



The Symbiosis of Design and Inquiry-Based Learning in Creating Robotic Models of Biological Systems

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Abstract

This paper considers an approach, in which design and inquiry-based learning are combined to meet the challenge of inquiry into a biological phenomenon and development of its technological representation in the form of a robotic model. Our multi-case study involved middle school students and prospective teachers. The study considered learning processes, in which the students used the PicoCricket robot construction kit to create a variety of bio-inspired robotic models. We propose the outline for such learning processes. Based on analysis of learning activities along with the studied cases, we extracted characteristics of the robotic modelling environment, formulated principles of the integrative learning, and evaluated its educational outcomes. The findings indicate the potential of robotic modelling as a way to symbiotically combine engineering design and scientific inquiry into an integrative learning activity.

Keywords

Science-technology education, Design, Inquiry, Robotics, Biological system, Modelling, PicoCricket.

Introduction

Recent literature emphasizes potential benefits of the "accommodation between science and technology education in the curriculum" (Lewis, 2006; Fensham, 2009). Lewis proposes to study engineering design and scientific inquiry at school in ways that utilize their complementarity and conceptual proximity. One way is to employ design as a vehicle for teaching scientific content, and the other is to harness science as the driving force for prompting design. Lewis suggests design as a bridge between science and technology education towards achieving scientific and technological literacy. This goal, so he argues, calls for new interdisciplinary pedagogies "that are integrative in approach, showing fluidity between engineering and science". In this regard, Fensham (2009) points to the need of studying technology as the real world context of science and as the way for applying science to serve society.

Resnick, Berg and Eisenberg (2000) emphasize yet another argument in favour of keeping the technological content in the curriculum: failing to do so may lead to a situation in which technological systems utilized in science education are grasped as "opaque" black boxes, without understanding the principles of their operation. To avoid this circumstance, the students should be nurtured to "look inside" the technological artefacts in the world around them and develop their own tools for exploring phenomena in their immediate environment.

Researches considered possible ways to implement learning by design and inquiry in the middle school science and technology curriculum. Kolodner (2003, 2009) analyzes learning-by-design



processes, in which the learners, triggered by an explicit design challenge, “mess about,” generate ideas, identify what they need to inquire, collect data, and gradually build artefacts. Kolodner presented a learning model that combines design and inquiry activities organized in two connected cycles: the "Design\Redesign" cycle answers the "need to do" while the "Investigate & Explore" cycle answers the "need to know". The proposed model is grounded on the principles of constructionism (Papert, 1991) arguing in favour of involving the learner in the creation of artefacts serving as “objects to think with”. In the cases presented by Kolodner (2003), design of technological artefacts was motivated by the need to understand scientific concepts.

When acting towards integrative teaching of natural science and technology through binding design and inquiry, or in any other way, we need to take into account the different nature of the two domains. Science focuses on natural phenomena, while technology deals with man-made creation (Ropohl, 1997). Standards for technological literacy define the relationship between science and technology from the perspective of symbiotic interdependence: "Science is dependent upon technology to develop, test, experiment, verify, and apply many of its natural laws, theories, and principles. Likewise, technology is dependent upon science for its understanding of how the natural world is structured and how it functions" (ITEA, 2000). Another manifestation of the relationship between science and technology is based upon the aspiration in both domains to borrow ideas of one another (Verner and Cuperman, 2010). Robot design, as well, is greatly influenced by the attempt to imitate appearance, functionality and behaviours of nature-made creatures and, in particular, the human being locomotion and intelligence. In the opposite direction, science is trying to understand and explain natural phenomena by exploring existing, or specially developed technological systems. The above mentioned manifestations are explicitly based on analogies between natural and technological systems. Researchers note that exploring such analogies not only facilitates the development of science and technology, but can also make a strong contribution to education (Gilbert et al., 2000).

The principles of integrative learning of science and technology are discussed by Resnick, Berg and Eisenberg (2000). They proposed a constructionist approach that encourages students to design their own instruments and use them for experimental inquiries. The authors point out that this approach can "deepen students' understanding of the scientific concepts involved in the activities." Based on the constructionist approach, this paper proposes to facilitate learning of science and technology by a practice in which the learner investigates and explores a biological system along with the design and construction of its robotic model.

