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Robotics: An opportunity to introduce Mathematics, Physics, Engineering, and Technology.

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Abstract:

Outreach programs organized and supported by universities, government and industry have been used to mobilize educational resources and to address current social, cultural, and economic issues facing the world. Towards this direction, robotics has been a medium of outreach programs that has found wide support. Robotics has been received with success by many of the middle and high school students. There are various options to implement a robotics program and many organizations that sponsor regional competitions of these programs come out with a different theme every year. In addition to the robot, which is the central piece of the overall activity, the activity includes research to a prescribed topic, presentation of findings, team work, construction of the robot and its accessories and programming to perform a specific task using an object oriented language or simple programming. Although these activities are designed to inspire Science, Technology, Engineering, and Mathematics, a connection with them is missing during the preparation for the competition. In this paper we discuss a formal presentation of topics from Mathematics, Physics, Engineering, and Technology, which are used directly or indirectly in the final product, a working robot that performs a specific task. We integrate various topics from Mathematics, Physics, Engineering, and Technology known already from school. Other topics may or may not be known to all members of the team. Abstract topics are applied, make sense, and are used to solve practical problems.

Introduction

Various studies have addressed the subject of poor performance of students in Science, Technology, Engineering, and Mathematics, (STEM) [1]. Robotics has been proposed as a way to improve the performance in the various fields composing STEM [2]. During the Third International Mathematics and Science Study (TIMSS), the students in the United States test well in both mathematics and science in fourth grade as compared to their international counterparts, the eight graders performed near the international average, and the twelfth graders performed below the international average [3]. Four years later at the Third International Mathematics and Science Study Repeat, (TIMSS-R) the U.S. students showed no improvement since TIMSS [4]. The reported results indicate that the progress in STEM is inversely proportional to the grade for U.S. students. The House Science Committee developed a new National Science Policy, which aimed to strengthen STEM in preschool through college [5].

As an approach to implement increase interest and hopefully the number of students seeking to study and have a career in an area in STEM, outreach programs have been developed, funded and supported by various government agencies [6], private companies [7], universities [8], and associations[9-11]. An extensive report of STEM programs can be found in a report published by the Office of the Under Secretary of Defense, Acquisition, Technology and Logistics [12]. States are passing legislature in support of STEM [13]. Outreach program have been developed all over the country; middle schools, high schools, and universities promote the STEM effort [14]. The usual outcome in robotics is the constructions of a structure usually a "robot" that performs a specified function. Other efforts have been developed also that used computer based construction [15], construction and simulation [16], and mathematical modeling in physics [17].

Hands on learning opportunities are necessary to provide students with the essential excitation to explore Science, Technology, Engineering and Mathematics. Currently, hands on experience usually stops at the build and program phases [18].

Robotics and STEM (Science, Technology, Engineering, and Mathematics)

In the following sections we propose a number of topics from science, technology, engineering, and mathematics to be integrated with the various activities of robotics. The concept of all proposed topics are presented and briefly discussed. An example is presented in some cases. Figures, tables, and equations have been used to illustrate some of the concepts.

The purpose of the proposed enhancement is to introduce the students to the applicability of the various topics, possibly already known from the STEM relates courses, to stimulate the thinking process on how to apply principles already known to the problems under consideration, and finally, to clarify misconceptions and provide understanding. Due to space limitations only a limited number of topics are discussed.

Problem Solving

Problem definition, solving, and optimization are among the basic functions that need to be taught, studied and practiced. There is an extensive literature on the subject [19] but here we shall consider the case of STEM in Robotics. The typical problem is of the form "Design a robot that can accomplish a number of tasks." Then, most of the times in the various robotics teams, the solution follows in a trial and error approach for both construction and programming. This, clearly, is the synthesis process. Although the trial and error approach has its own importance in a number of problems, typical robotics problems of our interest can be solved in a more efficient way by a student that has experience of the analysis process, knowledge of basic physics, mathematics, and technology, and can integrate all these towards the final goal.

We propose the implementation of a formal solution process that as a first step includes the problem definition. There is not a unique approach to solve a problem. But the problem definition is the first step. Figure 1 shows a possible basic problem solving approach.

