Lessons Learned in Teaching Science using an Integrative Approach that used the Engineering Design Process

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Abstract

Fifth grade students in a school district in the southeastern United States used robots in their study of science. The study required students to find an optimal path to a volcano and other locations of interest on a grid.   The integrative approach offered a unique opportunity to use mathematics and the engineering design process to solve problems. Learning activities led students to define and understand the problem at hand, research ways to access selected locations on the grid, develop a list of requirements and constraints, converge to an optimal path, and share results. Students worked in teams to find solutions to the problems presented. The activities allowed students to build, program, and actuate robots using them as vehicles to access locations of interest, retrieve information, and return to their headquarters in a given time frame. Results demonstrated increased student engagement in learning science and mathematics and a positive impact on learning climate. The paper will present a mixed methods research approach that includes interviews with students and teachers and analysis of data based on students' solutions.

Introduction

The National Science Teachers Association (NSTA) supports elementary school science. Among the factors stated by NSTA that help students learn best include: a) involving them in first-hand exploration and investigation; and b) when mathematics and communication skills are integral part of science instruction [1]. The aforementioned factors are an integral part of the engineering design process as in research "Brainstorm" to for possible ways to address a problem and "calculating" for optimal solution. Engineering design process can be a very useful tool in learning science, however, in many cases though, is often ignored in many elementary STEM education activities. Engineering may be defined as the process of design, building, and using engines, machines, and structures [2]. Because of its complexity and time demand, many teachers prefer not to invest in the time it would require to learn and adopt it in the class. Teachers also know that involving hands on activities takes more time than lecture style learning. Hmelo-Silver et. al. [3] compared Project Based Learning (PBL) students to lecture instructed students and concluded that although the PBL students made more errors, they also created more elaborated explanations compared to the sparse explanations of students in the traditional curriculum. There is richness in student active involvement in learning.

Recently, industry and academia joined hands to create a science lesson using robots as part of learning. The activity morphed into an engineering design process learning experience including using math concepts to problem solve. A team of school district teachers, administrators,

graduate students, and university faculty designed a 5th grade lesson titled "Danger Zone" to study volcanos using robots. This paper describes lesson learned and results.

The Lesson "Danger Zone"

Active volcanos can be dangerous in many ways. Fifth grade science curriculum requires students to learn about them. The lesson was created and presented in a form of a question as follows: if a person cannot explore an active volcano safely, what can he or she do to actively learn about it? Several options were explored but the robot solution was found to be more practical, that is, it could explore without endangering human life. The special robot can be sent to the volcano to investigate ongoing activities plus it can bring back samples of materials of interest. This type of thinking resulted in planning and creating lessons about exploring a volcano using a robot that was required to visit several sites of the volcano while taking the shortest time possible. The lessons are shown in Table 1.

Table 1: An overview of eight robotic lessons for 5th grade

Lesson	Name	Driving Question
1	Danger Zone	How can scientists study dangerous environments?
2	Build a Bot	How do engineers build robots to accomplish specific tasks?
3	Primary Programming	How can the basic movements of a robot be controlled using simple programming commands?
4	Purposeful Programming	How can sequential movements of a robot be controlled using sequential programming commands?
5	Terrain Task	How can a robot be programmed to perform a specific task?
6	Prime Optimization	How can math be used to efficiently program a robot to perform a specific task?
7	Making Sense	How can sensors be used to program a robot to efficiently perform a specific task?
8	Share	How does the engineering design process help with problem solving?

Method

Problem formation

University faculty and school district teachers developed a plan on to study volcanos. The "team" intentionally made the learning experience to be a regular class activity and not extra curricula. They develop a 6 x 6 grid (see figure 1) which had five "visit" sites and three collection sites. The visit sites included the mud flow; lava, side vent, volcanic bomb, and ash. Collection sites were distributed within the grid.
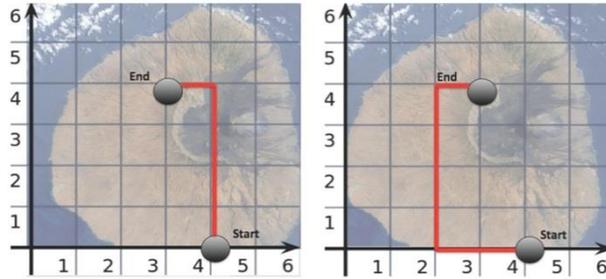
Figure 1: Sample grid

The Robot

Sponsoring industry provided robots to be used in the learning experience. All student teams were given a robotic kit and were asked to 1) assemble the kit into their own robot design, 2) program the robot to administer the given task autonomously, and 3) to complete all tasks and return to the starting point at the shortest time. The task was to travel to the sites of interest.