Learning with Robotic Models

Elmer and Davies (2000) point out that the purpose of modelling activities in design and technology education is more than acquisition of technical capabilities; it includes development of thinking skills. The same view underlies the concept of digital manipulatives introduced by Resnick et al., (1998). Accordingly, manipulative materials with embedded capabilities for sensing, computing and communicating open opportunities for creative construction of technological systems and foster systems thinking. A key feature of a digital manipulative is that it can be programmed to demonstrate a reactive behaviour. In educational practice, the inspiration to develop a digital manipulative and program its behaviour usually comes from the desire to reflect on phenomena and imitate behaviours existing in the world around us. Thus, the digital manipulative serves as the object-to-think-with in learning practices of its construction, programming, and exploration. We consider such a digital manipulative to be in essence a robotic model which is both a technological system and a representation of a phenomenon. Learning with a robotic model can occur in two domains: one in which the model is designed, built, operated



and evaluated as a technological system, and the other, in which the model is understood and assessed as a representation of a phenomenon.

The concept of robotic model can be better understood when contrasting it with the concept of model commonly used in science education. It seems reasonable to make this comparison in terms of the following categories used by Ropohl (1997) for the comparative analysis of knowledge types in science and technology:

- Models in science education are *objects* usually presented in a generalized symbolic form. Physical models, and especially dynamic ones, are rare and mainly used as visual aids (Lipson, 2007). A robotic model, on the other hand, is a dynamic physical object which facilitates learning through hands-on activities of its construction and operation.
- The *objective* of modelling in science education is to assist understanding of phenomena and share knowledge (Seel & Blumschein, 2009). Practice with a robotic model serves an additional purpose of fostering systems thinking through devising an artefact.
- Regarding the *methodology*, a model in science education is treated as an ideal representation, while practical considerations are overlooked. Robotics education, in contrast, deals with models that function in the real world.
- Regarding the *characteristics of results*, the outcome of modelling in science education is a mental model that is formed in learner's mind. Modelling in robotics education prompts several outcomes: a mental model of a scientific concept, a mental model of a technological system, and a robotic model. Here the robotic model is a technological expression of scientific concepts acquired by the learner (Papert, 1991).
- *Criterion of quality* of a model in science education is its suitability to promote the acquisition of valid conceptions while avoiding misconceptions. A robotic model answers yet an additional criterion of proper functioning.

To summarize the comparison, a robotic model can feature as a science model with the added value of being a real technological system. In the context of this study, the learner, being engaged in devising a robotic model that represents a biological system, develops interconnected mental models of the biological and technological systems.

The proposed approach to learning with robotic models goes beyond robotics courses that concentrate on building simple mobile robots and programming basic reactive behaviours. We follow the new strategies for introducing students to robotics, as recommended by Rusk et al. (2008): focusing on themes, not just challenges; combining art and engineering; encouraging storytelling; organizing exhibitions, rather than competitions.

Indeed, creation of a robotic model of a phenomenon is a theme which combines engineering thinking with personal artistic expression. The developed robotic model is used not for competition, but serves as a tangible exhibit which assists storytelling concepts of science and technology.

Rusk et al. (2008) noted that there are different robot construction kits, each of which supports some type of activities and learning styles better than others. In this regard, the authors recommended the PicoCricket kit as suitable "to combine art and technology, enabling young people to create artistic creations involving not only motion, but also light, sound, and music".

Modelling Biological Systems

Based on the discussed view of learning with robotic models, we developed an instructional unit



"Control in Technological and Biological Systems" and delivered it to prospective teachers of science and technology, high school and middle school students. Dozens of instructional models were developed by our students in the framework of teacher training and outreach courses. The models featured topics such as: plant tropism, animal behaviour, control in biological systems in general and homeostasis in particular. All the models were built using the PicoCricket robot construction kit. The kit consists of a programmable microcontroller that can operate different actuators and manage input from various sensors. The microcontroller provides bi-directional infrared communication with a host computer or other PicoCrickets. In addition, data management capabilities are offered, with an opportunity to sample data from the sensors, implement reactive behaviours, and upload the data to a computer for graphical representation. These capabilities can further promote the use of the kit as a tool for inquiry based learning. The PicoCricket "specialties", such as pre-programmed animal voices, colorful lights, and craft materials, are useful for building robotic models of animals and other biological systems.

A Venus Flytrap Model

The nature phenomenon studied and modelled in this project was the ability of the Venus flytrap plant to detect and trap a prey.