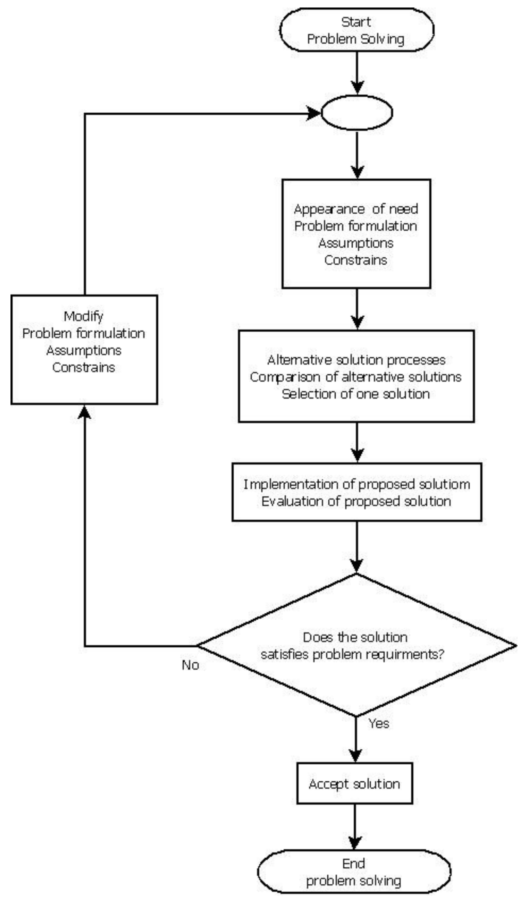

Figure 1. A problem Solving Process

Programming

The following definition applies to programming according to the IEEE: Programming is the ordered listing of a sequence of events designed to accomplish a given task. Computer program is a plan or a routine for solving a problem on a computer. A combination of computer instructions and data definitions that enable computer hardware to perform computational or control functions. Trade off is the parametric analysis of concepts or components for the purpose of optimizing the system or some trait of the system [20].

The programming language used depends on the robot setup but the programming principles are universal. The programming language C is used mostly with FIRST Tech Challenge (FTC) and FIRST Robotics Competition (FRC), while the First Lego League, uses the object oriented language NXT-G. The programming environment for LEGO Robotics is shown in Figure 2.

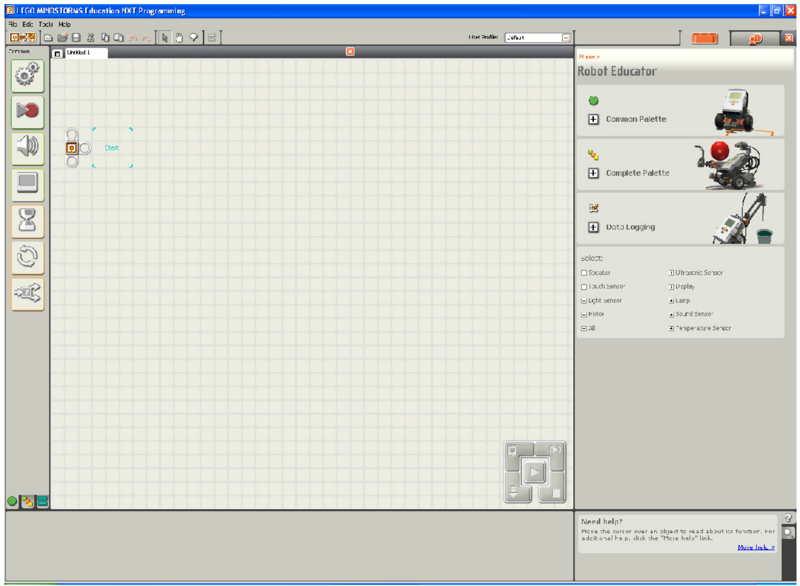

Figure 2. The programming environment for LEGO Robotics using Mindstorms NXT-G

Algorithms

Before the writing of the program code itself (the equivalent of the solution process), an algorithm can be developed of the steps needed to solve the problem under consideration. Two components of an algorithm are the actions needed to go from the statement of the problem to the solution of it, and the order in which these actions needed to be processed.

