C-K Theory based Bio-inspired Projects in a Sophomore Design Course

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Abstract

Courses incorporating bio-inspired design into engineering curricula, might help students to think innovatively and from multidisciplinary perspectives. The Concept-Knowledge (C-K) Theory is a well-established approach for integrating multiple domains of information and facilitating innovation through connection building. Students learn about the two major paths to bio-inspired design (biology-driven and problem-driven), as well as how analogies are used to assist with transferring knowledge from biology to engineering. For the purposes of evaluating the benefits of using C-K theory and its application to bio-inspired design, students in sophomore engineering design were assigned a project that require them to develop a bio-inspired design using C-K theory. This paper reviews the C-K theory approach and its application to bio-inspired projects for college sophomore engineering students at the University of Georgia and James Madison University. The results of student projects and the impact on their knowledge and innovation in design activities are presented. Also, discussed are survey results of students' perceptions towards adopting the C-K theory approach to design innovation during the conceptual phases of design.

Keywords

Bio-inspired Design, C-K Theory, Design, Engineering, Course

Introduction

The engineer[1] of 2020 is expected to not only offer technical ingenuity but also adapt to a continuously evolving environment while being able to operate outside the narrow limits of one discipline and be ethically grounded in solving the complex problems of the future. To address the competencies of the future engineer, undergraduate education must train students to not only solve engineering challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. One approach to train engineers in these competencies is teaching biomimicry or bio-inspired design in an engineering curriculum, which offers relevance to professional practice as well as an affective hook to frame complex, cross-disciplinary problems. This research addresses the need for undergraduate student training in multidisciplinary design innovation through the creation of instructional resources grounded in Concept-Knowledge (C-K) Theory. C-K theory is used as it is known for integrating multiple domains of information and facilitating innovation through connection building.

The C-K Theory instructional resources were deployed at two predominately undergraduate institutions (PUIs) in the second-year engineering curriculum. All students were given a lecture on bio-inspired design and asked to complete the C-K mapping template in class as part of learning activities to understand the process of discovery, and again in their assignment to scaffold application to the course project. Analysis of the student-generated templates using a rubric shows

that students were able to successfully use information (knowledge transfer) to make connections between biology and engineering for creating solutions for design problems. Additionally, all students were asked to respond to six reflection questions regarding the content (biology) and process (bio-inspired design). Qualitative content analysis of second-year engineering student reflection statements shows that in both populations the instructional resources resulted in significant learning of both biology and bio-inspired design, as well as learning engagement and value of the experience. An unanticipated, but significant, result is that some students used existing biology knowledge to help understand engineered components and systems, meaning they learned more about engineering through biology. This unanticipated result points toward the significance of teaching bio-inspired design in an engineering curriculum. Teaching bio-inspired design in an engineering curriculum using interdisciplinary approaches will not only develop competencies of the 21st century engineer but also enable undergraduate students to become change agents and promote a sustainable future.

Literature Review – Bio-inspired Design

Multiple institutions offer semester long engineering courses in bio-inspired design or interdisciplinary courses that bring together students from STEM and art at the undergraduate level. Probably the most well-known institution is Georgia Tech, which offers multiple courses and a certificate through the Center for Bio-inspired Design.[2-3] The undergraduate interdisciplinary course is co-taught by faculty from biology and engineering, and admits junior and senior level students from all fields of engineering and biology. Two processes for bio-inspired design, problem-driven and solution-driven, are taught in the course, and analogies are formed through functional decomposition similarly to functional modeling in engineering design.[2] More recently, the four-box method that identifies function, operating environment, constraints, and performance criteria as dimensions for matching biological analogues with the design problem has been implemented.[4] Students work in interdisciplinary teams on assignments and projects throughout the course. Honors-level undergraduate courses similar to the one at Georgia Tech have been offered at institutions such as Virginia Tech.

The mechanical engineering department at Montana State University offers a senior level technical elective on bio-inspired engineering.[5] The course covers relevant bio-inspired design and engineering design processes with a focus on structures and materials from both nature and engineering. The practices taught in the course include reverse engineering and tabulating a variety of relationships. Thus, the focus is more on comparison than innovation. Texas A&M is currently developing an undergraduate course to introduce interdisciplinary engineering students to multiple methods of bio-inspired design.[6] The course will be an elective in the mechanical engineering curriculum that focuses on breadth of approach rather than depth, exposing students to the state-of-the-art in bio-inspired design research tools and methods. At the Olin College of Engineering, all students take a course that introduces bio-inspired design in their first semester. The course is called Design Nature and is an introduction to the engineering design process that also weaves in concepts from nature. Students complete individual and team projects in the course. Similarly, all first year engineering students at the University of Calgary are introduced to biomimicry in their design and communication course.

