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Fostering innovation through bio-inspired projects in engineering design education

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Abstract

This paper discusses the C-K theory approach and developing templates for student's use in design courses, specifically for the conceptual design phase. Examples of C-K templates are reviewed to demonstrate the process leading to a design solution. Analysis of student's work using these templates are presented and discussed with respect to design learning attributes and design innovation during the conceptual design. Student reflections from their final design reports indicated that students did develop knowledge and skills in bio-inspired design, collaboration, and interdisciplinary mindsets.

Keywords: bioinspired design, C-K design theory, conceptual design, design education

1. Introduction

Twenty-first century engineers must possess design innovation skills that enable them to reach beyond the traditional disciplines, and into communities to identify issues and develop solutions that increase both resilience and sustainability. To prepare this new kind of engineers, engineering design training must embrace innovative approaches that inculcate design innovation skills that transcend disciplines and prepare engineering students for a diverse range of career choices. One of the ways in which the multidisciplinary approach has been incorporated in design engineering curricula is through its integration in bio-inspired design and projects into engineering courses (Nagel et al., 2019; Yen et al., 2014; Goel, 2007; Lynch-Caris, et al., 2012; Bruck et al., 2007).

Previous research has established that the integration of biological and scientific knowledge in the design process can be successfully achieved through implementation of the C-K theory based bio-inspired process (Hatchuel and Wei., 2003, 2009). The C-K theory explains the method of connecting, exploring and expanding biological and engineering concepts and knowledge spaces. A qualitative analysis of biomimicry-based student design projects revealed that the C-K theory based bio-inspired design process resulted in significant increases in student learning and engagement (Nagel et al., 2016). Recently, Dominguez (2023) introduced the C-K theory as a new paradigm for game studies with ontological characteristics as a design theory and demonstrated how C-K theory exemplifies it by visualizing the design of a published game.

This study uses quantitative analysis techniques to address the research gap in demonstrating the capability of C-K theory-based templates used in bio-inspired design process to produce innovative design solutions. The engineering design performance scores and data related to a biomimicry-based student design project were mapped on the C-K theory template and a statistical analysis was completed. The design performance scores were assigned to design engineering process attribute of the design project following an evaluation criterion. Qualitative analysis results of students learning and interest are presented and discussed in the paper.

2. Bioinspired 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. Several institutions including Oregon State University, University of Georgia, James Madison University, Baldwin Wallace University, Purdue University, Clemson University, Penn State University-Erie, University of Maryland, Indian Institute of Science, University of Toronto and Ecole Centrale Paris were implemented bio-inspired design projects. 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.

3. C-K theory approach to bioinspired design

Our approach is to use Concept-Knowledge (C-K) theory (Hatchuel and Wei., 2003, 2009) 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 I – 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 there are no instructional resources, we created a C-K mapping template as shown in Fig. 1 to guide students through the knowledge transfer processes for the two major paths to a bio-inspired design (biology-driven and problem-driven). The details of C-K mapping template are described with examples, especially from student learning and engagement (Nagel et al., 2016).

One of the research questions is being addressed is that how engineering design attributes contributes to bioinspired design, specifically using C-K theory approach. This research question is evaluated through student's work through C-K templates, and the application of this resource (C-K templates) and its pedagogical impact are summarized in the following sections.