Table 1. Components of an algorithm

Algorithm
- Actions
- Order

Developing of an algorithm can be a one person's job but final development and optimization demands a brainstorming session. So, Algorithm development gives the opportunity to introduce the concept and practice of brainstorming. Software tools are available to assist in this process [21]. All approaches have been used successfully by the author to a number of LEGO FLL teams.

Flowcharting

An advantage of flow charting is the pictorial vie of a sequence of events. A serious disadvantage is the fact that such a diagram becomes complicated for a complex problem. But even in this case, flowcharting can still be used if the main problem is split in smaller problems. Furthermore, it can be used to describe the overall programming approach. Flowcharting should start with learning the alphabet of flowcharting. Few flowcharting symbols as shown in Figure 3.

Figure 3. Flowcharting symbols

Structured programming

Structural programming is any software development technique that includes structured design and results in the development of structured programs. And, structured design is the any disciplined approach to software design that adheres to specified rules based on principles such as modularity, top-down design, and stepwise refinement [22].

An advantage of structural programming is the use of the various constructs. These can be used to demonstrate the development of logical statements. Figure 4 presents the three basic constructs of Sequence, Repetition, and Selection. Figure 5 illustrates the implementation of the Repetition (loop) construct in Lego Mindstorms NXT-G Robotics programming language.

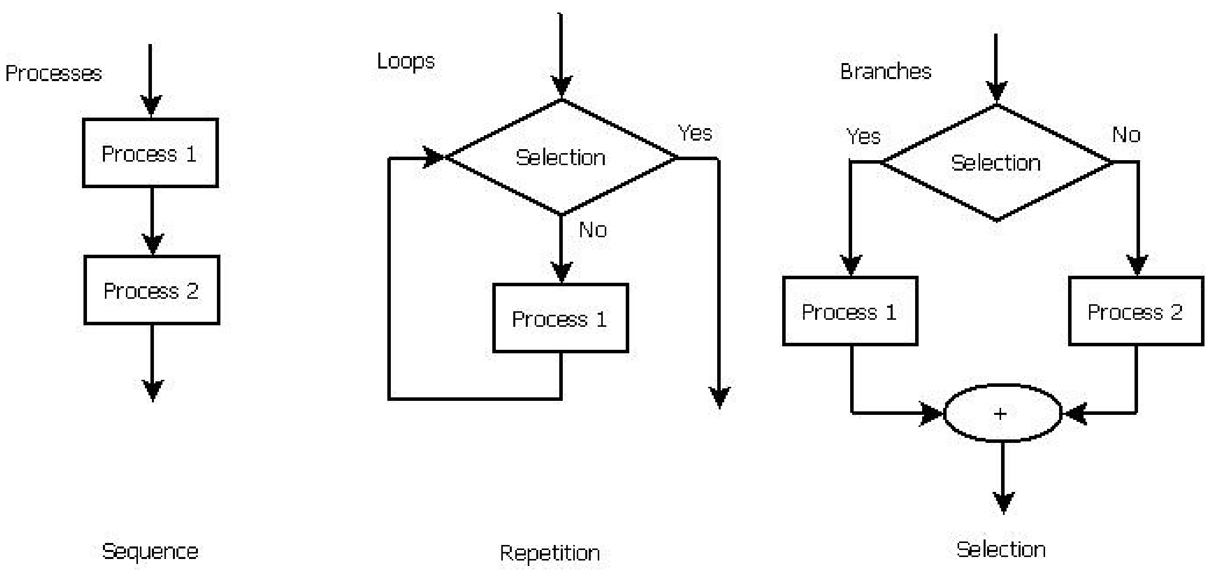

Figure 4. The three basic constructs of Sequence, Repetition, and Selection

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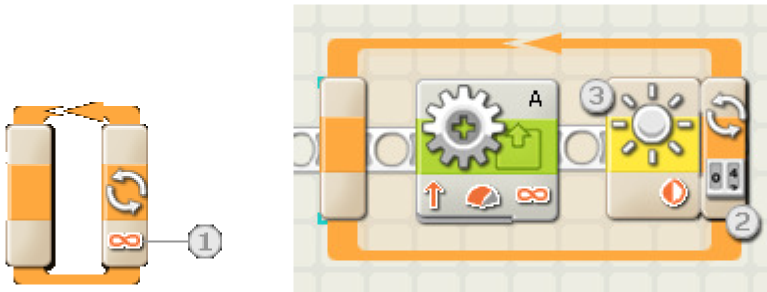