Inquiry into the phenomenon. Closure of the Venus flytrap is one of the fastest movements in the plant kingdom. The trap consists of two lobes, which close together forming an enclosed pocket. The center of each lobe contains three mechanosensitive trigger hairs. When a prey crawls into the trap it bumps into the small trigger hairs. Two touches of a trigger hair are needed to activate the trap which snaps in a fraction of second. The closing process essentially involves a change of the leaf's geometry. The upper leaf is convex in the open position and concave in its closed position. The driving force of the closing process is most likely the elastic curvature energy stored and locked in the leaves. (Volkov et al., 2007; Pavlovic et al., 2010)

The model. The Venus flytrap model, shown in Figure 1 includes two touch sensors, and a dc motor driving a crank that can open or close a trap shaped mechanical structure. The PicoCricket executes the program written in PicoBlocks to implement the model behaviour. When creating the model, the students used technological means for developing a sensing mechanism to imitate the mechanosensitive trigger "hairs", and a trap mechanism, to imitate the Venus flytrap "lobes". The PicoBlocks program implements the following behaviour: when two successive touches on any of the sensors or a simultaneous touch on both sensors are indicated, the motor is actuated and the trap mechanism closes.

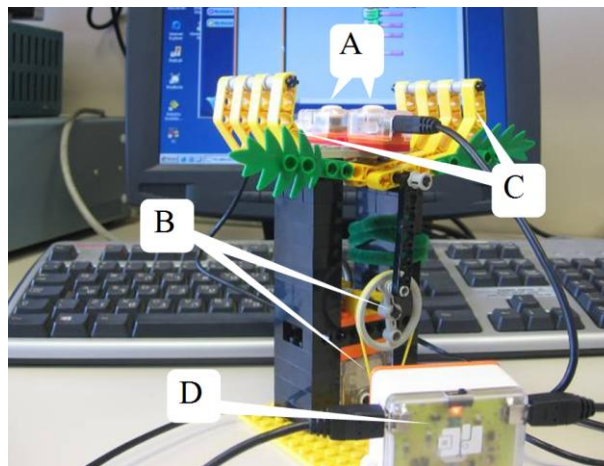


Figure. 1. The flytrap model: A. Sensors; B. Motor & crank; C. Trap mechanism; D. PicoCricket.

Educational Study Framework

The goal of this study was to develop and evaluate an approach to integrative learning of robotic and biological systems through modelling activities. We conducted a series of case studies in which the instructional unit "Control in Technological and Biological Systems" was delivered to prospective teachers of science and technology (N=22), high school students (N=14), and middle school students (N=73). The multi-case study framework enabled us to examine the proposed integrative learning approach across differences between the groups in their backgrounds and learning objectives.

The instructional unit was crystallized along with the case studies. As a first step, two case studies were conducted in the framework of our course for prospective teachers. Data were collected by means of pre-course and post-course questionnaires, semi-structured interviews with the students, and by artefact analysis. The insights we got from those two preliminary case studies helped us to refine the instructional unit for further case studies of teaching school students.

While striving to follow up implementation of the educational strategies, proposed by Rusk et al. (2008), we applied the inductive reasoning method (Lodico et al., 2010), trying to systematically examine our course in different learning situations. We observed typical learning behaviours, as well as features of integrative learning. The data were collected, triangulated and analyzed by mixed methods, following the integrated methodology (Plowright, 2011, pp. 6-22). Learning behaviours and their dynamics were observed along with the development of robotic models, while data were collected through observations, videotaping, interviews and questionnaires. Meaningful information was also obtained through artefact analysis and evaluation of the models developed by the students. In this evaluation we referred to model's complexity and to the characteristics of analogical resemblance between the model and its source, such as appearance, functionality and structure (Verner and Cuperman, 2010).

Findings

Attitudes towards Learning with Models

Prospective Teachers

A post-course questionnaire was offered to part of the students (N=12). It asked about attitudes



towards learning with models and requested recommendations about ways to incorporate physical computerized models into learning activities. The questionnaire indicated that all the students were strongly interested to build physical computerized models and use them as teaching aids. More than 83% of the students recommended in-class demonstrations and experimentation with ready-made models, while all the students strongly recommended engaging learners in making models as part of inquiry activities. These results are in line with students' reflections expressed in the post-course interviews. The students recognized the advantages of learning with models, and especially, the value of models as means for visualizing dynamic processes:

"There are things you can only visualize using physical objects, which you can touch, change and play with." (A student majoring in technology education)

The students stated that the educational benefits of practice with models justified the effort of model making, and that this effort was less than expected:

"The effort was justified. When you create, build something, this enhances the learning process." (A student majoring in technology education)

School Students

Pre-course and post-course questionnaires on attitudes towards learning with models were conducted in the course delivered to high school students (N=14). Before the course, all the students expressed interest or strong interest to practice learning with physical computerized models. They all were more interested to focus practical activities of the course on building instructional models rather than on using pre-build models. Over 78% of the students assumed that practice with models will be helpful. After the course, all the students stated that practice with robotic models, and especially designing and building robots, really helped to learn the science and technology concepts of the course.

