LINKING MATHEMATICS CURRICULUM AND CONCEPTS TO ROBOTICS ACTIVITIES

Vladimir Estivill-Castro

Griffith University (AUSTRALIA)

Abstract

We regularly receive at the university students from high school as part of our STEM educational activities. The students have very different backgrounds because they can be as young as year 6, or already in year 12. Thus, we face the challenge of designing learning activities that teach robotics concepts within two hours, and that can be adapted to the diversity of the group in turn. We want to make explicit to the visitors the links between STEM (Science, Technology, Engineering and Mathematics). We have designed a stream of activities accompanied by a book of problem-solving exercises that jointly offer a series of challenges. The activities involve programming LEGO-Mindstorms. The problem-solving exercises introduce many concepts and provide a rapid learning curve, from simple problems to even open issues within the research community. The aim is that students would be motivated to study further the exercise book, suggest problems to their teachers back at school and gain an appreciation by the motivation the problems provide for several mathematical ideas.

Keywords: STEM, Mathematics curriculum, Forums for Mathematics and technology teachers.

1 INTRODUCTION

We regularly receive at the university students from high school as part of our STEM educational activities. The students have very different backgrounds because they can be as young as year 6, or already in year 12. They also may have chosen a profile for Engineering and Technology (and thus they are studying or completing different mathematics curricula), or because they are not even in high school (Year 6), they have an initiation to mathematical concepts and programming.

Thus, we face the challenge of designing learning activities that teach robotics concepts within two hours, and that can be adapted to the diversity of the group in turn. We want to make explicit to the visitors the links between STEM (Science, Technology, Engineering and Mathematics). We want to excite the students about the changing technological world and leave them with opportunities for further investigation and exploration.

We have designed a stream of activities accompanied by a book of problem-solving exercises that jointly offer a series of challenges. The activities involve programming LEGO-Mindstorms. The problem-solving exercises introduce many concepts and provide a rapid learning curve, from simple problems to even open issues within the research community. The aim is that students would be motivated to study further the exercise book, suggest problems to their teachers back at school and gain an appreciation by the motivation the problems provide for several mathematical ideas.

We have used the design activities and the book of problem-solving exercises in 4 sessions with students. We have also described the activities to 3 groups of high-school teachers as part of two professional-development conferences to teachers. Feedback from teachers and student participants has been very positive regarding the motivation implied by the challenges and open problems.

For example, our first activity may be rather simple. It requests to build a program so the robot moves its arm in a specific position. The configuration of the robot is such that there is only one fine motor and the program is tiny. It only uses one block. By using the vast amount of resources about LEGO-Mindstorms or the guidance of the instructor, we have seen every Year 6 child or older complete this task. Thus, every child succeeds with the first problem.

However, from here one can communicate the next challenge to the pupils that is conceptually quite advanced. But this is the virtue of our problems, they are understood across the diversity of the students. We immediately suggest creating (coding) behaviour, so the robot can engage, or compete against other similar robots in a tournament of the game, scissors, paper, rock. We introduce concepts such as Nash equilibrium and mixed strategies.

Children change of perspective when we think of machines as instruments that deterministically repeat a task, such as ordinary microwaves. It is another matter to think of machines which would execute a random choice. That is, under exactly the same settings and circumstances, they may act differently. Even more fundamental, whether machines could think.

Later challenges introduce frame of references, similar triangles, trigonometric functions, vectors, limits, differential calculus, control theory, and connections to ethics, science, and the theories of the mind. All of these enable children to at least understand the problem and what is a suitable solution (even if such solution is hard to obtain).

There is a long history of stimulating interest in STEM using robots and in particular LEGO Mindstorms [1]. As a result, numerous camps and competitions have been part of extensive programs where robotics is applied to stimulate the interest in STEM subjects with positive outcomes [2,3,4,5,6,7]. Our immersion or intervention is short, and has no intention to culminate in a competition, as has been the case of other uses of robotics to stimulate interest in STEM [8]. We aim for an approach that promotes cooperative learning [9].

2 METHODOLOGY

Our methodology for the design of the activities consisted of an evolution of the design of the learning objects and the learning materials. Initially, the materials were designed for a robotics club in a high school. We developed four sessions with practical exercises. We see several advantages of using LEG)-Mindstorms: value for money they constitute very robust hardware. They hardly break, and although the rechargeable battery pack is sold separately, investing in it is rewarded by the savings in batteries and the elimination of disassembling/reassembling the robot when batteries need replacement. Also, batteries left on the robot for too long do eventually leak and damage it beyond repair.