(a) (b)

Figure 5. The Repetition (loop) construct (a): Implementation (b) in Lego Mindstorms NXT Robotics programming environment

Design Process

The design process is applied equally well to the algorithm development, and the solution process of a problem. The students have the opportunity to immerse themselves into the design process. Due to the nature of the design process, many solutions are possible (parametric solutions). The student has the opportunity to evaluate each one of the solutions against the specifications and constrains of the problem and to select the one that best fits the current needs. It was applied by the author to a group of middle school students to teach construction skills using the step by step approach to build various LEGO based structures [23].

Algorithm and Top-Down Design

Simple problems can be solved using an algorithm, following the top down approach, which provides the solution in sequential steps. For more complex problems the principle of "Divide and Concur" can be applied again and again until the problem is reduced to a number of simple problems that can be solved in sequential steps. These steps are shown in the following flow chart of Figure 6.

Pseudocode

Pseudocode is natural language like programming language statements. Pseudocode can help in the writing process of the programming code. The pseudocode, normally only describes executable statements (input, calculation, output).

Analysis

Analysis is a process of mathematical or other logical reasoning that leads from stated premises to the conclusion concerning the qualification of an assembly or components.

Analysis is examination for the purpose of understanding. [24] The analysis is suggested as the first stem in learning new concepts. It has a unique solution and can be found using sequential steps.

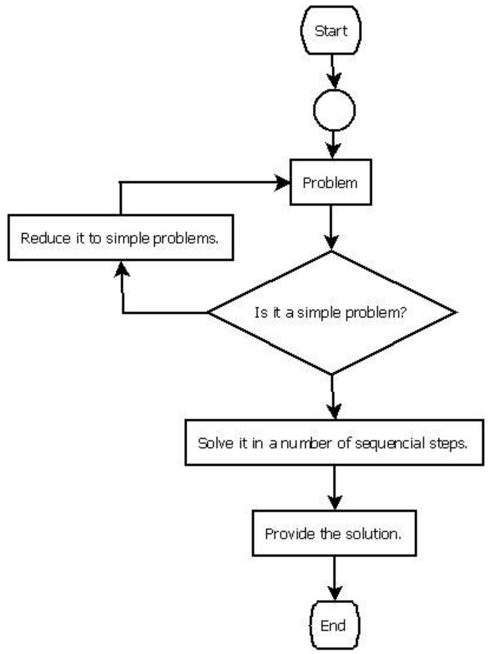

Figure 6. Algorithm development for the algorithmic top-down solution of a problem

The Synthesis or Design Phase

The student has to solve the opposite of the analysis problem. The same basic problem that was analyzed earlier now need to by synthesized. One approach must be selected in order to be implemented. Here is important to stress the differences between the analysis and the synthesis processes. Design is the process of defining the architecture, components, interfaces, and other characteristics of a system or component. Design is the results of the synthesis process that provide sufficient details, drawing, or other pertinent information for a physical or software element that permits further development, fabrication, assembly, and integration, or production of a product element. Design is the act of preparing drawings or other pertinent information for a physical or software element during synthesis within the systems engineering process [25].

Analysis, Synthesis, Physics and Mathematics

Physics and mathematics find a field of application in robotics. In particular mechanics and Euclidian geometry are among the major areas of application. The motion of a robot takes place on a plane. Commonly, the robot moves on circular wheels or reads from point to point, on a straight path, circular path, and makes turns at a specific angle. A common problem in programming the robot is “How many degrees must a wheel rotate in order for the robot to travel the distance from one point to another?”