Figure 2: Testing robot on movement on grid

Students used tools to build robots from kits. By doing so, they learned how to use equipment and how to read directions. Upon completion of building robots, students learned how to program the robots to direct them where they should go, when they should go, how far they should go, and at what speed they should travel. In engineering design, students learned how to solve problems within given constraints such as, operate in a limited space, limited time, and using limited tools. The constraints lead them to brainstorm for best solutions within the limitations. More so, students had to engage in using mathematics in calculating distance, speed of the robot, and time that they would complete their task. The mathematical concepts to be learned in 5th grade shown in table 2 fit to the designed lesson.

Mathematical concepts covered in 5th grade are shown in table 2.

Table 2: Mathematics Curriculum from CCGPS for 5th

Domain	Cluster
Operations and Algebraic Thinking	• Write and interpret numerical expressions. • Analyze patterns and relationships.
Number and Operations in Base Ten	• Understand the place value system. • Perform operations with multi-digit whole numbers and with decimals to hundredths.
Number and Operations—Fractions	• Use equivalent fractions as a strategy to add and subtract fractions. • Apply and extend previous understandings of multiplication and division to multiply and divide fractions.
Measurement and Data	• Convert like measurement units within a given measurement system. • Represent and interpret data. • Geometric measurement: understand concepts of volume and relate volume to multiplication and to addition.
Geometry	• Graph points on the coordinate plane to solve real-world and mathematical problems. • Classify two-dimensional figures into categories based on their properties.

Communication

The engineering design requires one to communicate their findings. Figures 3 and 4 show students working in teams and in a competition mode where they have to communicate with each other and with the judges.

Figure 3: Team work

Figure 4: Communicating results

Population

Two hundred fifty seven students from five middle schools participated in this exercise. Students worked in teams of two or three. Teachers were their coaches.

Analysis

Faculty and graduate students videotaped students as they worked through the learning exercise. Three specific lessons were targeted for video analysis: Lesson 4 during which students first learned to develop their programming solution to the task; Lesson 5 during which students learned to apply mathematics to make their programming more precise; and Lesson 6 during which students refined their final solution and then shared their solution, their development process, and their challenges. The process used for the video analysis involved viewing and coding videos that were edited to follow a team of two students throughout all three lessons. During the initial analysis a set of primary codes were developed and then, with additional analysis sub-codes were developed. The primary codes developed were: engagement in the engineering design process; displaying computational thinking; instances of embodiment; and collaboration.

Engineering Design Process

The code engagement in the engineering design process was applied to video segments in which students were observed to be actively engaged in the prototyping, testing, and revising of their programming solution. When observed in the video the engineering design process involved studying the task grid, determining the robot movements needed, programming the robot, testing the robot on the grid, and then determining the revisions needed. Throughout the three lesson video, the engagement in the engineering design process was applied to 27 unique video segments with 13 instances occurring in Lesson 4, 8 instances occurring in Lesson 5, and 6 instances occurring in Lesson 6. Upon further analysis it was found that while the number of occurrences of engaging in the engineering design process decreased as students progressed through the curriculum the amount of time spent in planning the programming moves incrementally increased from Lesson 4 to Lesson 6. In Lesson 4 the average amount of time that students engaged in each cycle of the engineering design process was 1 minute 7 seconds. In Lesson 5 the amount of time in each cycle increased to an average of 2 minutes 50 seconds. In Lesson 6 the average amount of time engaged in each cycle was 4 minutes 30 seconds. One potential reason for the decrease in the number of instances of engagement in the engineering design process and the simultaneous increase in the amount of time spent engagement in each cycle of the engineering design process is that as students' progress through the curriculum followed an intentional design. The curriculum itself has students begin with their own trial and error process and then provides them with additional knowledge that they can use to think more deeply and be more purposeful in their decisions as the curriculum progresses.

Displaying Computational Thinking

The primary code of displaying computational thinking was broken down into the sub-codes of abstraction, elaboration, reasoning, and automation. Throughout the three lessons, students showed multiple instances of displays of computational thinking with increased instances in Lesson 5 and Lesson 6 after mathematics was introduced through the curriculum design. For example, in Lesson 4 student displays of computational thinking were coded for reasoning only for the fact that displays were focused on generating new ideas for how to program the robot. In Lesson 5 and Lesson 6, as the curriculum and students' thinking evolved, their displays of computational thinking began to include abstract thinking, automation, reasoning, and elaboration. Abstract thinking came in the form of displays such as students being able to look at the code on the screen, rather than at the robot's actual movements, and understanding where to make changes in their code. Instances of displays of elaboration and abstraction combined were observed in the form of students being able to create their own algorithm for chips needed to program the robots' movement from one point on the grid to the next and being able to apply that algorithm to future movements throughout Lesson 5 and Lesson 6 leading to automation of the programming.