The second step consisted of inviting high-school students to have an industry-experience stay at our laboratory in the University and act as the first testers of the activities and explorers of our book. We had one sixteen-year-old (grade Year-10), Erasmus college student, participate in a one week stay exploring the learning objects we had at the time.

Besides conducting the activity already four times, we have also described the activities to 3 groups of high-school teachers as part of two professional-development conferences to teachers. We performed a survey with the school teachers. Figure 1 shows the questions in the survey.

1. How much do you believe the robotics activities would stimulate interest for students to self-explore some topics in mathematics?

2. How much do you believe the robotics activities as presented could produce cross pollination of topics from mathematics, science, technology and engineering or even history, English or social science?

3. How much do you believe the robotics activities as presented could show students challenges, which are simple to state, are a path to researching topics where even the most advanced techniques are not the definite answer?

4. How much do you believe the robotics activities as presented could engage students in developing skills at higher levels of the Bloom taxonomy (applying, evaluating, creating)?

5. How much do you believe the robotics activities as presented offer open-ended challenges where there is not a single correct answer?

6. How much do you believe the robotics activities as presented offer opportunities for interaction in teams of students of different levels (year 9 with year 10 and year 11, or even year 12)?

7. How much do you believe the robotics activities as presented could be as interesting to females than to males?

8. How much do you believe the robotics activities as presented could suggest to students there are career opportunities in STEM (science, technology, engineering and mathematics)?

Figure 1. Questions in survey for educators.

The judging instructors used a 5-point Likert scale [10] with options a) Not at all b) Little c) Neutral d) Some interest e) Definitely.

3 OVERALL DESCRIPTION OF THE ACTIVITIES

3.1 The link from start to end

Our first activity may be rather simple. It requests to build a program so the robot moves its arm in a specific position. The configuration of the robot is such that there is only one fine motor and the program is tiny. It only uses one block. By using the vast amount of resources about LEGO-Mindstorms or the guidance of the instructor, we have seen every Year 6 child or older complete this task. Thus, every child succeeds with the first problem. Figure 2 shows that using the LEGO visual programming tool, the program is elementary. However, the learner must overcome all the other challenges of turning the robot on, porting the application to the robot and executing it.

This simple setting may already motivate the introduction of trigonometric functions, their presentation using the unit circle.

Moreover, teachers also succeed because the robot we use is the LEGO-Mindstorm design named TRAC3R. It is a configuration whose building steps are provided in the kit that includes the pieces. It can be constructed with an hour and provided a differential robot with the precision motor holding one arm.

However, from here one can communicate the next challenge to the pupils that is conceptually quite advanced. But this is the virtue of our problems, they are understood across the diversity of the students. We immediately suggest creating (coding) behaviour, so the robot can engage, or compete against other similar robots in a tournament of the game, scissors, paper.

The game of scissors, paper, rock is remarkably international. However, the concept that the tournament has the variation that submission of a competing code must be accompanied by the disclosure of the code, enabling opponents to adjust their program under the knowledge of their adversaries' program is initially surprising. Nevertheless, children rapidly understand that a program that acts deterministically and plays ten choices can be beaten by a program that chooses the winning posture for those ten choices. Notions like determinism and randomness rapidly come into the imagination, and with little prompting but perhaps some oriented debate children realise that a randomised strategy is in some sense optimal. What we are saying is that students of all the age groups we have mentioned can be guided with this illustration to understand the notion of Nash equilibrium, utility, a mixed strategy, probability and expectation.

The mathematical intuition behind the concept can be motivated this way, and some fundamental notions of mathematics as well, such as probability, determinism and non-determinism. And as we mentioned early, some of the most profound problems of the research community (such as randomness, which is crucial today to cyber-security and cryptography) can be explored as a result of the debate this problem generates.

Even at this level, some advanced concepts can be debated. Children can be invited to reflect what types of 2D shapes can be produced by a robot with only one rotor. The problem can first be described in 2D, but very interesting problems can be debated regarding what can be drawn (in 2D) with an arm of 2 links (or in 3D with different types of joins). We hope to illustrate here how the problem remains realistic but rapidly complex. It is easy to express the question for students to appreciate the problem, it may be a long way to describe the notation and concepts to produce a solution.

