these classes and their design are discussed. Feedback generally indicated that the classes were successful and appreciated by the students but they experienced difficulties in incorporating the virtual robotic element. Lessons learnt from the project, including the development of employability skills, the potential impact on students with autism, and the effective use of peer students, are discussed. The possibility of combining the two styles of class together is proposed.

Keyword Developmental research • Learning by design • STEM education • Robotic kits • LEGO MINDSTORMS • Virtual robotics • Geogebra • Employability skills

1 Introduction

According to Sanders [1] interest in science, technology, engineering and mathematics (STEM) education increased rapidly in the USA following the publication of Friedman's book [2] in 2005. Friedman concluded that China and India were on

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course to overtake the USA in the global economy by surpassing their STEM education output. The supply of employable STEM graduates has also been an increasing cause for concern in Europe in recent years [3–5]. The international comparative Relevance of Science Education research project which investigated the views of adolescent students [6] found a strong negative correlation ($r = -0.85$) between their interest in a future science career and the wealth of their home country. This indicates that many developed nations, including many in Europe, face the challenge of meeting the demands for STEM employment. Furthermore, inquiries into employers' views indicate that, in addition to subject knowledge, many STEM graduate roles require softer skills, such as communication, using initiative, problem solving, teamwork and creativity [7, 8] which are not traditionally taught in secondary or tertiary education.

In response to these concerns, government programs and institutional research projects have been initiated on both sides of the compulsory education threshold. Their strategies have included creating greater awareness of STEM careers through employer partnerships [7, 9] and seeking to make STEM education more enjoyable [9]. Others have encouraged the acquisition of softer skills by introducing project enhancement work into the curriculum [10] but these have mainly taken place in Higher Education due to the pressures from national and international league tables on compulsory school education [11]. These encourage schools to emphasize individual performance and teaching to test rather than promoting divergent thinking [11], preparing students for the collaborative and unpredictable world of employment, or developing a love for academic subjects, or a deeper emotional engagement with them [12].

Some initiatives to make STEM subjects more enjoyable have been criticized for lacking effectiveness [9]. However, we assert that it is not the subjects that need to be made more enjoyable, but the use of appropriate challenges in the experience of engaging with the subject that needs to be encouraged, as the subjects themselves are potentially intrinsically enjoyable to many students. The first author has described this approach as "putting the curriculum into the fun rather than the fun into the curriculum" [13, 14]. In the context of learning technologies, what is required is an understanding of which technologies are intrinsically engaging and enjoyable from the perspective of students' informal use in their free time and how such technologies could be incorporated into the curriculum [14].

One potential type of learning technology is *educational robotics*. There is growing evidence that these have the potential to enhance learning, engagement and employability skills in STEM subjects provided that they are deployed carefully [15–17]. There is also evidence of the potential of *integrated computer algebra systems* (CAS) with *dynamic geometry systems* (DGS) to enhance mathematics education when used thoughtfully [14, 18]. This paper reports on an ongoing developmental research enhancement project over the last 5 years between a secondary school and a university in the UK to develop extended robotic enhancement classes with Years 10–13 students using robotic kits in conjunction with an integrated CAS/DGS.

The background to these classes is introduced in Sect. 2. Section 3 provides a summary of the research and development framework used in the classes. Performance and feedback on the classes is reported in Sect. 4. Finally, Sect. 5 provides a discussion of the outcomes of this developmental research project as a whole and a possible improvement on the class design.

2 Background

The origins of our collaboration was a teaching idea paper [19], written by the first author and published in 2010, which suggested using robotic kits along with a mathematical simulation environment called GeoGebra (http://www.geogebra.org/) in a context of open-ended project work in order to motivate mathematics learning. The School has a selective intake and aims to develop well rounded students by blending traditional style lessons with enhancement activities, both within and outside class time. Under the UK General Teaching Council's Teacher Learner Academy (http://www.gtce.org.uk/tla/) staff were encouraged to undertake projects to stimulate their learning experiences and that of their pupils, supporting each other within and beyond their normal settings to enrich their pedagogy, thereby fostering innovation. In 2010, they were awarded LEGO Innovation Centre status [20], which enabled them to purchase LEGO MINDSTORMS robotic kits (http://www.lego.com/en-gb/mindstorms/) for use with older students, and were seeking a way to use them effectively. A member of staff from the School read the paper and contacted the first author who was given permission to work with the School.