Features of Integrative Learning

Based on the observation of students' activities of model creation and analysis, in the first case studies, we found that the activities can be divided into five stages:

Stage 1. Acquiring technological knowledge. The learners were provided with knowledge essential for using the construction kit and building simple robotic systems. In particular, the students learned about sensors, control, simple mechanisms, motors, actuators, and intuitive brick programming. When introducing concepts related to technological systems we deepened into their scientific principles and explained them using their connection to similar concepts related to biological systems.

Stage 2. Selecting a biological process. The students were assigned to inquire a specific biological control mechanism within a selected topic. They selected the modelling tasks, while taking into account technological opportunities provided by the construction kit. In one case study, for example, the students selected from various phenomena of plant tropism. They examined ways to model this plant behaviour using the sensors available in the kit.

Stage 3. Inquiry into the biological system. The learners were engaged in a self-regulated inquiry, in which they studied the characteristics of the nature phenomenon relevant for creating the robotic model. Special attention was paid to the biological mechanisms to be imitated by the robotic model.

Stage 4. Building the model. The learners designed and built the robotic models through rapid prototyping rounds, in which characteristics of the model prototype were examined and improved to match those of the biological system.



Stage 5. Assessing differences and similarities. Once the model development was completed, the learners were assigned to individually answer the post-course questionnaire and systematically analyze the analogy between the model and the biological system.

One can see that the constructionist approach underlies the integrative learning process, so that at each stage learning occurs while a sharable artefact (physical or conceptual) is created.

When examining the integrative learning process our focus was on students' perceptions of the environment and indications of learning that repeated throughout the case studies. The features of integrative learning that emerge from this examination are as follows:

- The interplay between construction and inquiry in the creation of a robotic model is a motivating factor for integrative learning of science and technology.

Observations indicated that the interest to build a robotic model triggered students' curiosity to the biological phenomenon. We also noticed that the aspiration to implement discovered knowledge into an authentic model drove effort to adequate construction. Those findings emerged also from reflections of both the prospective teachers and the school students participated in the study.

"The method arouses motivation to learn. Working with the robotic kit was attractive and interesting. The combination with scientific content was good and helped us to learn, so the concepts were better understood and remembered." (A student majoring in mathematics education)

- Constructing robotic models through rapid prototyping is an effective strategy for supporting integrative learning.

While the construction of a robotic model using the PicoCricket kit was rapid (a few hours) it drove the student toward an experiential learning cycle of technological prototyping along with agile scientific inquiry.

"When I built the model I went back and check the scientific concepts behind the model." (A student majoring in technology education)

- Students' involvement in the analysis of similarities and differences between the model and the biological system can facilitate integrative learning of robotics and biology. Limitations of modelling tools can reinforce the challenges of the inquiry and design-based learning.

This effect was observed in several cases. An example is the process of perfecting the mechanism for modelling tropistic movements in plants, observed in the Venus flytrap project. In this model, described in Section 3, the "trap" movement is generated by powering an electric motor that changes the orientation of two "lobes" via a crank mechanism. Further inquiry of the trap closure in the plant revealed that its mechanism is different and utilizes stored elastic energy to change leaf's geometry. This finding motivated the development of a more realistic mechanical solution in the succeeding project. The developed solution, that imitates the plant hydrostatic pressure movement mechanism, utilizes pneumatic pressure to simultaneously unfold two "leafs" and move them apart.

To further facilitate the integrative learning, we asked the students to evaluate the similarities and differences between the model they built and its source. Analysis of those written evaluations indicated that the students, when comparing the biological systems and robotic models, examined the features of appearance and functionality.

Characteristics of the Learning Environment

We found that the following features of the environment are essential for sustaining the learning process:



- The learning environment should provide the integral infrastructure for both conducting scientific inquiry and building robotic models. From our experience, in addition to facilities for inquiry (web access) and modelling tools (robot kit, craft materials and instruments for modular construction and programming), a gallery of previously developed models serves as a worthwhile constituent of the environment.
- A team of two or three learners was found preferable for providing self-expression and opportunities of contribution, while still allowing the benefits of team diversity and collaboration. As observed, the students formed the project teams by themselves. Each student typically took leading in one of the three project areas: inquiry, building and programming.
- A framework, in which teams share the same open workspace, facilitated active interactions within the teams, between the teams and between the students and the teacher. In our course, team workplaces were organized to provide space for individual and team activities, while collectively using facilities for inquiry and modelling. During the workshops the teams were free to communicate and discuss their ideas and insights. The teacher's guidance was directed to facilitate both inquiry and model building activities. The teacher stimulated students' inquiry by asking questions that invoked further investigation and prompted the need for validation of results.