More interestingly, children can be set up to follow a path of exploration by asking to experiment what trajectories a differential robot can produce.

3.2 Linking the challenges to Kinematics

The positioning of the robot arm in a particular position enables connections to the notion of a frame of reference. Are angles measured positively in what direction? What is the front of the robot? What is the frame of reference of the robot? What is the frame of reference for its environment? What is necessary to describe a robot posture, (and thus how many degrees of freedom)?

What are the units? Some students will be inspired to recognise radians as opposed to degrees.

And depending on the student's background, we can introduce trigonometric functions (maybe similar triangles needs a presentation).

However, in our experience, all students appreciate what the different problems mean. At least two problems are very relevant. First, how to convert (translate) from one frame of reference to another - again, even polar coordinates are a good example of this type of challenge).

Secondly, how given the space of arms positions, determine the position of the end effector (that is forward kinematics). And simultaneously, given the position of the end effector (in the world's frame of reference), describe the angles (that is, and positions of motors) to place the need effector (inverse kinematics).

Again, not all students would be able to solve these problems, but they should understand the question. What is required of a solution is the main message we are trying to convey. For instance, we also explore the qualitative difference between manipulation and locomotion. Namely, dictating the final position of angles to an arm joins rarely affects the position of an end effector (except for potential collisions with itself).

However, for mobile robots, the situation is qualitatively very different. Knowledge of angles or rotations of encoders rarely determines the final location of the mobile robot in the environment.

3.3 Kinematic modelling could be quite challenging

A more elaborate and challenging problem is to request the construction of a behaviour that drives the robot in a circle. It takes almost no effort to experiment (or imagine) that in the differential robot, if both motors are set at the same speed, kinematically the robot travels in a straight line. Similarly, if one engine is spinning in the opposite direction of the other, then the robot rotates in its place. However, it is harder to become convinced that the robot will perform a circle if one motor is spinning slower than the other, although both are in the same direction. It may be evident that if one motor is not moving and the other is, the robot's centre travels in a circle. Some reflection is necessary to realise that the straight line is a special kind of circle with its centre at infinity, and also rotating without translating is another type of circle with radius zero.

In order to inspire a path of investigation, the potentially extremely demanding challenge is to require that the robot travels in a circle, but that the same circle be performed at different speeds. Setting some parameter before the program runs should change the speed around the path, but not the path. Suffice to say that a significant understanding of a few mathematical concepts such as limits, similar triangle, decomposition into orthogonal vectors may be introduced to actually develop a kinematic model (several are possible) that enables to fully construct a program that enables a differential robot to travel on a circle at a particular speed. But a starting point is that rotating one of the motors/wheels does not contribute to the robot moving left or right, but only backwards and forwards.

3.4 The birth of engineering

The second major challenge is to use the sonar sensor to design behaviour for the robot that ensures the robot stays within a given distance from an obstacle. We accompany a video with the description of the challenge and historical references to Watts governor. Pictures and videos of Watt's governor operation are understandable to the students in our age groups (despite Watt's governor is not visible in modern tractors and engines as it was around 1880.) Students can all anticipate that the faster the governor spins, the balls raise the connection to a valve. Also, links to the history of engineering, and the technological boom named industrial revolution can be postulated, and teachers can illustrate the parallel developments in engineering with the progress in differential calculus, enabling the field of control theory.

Students can notice the many examples of feedback-loop control effects, form setting a car on cruise control, to being able to stand up on two legs, ride a bicycle, or regulation air-conditioning in a room. One can initiate exciting debates about the power of the feedback loop as an enabler of automation and automation as a driver or radical economic and social change. Depending on the inclination to establish connections between applications and mathematics, illustrations of control theory can be given that motivate the notions of derivative (or integrator), also differential equations, and even linear algebra.

In our activities, we purposely miss-guide the student to construct a program that implements a proportional control for the challenge of using the sensor to maintain a distance to an obstacle. We suggest that the motors should be made to work at constant speed sufficient rotations to half the distance to the obstacle. This behaviour typically works reasonably well but exhibits oscillations, and if the constant speed is set to low, the robot seems irresponsive. One can then introduce regulating the speed of the motors in proportion to the distance to the obstacle. Since the rate of change of distance is speed, we are introducing derivative control.