Table 1 Summary of robotics classes

Year	Class type	Length (days)	No. students	Technologies used	Evaluation
2011	Free time, student-led projects, individual and group	5	5	LEGO MINDSTORMS, GeoGebra and Bioloid	Presentation and peer review
2012	Free time, student-led projects, individual and group	4	11	LEGO MINDSTORMS, GeoGebra and Bioloid	Presentation and peer review
2012	Enhancement class, themed challenges, group	3	17	LEGO MINDSTORMS and GeoGebra	Performance in challenges and sportsmanship
2014	Enhancement class, student-led projects, group	3	7	LEGO MINDSTORMS and GeoGebra	Presentation and peer review
2015	Enhancement class, themed challenges, group	3	11	LEGO MINDSTORMS and GeoGebra	Performance in challenges plus bonus

A summary of the classes which have been provided so far is shown in Table 1. The first two classes were slightly longer, operated in student free time and used a student-led project approach. The three later classes were organized in school enhancement lesson time; and two of them deployed a themed challenge approach.

3 Research and Development Framework

3.1 Research Methodology

The overall purpose of these classes was to *develop educational enhancement environments using real and virtual robots that are engaging, facilitate the acquisition of employability skills and motivate further STEM learning*. A research methodology appropriate for a partnership between researchers and teachers at a university and teachers and students at a school for the development of these classes was required. The nearest similar research known to the authors into the development of classes by a researcher/teacher using a similar technology is that used by Jaworski to develop classes using GeoGebra to teach algebra concepts [21]. She reflected upon her practice as a teacher in the implementation of her chosen pedagogy and concurrently as a researcher into the effectiveness of the pedagogy itself, referring to this approach as *developmental research* [22]. This paradigm was therefore chosen as it was seen to be more appropriate than analyzing and developing classes from a single role identity, such as in action research for researchers or reflection-on-action for practitioners.

3.2 Pedagogical Framework

The pedagogical framework for these classes combined several ideas from the teaching idea paper by the first author [19] with other principles elaborated in [23]. Fundamental to the former was the combined use of real and virtual robotics to motivate learning rather than teaching directly. The rationale for experimenting with this approach was the remarkable success, reported in [18], of the use of Classpad CAS/DGS calculators to motivate learning in algebra and geometry. As already explained, GeoGebra can also be used as a CAS/DGS. Using GeoGebra also provided a way to attempt to motivate mathematics learning using robotics through animations.

The *educational robotics* movement can be traced back to Papert's *Mindstorms* book [24] which encouraged social engagement and language development in a 'math' world, and which led to the (mainly virtual) turtle graphics movement. The combination of real with virtual robots is a novel idea, although it was anticipated by Burdea [25] in a wider context who foresaw one advantage being more effective *planning*. This is consistent with the use of simulations in other areas of mechanical engineering, such as computational fluid dynamics in aircraft design. Real robots are more kinesthetic than virtual ones and encourage greater social identification, which Catlin and Blamires [26] have called the principle of *embodiment*. Eisenberg [27] argued for a greater emphasis on physical robots in mathematics education as “transitional objects” which bridge the gap between concrete and formal reasoning.

Another important element of the class pedagogy was *learning by design* [28]. This promotes providing learning environments where students are given the space to create and develop their own ideas. It contrasts with *teacher-led challenges*, often involving constructing and programming a pre-planned robot design to achieve a pre-planned purpose, and *robotic competitions*, often involving pre-set challenges requiring some ingenuity. In a study of 64 engineering undergraduates, Cropley and Cropley [29] found that students without creativity training were so used to following instructions that they focused on conventional designs in robotics challenges even when they were marked for creativity. Learning by design was therefore employed as these classes were aimed at enhancing the curriculum and encouraging creativity.

The classes also made use of teamwork and peer learning. Teamwork is commonly used in robotics competitions, such as the FIRST which employs teams of 20 or more students (http://www.firstinspires.org/robotics/frc/what-is-first-robotics-competition). However, in their review of computer supported group-based learning, Strijbos et al. [30] found that teams of two or three were more effective for performing complex technical tasks due to the amount of effort required to achieve consensus. Atmatzidou and Demetriadis [31] argue that, “although the [educational robotics] practitioners have a clear orientation toward collaborative learning activities, they, nevertheless, lack a more detailed pedagogical perspective of how to tap the benefits of group-based learning”. By viewing former class members as an educational resource, peer learning [32] provides such a perspective. Consistent with [11], emphasis was placed on their experience with former classes rather than their ages.