Example: Analysis phase" "What is the rotation required by a circular wheel of radius R to cover distance L?" [26]

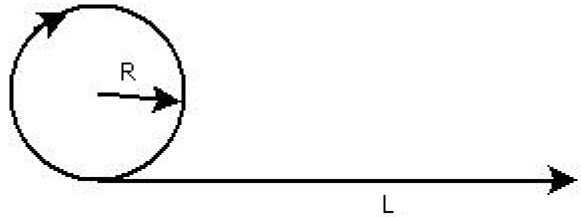

Figure 7. Wheel of radius R rotating along a straight path

Based on Figure 7, the distance traveled by a wheel of radius R or diameter D after rotation of d degrees will be:

$$L = C\frac{d}{360°} = 2\pi R\frac{d}{360°} = 2\pi\frac{D}{2}\frac{d}{360°} = \pi D\frac{d}{360°}$$

The synthesis phase problem will be of the form: "How many degrees d a wheel of radius R or diameter D needs to rotate in order to travel distance L?" Based on the analysis derivation the answer is:

$$d = \frac{L}{C}360° = \frac{L}{2\pi R}360° = \frac{L}{\pi D}360°$$

Virtual Prototyping

Virtual prototyping is used extensively today by the industry. It allows the construction, evaluation, and optimization of the performance of the design robot in a virtual environment. The designed structure is verified and the satisfaction of the specifications is verified. Virtual prototyping can save valuable time, and cost, while improving the overall design of the structure. Virtual prototyping naturally comes before physical but, for instructional reasons, somebody can introduce it after in order to give to the student the opportunity to grasp the physical reality before the virtual. After all, the virtual components resemble the physical. The closer the resemblance, the better and more accurate the simulation. Figure 8 shows an automobile virtual prototyping using MLCad [27].

Physical Prototyping

Various robotic constructions are available [28]. The student uses current technology and basic skills to build a structure. This phase requires persistence and repetitive testing to evaluate the performance of the designed structure. Due to variations of parameters between two "identical" structures, we get different performance. A common source is the voltage of the battery. Two "identical" structures have batteries at dissimilar potential difference. This will have an effect of the current through the motor, which will have an effect of the angular speed and eventually on the performance of the robot. The effect of the voltage applied on a motor and its angular speed is shown in Figure 9, [29].

Plotting data

The student needs to presents information in terms of tables, graphs, or equations. In order to understand the current performance, evaluate performance, and plan future approaches, the student needs to tabulate collected data, plot data, and express data in form of an equation.