Instances of Embodiment

One of the benefits of teaching through robots is that the robot itself has the potential to become and embodied agent of abstract concepts. These instances of embodiment were observed in Lessons 4 and 6. In Lesson 4 instances of using the robot as an embodied agent were observed on four separate occasions. In each of these four occasions the robot was used when during students initial thinking through the problem to consider what would happen if the robot were programmed using specific chips. In Lesson 6 there were 3 observed instances of the students utilizing the robot as an embodied agent, however in all three of these instances the robot was used to plan the next step in the programming sequence thus demonstrating an evolved purpose for the embodiment from one lesson to the next. Also, while there were no observed instances of embodiment in Lesson 5 there was an increase in the use of abstract thinking as students discussed the programming of their solution and students spent more time discussing the solution in terms of the chips that they would use.

Collaboration

The curriculum itself was designed specifically to allow for instances of collaboration between the students in each team of two. While there were ongoing instances of intra-group collaboration throughout all three lessons, two key sub-findings were evident in the videos. First, throughout lesson 4 and Lesson 5 instances of collaboration were centered only on intra-group collaboration. However, in Lesson 6 instances of inter-group collaborations were observed. Two examples of this were when one group showed another how to program the robot to 'stop' and

then when one group stopped to help another group think through a challenge that they were having in getting the robot to make a 90 degree turn on the task grid.

The second interesting finding was in the role that gender played in the intra-group collaboration. In the observation of a boy/girl pair, in Lesson 4 the boy seemed to take the lead on the programming decisions as he was the one to use the robot to embody the potential movements and then told his female partner what chips to use in the programming. In Lesson 5, the female student begins to assert herself more and takes turns in the physical testing of the solution and begins to provide ideas, even though they were not used. By Lesson 6, the girl student began to disagree with her male partner and they worked through ideas together. For example, the pair had a disagreement about an abstract idea of how close was 'close enough' to making their robot stop at a specific spot on the grid. The pair was able to think through that definition and come up with ways to make 'close enough' a little closer to their target. This instance of disagreement and equal sharing of the idea was a significant shift in role dynamic from Lesson 4 where the girl was just very excited about everything and was eager and willing to try whatever the boy came up with to the girl being very thoughtful and willing to assert herself into the process in Lesson 6.

Summary of observation

1) Students engagement in learning science was very high, highly motivated. They learned

        a. how volcanoes are formed
        b. why volcanos were dangerous
        c. how to avoid dangerous situations – they provided ideas on safety
        d. effects of volcanos

2) Students engagement in learning mathematics was very high. They learned
        a. measurement – distances from one end of a gird to the other
        b. how to calculate speed of robots so that to accomplish their tasks faster

A pre and post survey administered to the 250 students indicates statistically significant differences. The participating students' mathematical thinking average out to 4.16 (*SD*=2.72) and 0.18 (*SD*=0.51) on the pretest, and 5.50 (*SD*=2.14) and 0.61 (*SD*=0.99) on the posttest. When compared to measurements taken before working with the curriculum, the students' performances after the curriculum indicate improvement.

3) Students engagement on programming was extraordinary. They learned

        a. basic programing to move from one point to another
        b. programing for a robot to move in a straight line… how to follow a grid
        c. about sensors and actuation

Engineering design process

Students engagement in science, mathematics, and programming was partly due to the engineering process which allowed them to first, identify and define the problem (excavating the

volcano area), listing requirements and constraints (the grid, tools, and volcano and collection sites), develop solutions, evaluate solutions, construct prototype, testing, iterate as needed, and final solution and communicate results. This process, helped keep students interested in the projects and on task. They learned the objectives of the lesson, and had fun as well.

Conclusion and Reflection

We learned that students will rise to expectation. We challenged them to work and operate within constraints and they performed exceedingly well. Some students took leadership of their teams but did not domineer, they learned to consult and find resources to complete their tasks. They were able to use the engineering design process and not only learn about volcanoes but use mathematics extensively to solve their problems. As researchers, we noticed uniqueness in student confidence. It seemed initially that females took a back seat but in the end they were assertive. One 5th grade teacher summed up the experience as follows: "After the project was done, I started seeing that same group of students become more independent when faced with problems across the curriculum, especially in math and science."

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