3.3 Choice of Technology

The main technologies deployed in the classes were LEGO MINDSTORMS NXT kits and the GeoGebra software environment. The first two classes also used a more sophisticated ROBOTIS Bioloid Comprehensive humanoid robotic kit (http://www.robotis.com/xe/BIOLOID_Comprehensive_en). This kit was inappropriate for the two challenge-based classes. The choice of appropriate kinds of technology for these classes is discussed in more detail in [33].

LEGO MINDSTORMS NXT kits comprise of a programmable brick which can generate sounds, LEGO bricks and other pieces, three different kinds of sensors, and servo motors [34]. They are used in conjunction with a visual programming language which controls the robot’s behavior according to a series of instructions or events based on inputs received from the sensors. Once a robot has been built and a program written it can be downloaded onto the brick. The ratio of available robotic kits to students was quite high but, in order to give each team an equal opportunity, they were limited to having *two kits per team*.

GeoGebra is an open source dynamic mathematics software environment. It comprises of six alternative views covering different aspects of mathematics and statistics. In particular, it integrates a dynamic geometry system with an algebra view, enabling the representation of physical objects, such as robots, to be constructed and animated, both visually and symbolically. [35] provides the animation of a LEGO MINDSTORMS robot moving through three points on a plane which was used as the basis of a minimal instruction activity in the first three classes.

3.4 Class Design

Each class began with a series of briefing sessions on the first day led by the University partner. These all included an initial challenge to construct and program the first robot design in the LEGO MINDSTORMS NXT instructions book and a GeoGebra training session and challenge. In the more recent classes the students were organized into groups and briefed on the activities for the main period of the class. Two different styles of class were then adopted:

- *Student-led project design*: Students were given the freedom to create their own projects within the parameter of being achievable within the time period available. In the fourth class the students presented and peer assessed their plans before they created and programmed their robots. This approach was similar to that used by another UK university with their first year engineering undergraduates [10].
- *Themed challenges*: Students were briefed on a number of specific challenges around an engaging theme for which they were required to build a robot. The third class included three challenges with an Olympic theme, coinciding with the 2012 Olympics. The fifth included a series of challenges with a Rugby theme, coinciding with the 2012 Rugby World Cup (see Fig. 1).

The middle class period lasted between one and three days and was facilitated by members of staff from the School and/or peer students who had participated in previous classes at a lower level. The final day of most of the classes started with a re-briefing session followed by a final period for robot development. This was either followed by the presentation of robot designs with a peer review of their performance in the themed challenges for which they were either scored or ranked. After this there was an award and certificate giving ceremony. Finally, students were asked to reflect upon their experiences and make suggestions for improving the classes in future.

Fig. 1 LEGO MINDSTORMS robot in the fifth class making a conversion 'kick'

The assessment of the robots for the themed challenges included a peer reviewed sportsmanship score in the third class and a peer student discretionary award for sophistication in the fifth class. These were included to encourage the students to look beyond the competitive aspects of the challenges to the wider purpose of the class.

Certificates were awarded according to the level of participation of the students:

- *Level One*: Participation in a class as an individual or group member
- *Level Two*: Facilitation of a class
- *Level Three*: Design and facilitation of a new class

Students who had been awarded a certificate were encouraged to engage in a later class at a higher level as a peer student.

4 Performance and Feedback on Classes

4.1 General Findings

Firstly, we note that these classes were held at a male secondary school with a selective intake. The students were therefore relatively intelligent, well behaved and competitive. Furthermore, in common with most UK secondary schools, the students were used to following instructions, so many found the idea of student-led project work, requiring creativity with limited rules, unusual and challenging. A surprising finding was the students' general lack of initiative with using the Internet which appeared to be due to their restricted access within their normal school environment.

Several planning meetings, sometimes involving peer students as facilitators, were held before each class took place. Students self-selected to attend classes which were advertised in the School. There were occasional issues with facilitators not fully understanding the design of the classes, which were quite different from normal lessons.