3.5 Wrapping up with machine ethics

We culminate the activities by introducing the Trolley moral dilemmas in the context of autonomous vehicles. We introduce notions such as utilitarian vehicles and the need perhaps by humans and machines to advance our moral values.

We touch on the fact that most of the influences for human societies are based on the very different, typically contradictory, views and values of different cultures and human groups. Nevertheless, it is likely that soon, machines would be in a position to make decisions that significantly affect the lives of human beings. We touch on the open and unanswered situations and challenges that such future represents for humanity, and how the current mathematical models provide answers few humans would find satisfactory.

For example, we argue that the fact that most humans believe machines should not take decision over humans well-being places all the responsibility back to some of the humans. But the machine may not be able to identify which humans are responsible for a situation in which the artificial agent must chose the well-being of some humans over others. Under such incomplete information, decision making may be best modelled by a randomized strategy (as in scissors, paper, rock introduced earlier). However, it is also unacceptable to humans that machines “gamble” with their well-being!

4 RESULTS

The histogram for the responses to our survey in Figure 1 appears in Figure 2. The survey was completed by 38 participants, in three sessions. The preferred response to all questions is highly indicative that the activities would reach their objectives in the opinion of educators. For all of the questions at least 84% of the responses were the extreme positive response “Definitely”. Moreover, never an educator chose the extremely negative response “Not at all”. For all questions, never more than 2 answers were not positive. For question Q2 and Q5 one respondent answered “little”. All other questions had 37 out of 38 respondents (97.4%) answer positively with “definitely” or “Some interest”.

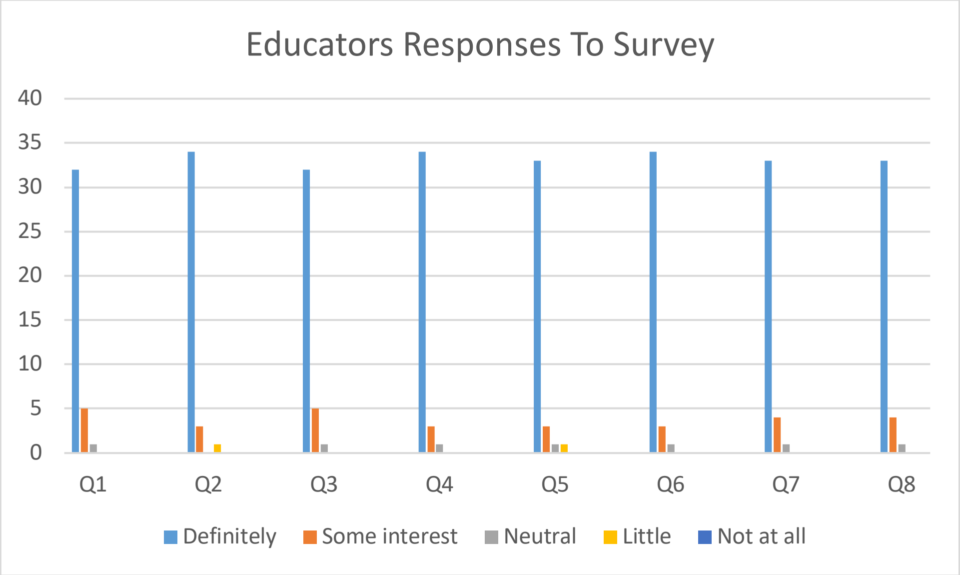

Figure 2. Histogram of responses to the survey in Figure 1.

5 CONCLUSIONS

Robotics combines disciplines such as artificial intelligence and control theory. While classical control theory studies dynamic systems typically regulated by feedback-loops, artificial intelligence involves models based on probabilistic decision making and logical reasoning. Therefore, it is possible to connect to the traditional mathematics of calculus, differential equations, linear algebra and trigonometric functions by touching on robotic challenges around simple regulation and control challenges. Similarly, it is possible to touch on probabilistic models, game theory, and reasoning by touching on problems associated with common sense reasoning or adversarial decision making. Teenager learners can discover broader connections analysing the impact of robotics on society in particular, by investigating the impact of machine ethics. Such initiation can be achieved across several grades and also across gender of the learners with rather simple and inexpensive robots and programming environments.

We have successfully inspired visitors to our campus to enjoy the introduction to terminology and challenges we believe motivate them to explore further their engineering and mathematical curiosity.

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