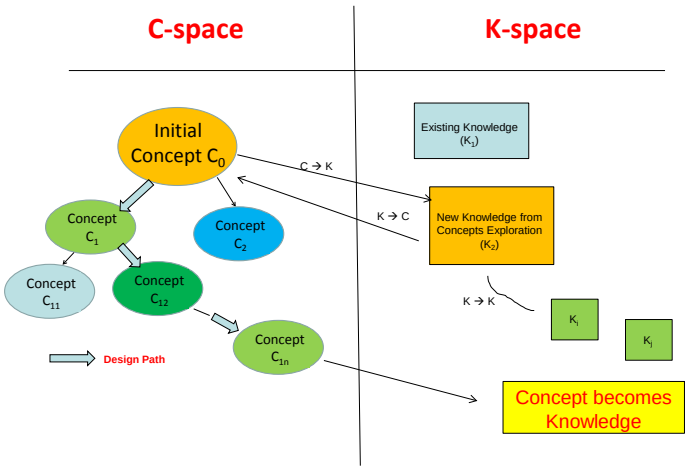
At Kettering University, in the Industrial and Manufacturing Department, biomimicry is integrated into an ergonomics course through problem-based learning.[7] Students work individually on

projects using the Biomimicry Innovation Tool, which blends aspects of problem based learning, innovation, biomimicry, and ergonomics into a single student experience. They present their bio-inspired concept at the end of the course. The University of Maryland offers a course in biomimetic robotics as a senior elective in the mechanical engineering program.[8] Students study biological locomotion and how it can inspire efficient mechanisms of motion.

Bio-inspired Design Modules and Projects

Bio-inspired design concepts and examples have been used by several institutions to educate students on design innovation and as another source of design inspiration. Institutions include Oregon State University, University of Georgia, James Madison University, Purdue University, Clemson University, Penn State University-Erie, University of Maryland, Indian Institute of Science, University of Toronto and Ecole Centrale Paris to name a few. Often the instruction is across less than four lectures, which reduces the burden of integration into existing courses. These institutions also require engineering students to complete assignments or a project involving bio-inspired design to practice the technique and demonstrate its value. Integration occurs at the freshman through senior levels, in a variety of departments, and primarily depends on when engineering design is offered in the curriculum. Consequently, varying levels of instruction and support are provided to the students, and many rely on the resources provided by the Biomimicry Institute, such as the database AskNature.org. This points to the lack of engineering-focused, evidence-based instructional resources available to faculty that wish to integrate bio-inspired design into their courses.

C-K Theory Approach to Bioinspired Design



Our approach is to use Concept-Knowledge (C-K) theory[9-10] as a theoretical framework to introduce bio-inspired design to sophomore students that integrates creative thinking and innovation by utilizing two interdependent spaces: (1) The knowledge space (K) – a space containing propositions that have a logical status for the designer (i.e., all available knowledge); and (2) The concepts space (C) – a space containing concepts that are propositions, or groups of propositions that have no logical status in K (i.e., have yet to be verified by knowledge) as shown in Figure right. As there are no instructional resources, we created a C-K mapping template to guide students through the knowledge transfer processes for the two major paths to a bio-inspired design (biology-driven and problem-driven). Our application of this resource and its pedagogical impact are summarized in the following sections.

Implementation

The C-K theory based resources/projects were implemented at the University of Georgia (UGA) in a sophomore design course that introduced the C-K approach at the conceptual design phase, and at James Madison University (JMU) in a sophomore engineering design course that focused

on the theory, tools, and methods of the engineering design process. This section describes those courses and how the resources/projects were implemented.

University of Georgia
Students in three engineering (Agricultural, Biological and Computer Systems) majors took the sophomore engineering design methodology course in the spring semester. It is a 2 credit hour course (meets once a week for about 2 hours) and provides an introduction to design methodology, emphasizing the design process starting from design need to requirements, conceptual design and evaluation and prototype testing. In addition to traditional homework and a mid-term test, a final project was assigned for students to demonstrate and implement the design methodology. In order to emphasize the innovative and creative aspects of design solutions during the conceptual design phase, students are introduced to bio-inspired design and are required to use of C-K theory in generating design solutions for their projects. Students are exposed to bio-inspired design and C-K theory through lectures as well as examples in class. Students work individually as well as in teams.