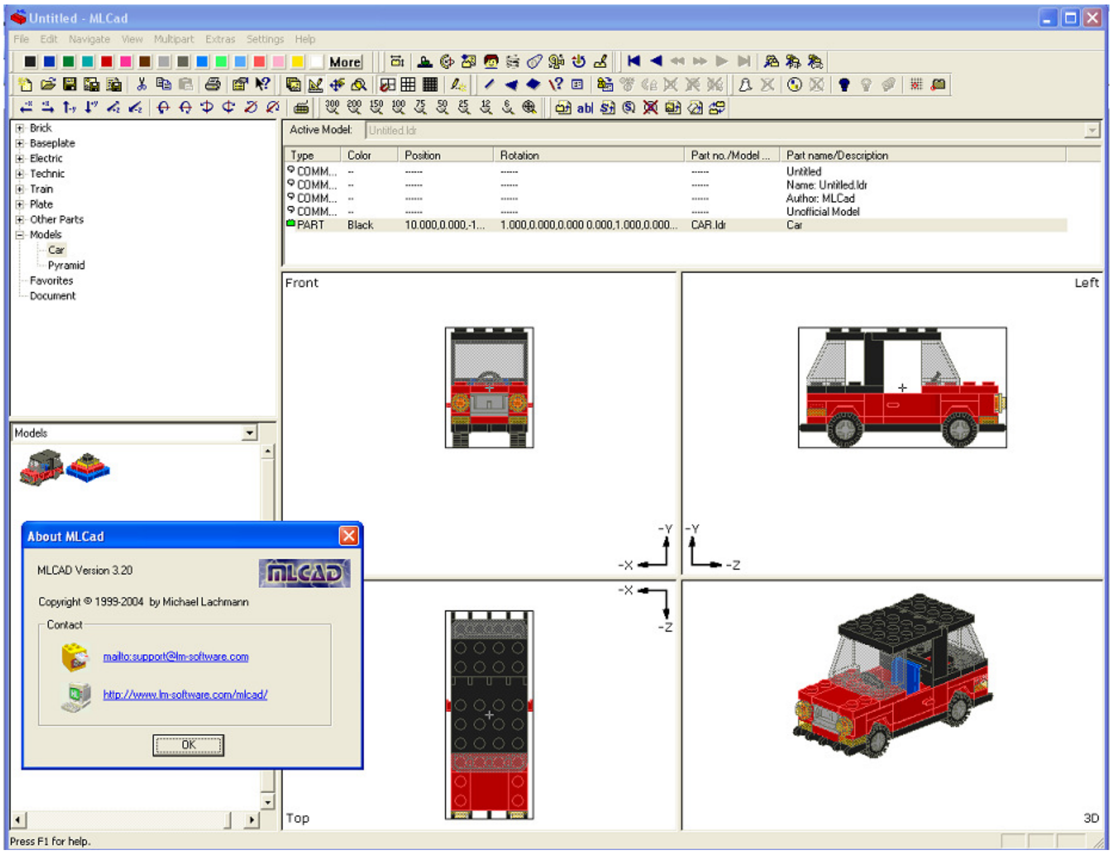

Figure 8. Virtual prototyping of a Lego pieces based automobile using MLCAD

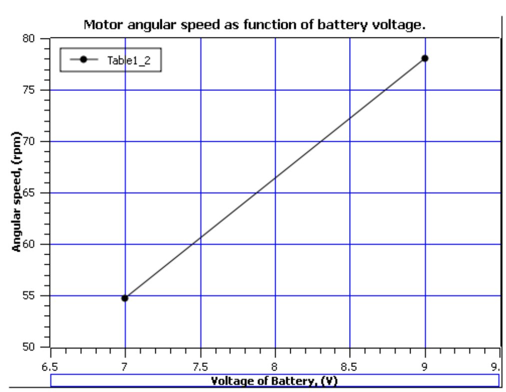

Figure 9. Angular speed as function of the applied for a LEGO motor

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System

System is a set of interconnected elements that achieve a given objective through the performance of a specified function, [30], an integrated whole even thought composed of diverse interacting, specialized structures and subjections. Any system has a number of objectives and the weights placed on them may differ widely from system to system. A system performs a function not possible with any of the individual parts. Complexity of the combination is implied. [31]

Example: The Self propelled automobile.
A self-propelled LEGO based automobile was designed for straight path and circular path motion. The linear distance traveled as function of the rubber band rotation of the wheel shaft provides material to discuss, linear and non-linear behavior, validity of domain, breaking of the rubber-band.

Table 2: Distance traveled as function of rubber-band rotations

Number of rubber-band rotations	Distance traveled (m)
0	0
1	1.57
2	2.92
3	4.42
4	5.23

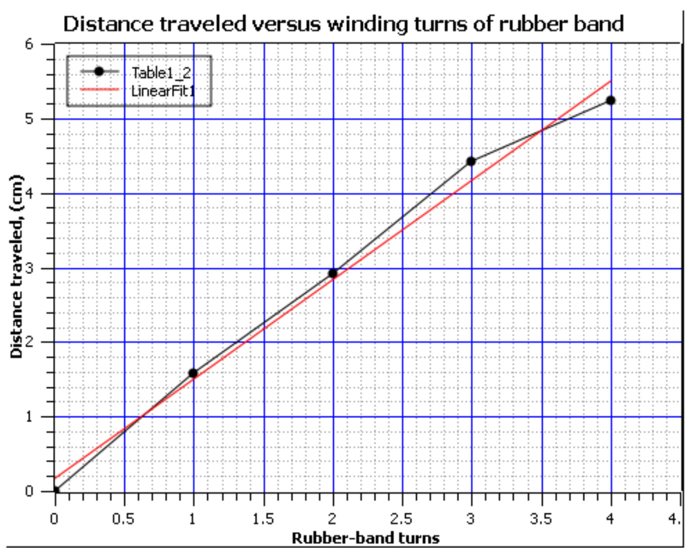


Figure 10. Linear distance traveled by the self powered LEGO based automobile

Here, data are collected and presented in the form of a table (Table 2), a graph (Figure 10) and an equation to be determined. The linear approximation of the data is provided by a graphics program [32].Approximation to a straight line of the form: $y(x) = mx + b$. We need to determine the slope m and the y intercept b. From physical considerations, $b = 0$, because there is not displacement when there is not windings of the rubber band. The slop can be found by selecting any two points, to a first approximation. Selecting different pairs will give different but close to each other, slope. The concept of best fit a straight line to data points can be introduced at this point, for the appropriate level students. In our case, we consider the y intercept as the first point, because the straight line must pass from there, and the last datum as the second point.