Observations and improvement recommendations were made by the university researchers, the staff facilitators, and the students as part of their reflection at the end of each class. The students participated in the training activities and generally picked up what to do quickly but some had the tendency to go off task quickly if they became bored. This confirmed the importance of the constructivist principle of seeing the training as *minimal instruction* [23].

An initial aim of the classes had been to motivate deeper mathematics learning by using GeoGebra to create accurate robotic designs requiring use of its algebra view [19]. However, the earlier GeoGebra training sessions were disappointing as some students with weaker mathematics backgrounds found the programming too hard and failed to connect virtual animation with the robotic kits. They also appeared to have a kinesthetic preference to use physical robot kits. The training was therefore simplified by only including a straight line movement, using a rectangle to represent a physical robotic table, and, moving away from a turtle graphics declarative style program, by adding a feedback event to represent an ultrasound sensor locating a wall—see Fig. 2. This was an improvement but there remained the challenge of encouraging students to use GeoGebra later in the classes. In view of these difficulties, the overall success of the robotic kits, and consistent with the developmental research paradigm, this aim was widened to motivating STEM learning in general.

Whilst the challenge-based classes were more competitive, some students lost interest once they had developed a robot to meet a challenge which initially captivated their interest. This was particularly evident in the third class when some students did not attend the full class once they had built a speed robot using gearing. However, their groups did not perform well on another more technical challenge to throw a ball. Whilst the students in the student-led classes found the freedom more daunting, they all remained engaged throughout the class. The possibility of combining these two approaches is discussed in Sect. 5.

The fifth class was mainly designed and led by two peer students from Year 13 who had participated in a previous class. They only received limited advice during their facilitation and were able to manage the sessions and keep the other students

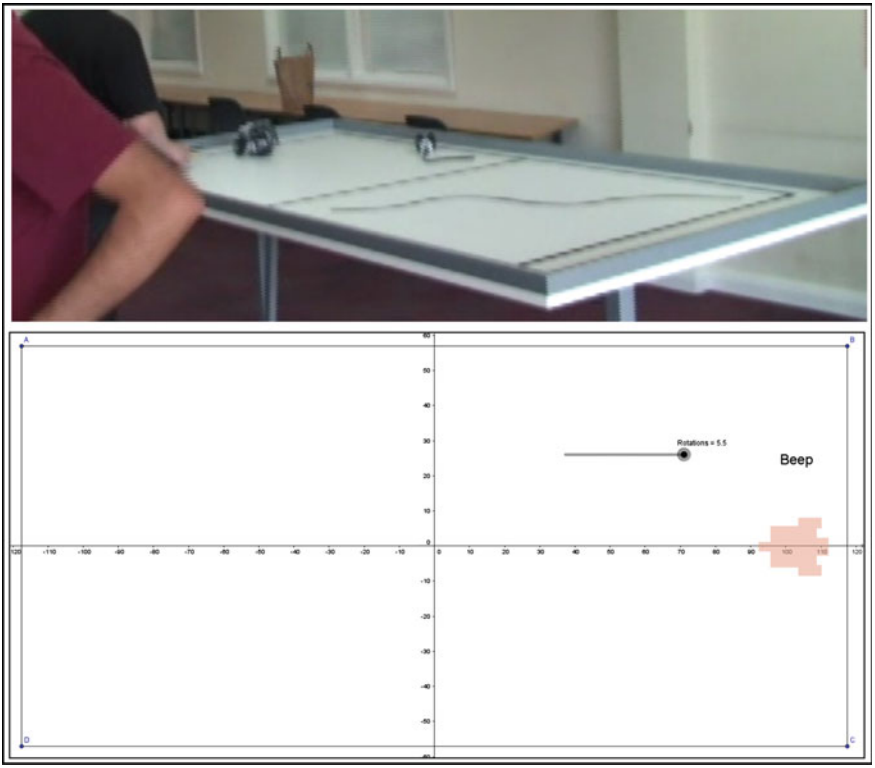

Fig. 2 Robot table and revised GeoGebra animation representing a robot translation on a table, beeping when it senses a wall (*source* https://www.geogebra.org/material/simple/id/2807751)

engaged. Whilst some of the decisions they made about rules and scoring of challenges were mildly criticized by the other students, this was seen as a positive learning experience for them to become more proficient in *design* and *facilitation*, which are themselves valuable employability skills.