James Madison University
The sophomore engineering design course sequence, Engineering Design I and II, is the cornerstone of the JMU design sequence curriculum. The objective of the course sequence is to not only teach students the design process, but also to drive students toward ownership of the engineering design process as well as provide the base knowledge to begin their capstone projects. To achieve this objective, a year-long, client-based, design project is woven into instruction in the area of engineering design theory and methodology. Throughout the year-long project, students interact with an actual client to design and build an actual product.

Bio-inspired design is integrated into the sophomore engineering design course sequence in the first semester. It is taught as a creative concept generation technique and contrasts the systematic technique of morphological analysis. Since the course meets once a week, the topic is given one class period and one assignment. All assignments in the sophomore engineering design course tie to the year-long course project, including the bio-inspired design assignment. To integrate bio-inspired design into the human powered vehicle design project each member of a team applies bio-inspired design to a different sub-system (e.g., propulsion, steering, braking) of their design to showcase a variety of design problems and analogies that enable bio-inspired design. All students complete the C-K mapping template three times, twice in class as part of a learning activity during lecture to understand the process of discovery, and again in their assignment to scaffold application to the human powered vehicle.

Study Details

The C-K theory based resources/projects were implemented at James Madison University (JMU) in a sophomore engineering design course (23 students enrolled, consented sample size n=15) that focused on the theory, tools, and methods of the engineering design process, and at the University of Georgia (UGA) in a sophomore design course in Spring 2016 (74 enrolled, consented sample size n=39) that introduced the C-K approach at the conceptual design phase. In both courses, a teaching module with learning activities[11] was given, as well as an assignment related to the course project, which are briefly described below.

The developed assignment that compliments the teaching module and learning activities includes three parts: 1) complete the C-K mapping template for a human powered vehicle sub-system, 2) use the sketches in the C3 level of the template along with the team generated morphological matrix to create a full human powered vehicle concept, and 3) a W/H/W reflection essay answering three questions about the content and process. The W/H/W reflections require learners to reflect on and respond to three questions: What did I learn?, How did I learn it?, and What will I do with it? These three prompts structure reflection so that learners focus on concepts, knowledge and skills, processes, and utilization/generalization/sustaining of learning. The W/H/W reflections provide formative snap-shots of learning and application that the learners are making as they progress through the material.

Results and Discussion

Assessment of student work was completed using a C-K map template rubric (Table 1) and a qualitative content analysis identified themes in student reflection statements. The results of themes that emerged from the reflection questions are provided in Table 1 below.

Table 1. Mapping of Reflection Questions to Themes related to C-K Theory

Reflection Question	Themes
What did I learn about the content?	• Valued what can be learned from nature and biology • In-depth understanding of chosen biological system • Cross-domain linkages • Biology is not always applicable
How did I learn the content?	• Scholarly or external resources • Course learning resources
What am I going to do with the content?	• Apply to immediate problem – course project • Facilitate a future design path
What did I learn about the process?	• Valued the inclusion of biology in engineering design • Recognized knowledge transfer between domains for problem solving is possible • Bio-inspired design is not always applicable
How did I learn the process?	• Course learning resources • External or other resources
What am I going to do with the process?	• Facilitate a future design path • Apply to immediate problem – course project

Currently, these reflection questions and the associated themes are being further analyzed to quantify the results. Also, student reflections revealed a positive response to the use of C-K theory-based instructional resources in the courses both at UGA and JMU. Student responses to what was learned about the process indicated that students recognized the value of using existing biology knowledge to help understand engineered components and systems. This emergent trend was unexpected, and points toward the significance of teaching bio-inspired design in an engineering curriculum.

Summary and Future Work

The C-K theory based bioinspired design projects demonstrated the critical thinking and creativity aspects observed in multidisciplinary problem solving settings. The students were actively engaged and displayed interest and excitement in coming up with innovative designs. The preliminary data analysis illustrated the effectiveness of using C-K theory instructional resources to teach bio-inspired design during the conceptual design phase of the design process. Future work will focus on obtaining more data related to this aspect and also developing and refining the learning resources based on C-K theory for sophomore design students.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 1504612. We would like to thank the JMU and UGA engineering students that participated in the study.

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