$$m = \frac{\Delta y}{\Delta x} = \frac{(5.23 - 0)\,\text{cm}}{(4 - 0)\,\text{turns}} = 1.3\,\frac{\text{m}}{\text{turn}}$$

Finally, the equation takes the form:

$$y(x) = 1.3x \quad \text{m}$$

The graphing program's linear fit option gives:

$$m = 1.33, b = 0.17, \quad y(x) = 1.33x + 0.17$$

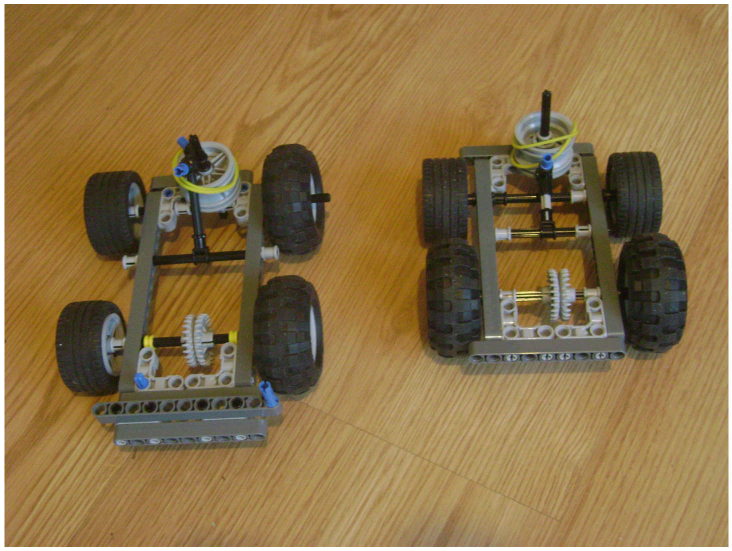
Now the student can go back and calculate, either from the graph or from the equation, the number of winding turns of rubber band in order for the self propelled automobile to travel a specific distance.

Although the current measured results point out to discrete system, the equation and graph transform it to a continuous system. An appropriate locking mechanism on the automobile will provide the fractional number of turns and thus the possibility of collecting more data.

Figure 11 shows a self propelled car for straight and circular path traveling. Various structures will travel to different distance, and this is another parameter of the study. In addition, the number of rubber bands will be another parameter of study. Further extension of the study can be made by considering the physical reality of the system. There is not system when the rubber band brakes. This provides an upper limit on the domain of the function, as well as on the range. In addition winding of the rubber band in the opposite direction makes the automobile move in the opposite direction leaving all numerical results identical. These introduce the concepts of an odd function, domain of a function, limits of validity of a model etc.

Other Topics

Other areas that find application are levels, gears, pulleys, sensors, motors, treads, electrical cables, beam structures, Bluetooth, mechanisms [33], USB, etc. All these alone and in combination can be introduced, explained, and applied, during the realization of a project.



(a) (b)

Figure 11. A self propelled car for (a) circular traveling (wheels of different diameter), and (b) straight path travel

Conclusion

A problem has been developed and persists in education with respects to students' low performance in Science, Technology, Engineering, and Mathematics. Robotics has been proposed, and implemented as an approach to increase awareness and interest in the subject, and the number of future professional in the areas of STEM. The popular approach is to build a structure, a robot, and program it to perform a specific task, by trial and error. In this paper we reviewed a number of topics from the STEM areas and we proposed their inclusion in the building and programming processes. Using a structured, methodological approach in implementing and interrelating concepts from all areas of STEM that apply knowledge acquired and resembles practice clarifies the various concepts and shows their value in solving problems and possible practical applications to the students.

Recommendations for Future Work

It is suggested that complete units of teaching either single discipline or multidiscipline of STEM to be developed. The units can be developed not only for the various Robotics teams but for Elementary, Middle, and High school level as well as for classes in University. Mathematics, Physics, Programming, Mechanisms, Systems, Sensors, etc. Emphasis will be placed on concepts and their use to solve problems.

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Biography

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