Learning Outcomes

Course assessment throughout the case studies provided notable indications of learning achievements in both scientific and technological competences. The assessment was based on oral and written descriptions of the inquired phenomena and their models, provided by the students in open discussions, presentations, project reports and knowledge questioners. Technological competences were also assessed by the analysis of robotic models and construction activities. Assessment results indicate that each student in the course advanced in knowledge and skills related to technological literacy, especially in relation to design, the nature of technology, and the abilities for a technological world. When creating the models, the students acquired and practically demonstrated skills of robot construction, programming and operation. The progress in learning technological concepts was indicated by the literate explanations given by the students when presenting their models. The gain of knowledge in biology was assessed through the analysis of students' oral and written explanations. Literate use of biological concepts was examined in collaboration with biology teachers.

The teachers helped students to validate information that they collected through inquiry. In some cases this was followed by an intriguing discussion. For example, one of the students built a robotic model of the sunflower heliotropism process, described in our previous paper (Verner and Cuperman, 2010). When inquiring sunflower's movement towards the sun (heliotropism), the student found in literature that the flower-head movement is caused by differential translocation of auxin (a plant growth hormone). The hormone causes greater cell elongation in the shaded side of the stem, bending the stem and ending in the flower-head facing the sunny side (Sherry & Galen, 1998). When he presented this information to the biology teacher, she first disagreed, arguing that the mechanism behind the phenomenon is probably related to changes in hydrostatic pressure. Such changes in the pulvinus (a joint-like thickening at the base of the stalk of a leaf) cause its expansion and lead to leaf movement. After a deeper examination the teacher acknowledged that the explanation given by the student was correct and that her version is relevant to leaf movement.



Discussion and Conclusion

Our research is motivated by the need for new ways to bridge science and technology education in middle schools. It proposes a learning environment, in which the study of a scientific phenomenon prompts and inspires practical activities, which in turn drive further learning of scientific concepts. Specifically, the students perform inquiry into biological systems to acquire knowledge needed for creating robotic models. In this setting, the robotic model becomes a "nucleus", which organizes and triggers the learning of technology and science subjects around the modelling process. All stages of this modelling process, i.e. the model ideation, materialization and exploration, have their specific educational roles.

The students are becoming involved in model ideation from the first experiments with the robot kit, when they explore analogies between its components and biological organs. From these analogies the students acquire a new perspective on biological systems and gain motivation to develop robotic models. The ideation continues, when the student selects a biological system and performs a self-regulated inquiry into its control mechanism. At this stage the student applies knowledge on control of technological systems to the study of biological systems, and ideates the concept of the model. At the materialization stage the student creates the model through iterations of rapid prototyping. The aspiration to improve the prototype directs the learning towards in-depth understanding of the biological system and development of effective technological solutions. At the model exploration stage, the analysis of similarities and differences between the model and the biological system guides the student to evaluate the model and the learning outcomes. From the aforesaid, the student can derive additional benefits from the design and construction of a robotic model beyond those that can be obtained from the analysis of a prebuilt model. This conclusion is in line with findings of other researches (Milard, 2002).

Our study indicated that the proposed course of action fostered growth in learners' scientific and technological literacy, positive attitudes towards teaching and learning with models, and motivation for building robotic models. Because of the limited assortment of components and materials in the kit, the robotic model can provide only partial analogical resemblance to the biological system. This opens a room for examination of similarities and differences between the source and the target, a systematic activity that facilitates integration and better understanding of both subjects. Findings of our research indicated that the examination of both similarities and differences was a meaningful learning experience for the students.

While guiding inquiries into biological systems towards creating the model, we acted to avoid inaccuracies in acquisition of biological concepts that might happen while self-regulating learning. We encouraged the students to carefully analyze specific features of the biological systems and consult with biology teachers to validate findings of this analysis.

In conclusion, we acknowledge the potential of modelling as a thread, tying together engineering design and scientific inquiry into an integrative learning activity. We continue the study of the proposed approach towards deeper understanding of cognitive mechanisms and wider implementation of learning with analogies.

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