4.2 Feedback

On the whole the students' feedback at the end of the classes about their experiences was positive, indicating their affective engagement [11, 12, 36]. Of the 33 written student feedbacks obtained from three of the classes 42 % mentioned enjoyment or fun whilst none of them made a negative comment about their overall experience. 12 % also mentioned that they thought the class design idea was good. Student enthusiasm was also demonstrated by some having to be told to leave at the end of the day in the school time classes whilst others gave the course leaders gifts.

In terms of the technical skills learnt, student feedback made predictable references to learning to construct (27 %) and program (36 %) robots that achieved the required goals. The LEGO visual programming language was often criticized, especially by students who had experience with other programming languages. One specific technical skill several students reported was learning how to use *gearing* (12 %) in order to make robots move faster.

Student feedback made frequent references to acquiring employability skills. The most common themes identified were *teamwork/cooperation* (79 %), *time management* (36 %) and *creativity/problem solving* (30 %), indicating that most students perceived these to be important skills that they had developed, enhancing what they had learnt from the standard School curriculum. However, there was little mention of *planning/designing* (15 %) which may have been due to the immediacy of the robotic kits encouraging repeated experimentation rather than reflection. This is discussed further in Sect. 5.

On the negative side, 53 % of students in the third class reported that the sportsmanship peer evaluation had not worked well. A reason given for this was that some teams had used tactical scoring. It was therefore decided that the facilitators should be made responsible for this in future. This appeared to work well with the fifth class as the student feedback did not comment on this aspect negatively.

4.3 Impact of Class on Students with Autism

An unexpected consequence of the first two classes was their positive impact on some autistic students. Over 10 % of students who had attended a class were identified as autistic, representing a much higher than average prevalence rate. However, all the autistic students joined in and performed well in the classes. For one student in particular the classes had a completely transformative effect to the amazement of his teachers, one of whom stating that she had "never heard him laugh before". He was even willing to be videoed demonstrating his new-found understanding of the principle of gearing—see Fig. 3. He then progressed to facilitate a second class he attended. This success is consistent with the aspirations of [37].

It is believed that Catlin and Blamires' principle of *embodiment* [26] is particularly relevant to autistic students as they appear to be comfortable with relating to robots as a projection of human relationships but without fear of violating social rules. Relating to other people in this context also appears to be less threatening to them, thus increasing their confidence in social engagement. Dautenhahn and Werry [38] go further in claiming that it may also be the physical movement by the autistic students themselves within the robotics class which might be therapeutic.

Fig. 3 Autistic student demonstrating to the camera the effectiveness of gearing

5 Discussion

This developmental research project has made progress towards its aim of developing an educational enhancement environment using real and virtual robots that is engaging and facilitates the acquisition of employability skills. The aim to motivate further STEM learning affected the design of the classes but was not evaluated. LEGO MINDSTORMS kits, although their software was not universally liked, have the potential to be used effectively in such classes. The use of a three level certification structure, employing peer students from previous classes as facilitators and class designers has demonstrated the value of seeing former students as an educational resource. The classes were also unexpectedly successful with autistic students, with the first two having a profound effect one student in particular.

The virtual robotic element with GeoGebra has yet to be proven, although the GeoGebra training activities have been improved. The class designers still believe that GeoGebra should be retained in order to encourage awareness and use of the employability skill of planning. Based on feedback from students in the fifth class, a possible way forward was identified. As the challenge-based activities are easier to follow but may not be as engaging it is proposed that the middle class period should be split into two halves, the first half being a series of challenges and the second half a student-led project. In order to encourage planning, as in the fourth class, students will be required to submit a plan of their project ideas for peer review before they develop and present the project itself. They will not be forced to use GeoGebra but it will be provided as an option (along with alternatives, such as animations in Microsoft PowerPoint). This new design will be investigated in the next class. The use of GeoGebra and alternatives to represent other robotic sensor events will also be explored.

The success of the project's pedagogy has also impacted positively upon the approach of the class designers in their other teaching enhancement activities, causing them to trust students more to develop their own ideas and providing them with less direct guidance. We believe this style of robotics class could be employed in similar contexts to encourage engagement with STEM education and the development of employability skills.

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