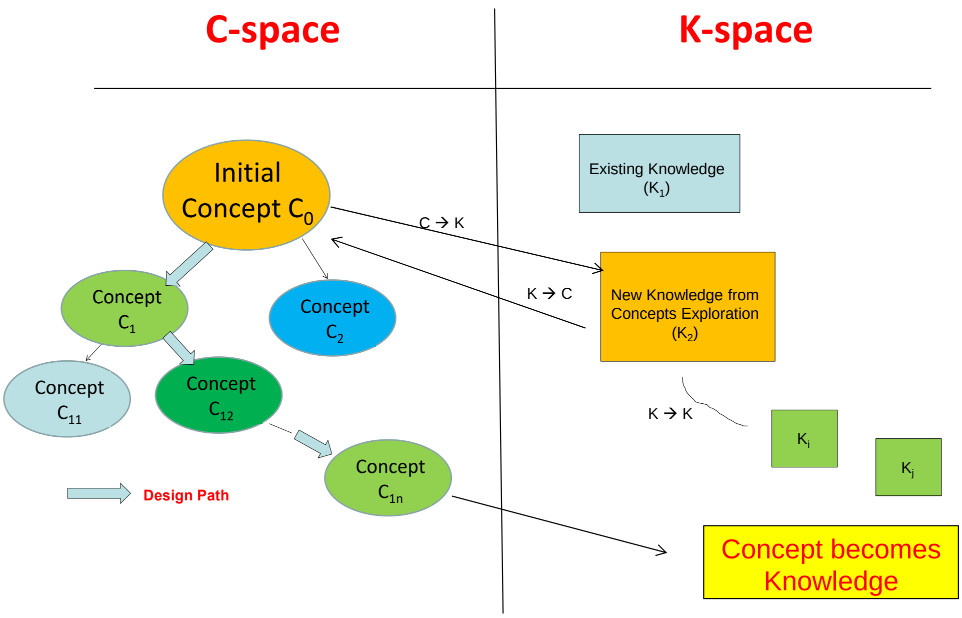

Figure 1. C-K template used to investigate bio-inspired design process

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3.1. Implementation

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

At UGA, students in Agricultural, Biological and Computer Systems engineering majors took the sophomore engineering design methodology course. 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 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 worked individually as well as in teams.

At JMU, students in 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. It is a 2 credit hour course that meets once a week and students work in teams to complete a client-based design project. 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. 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. Figures 2 and 3 show typical student work from both UGA and JMU in completing the C-K maps.

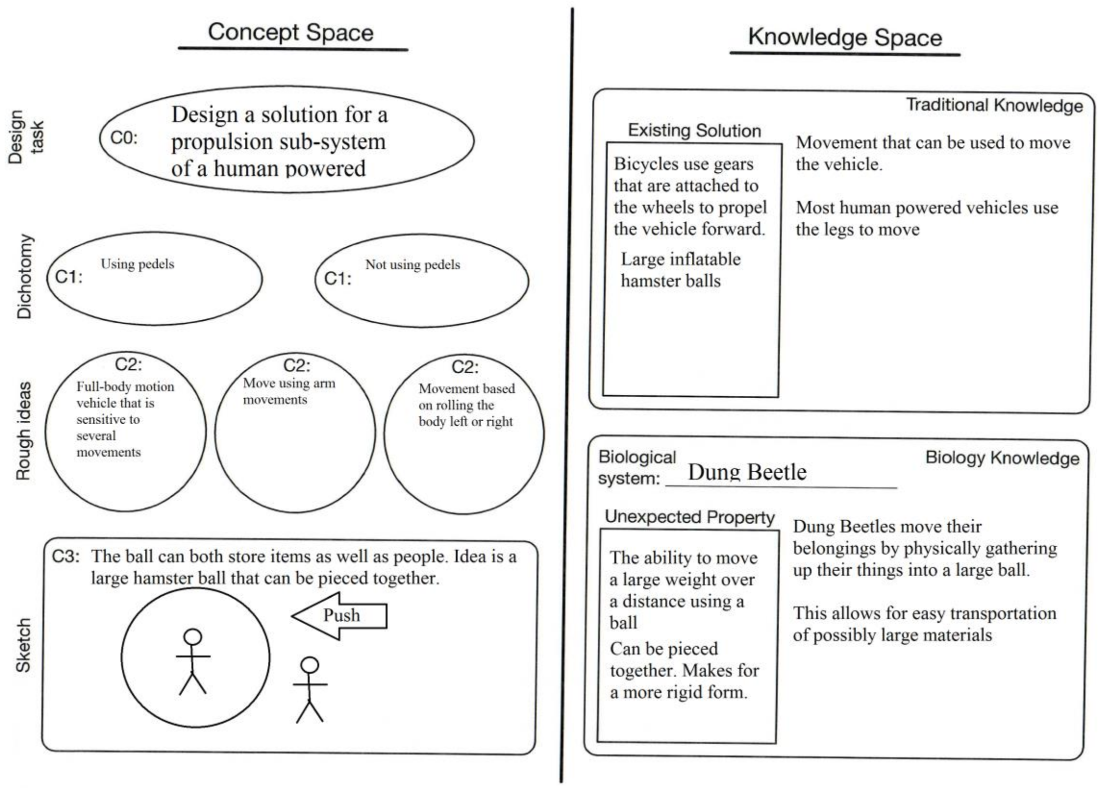

Figure 2. UGA student C-K mapping

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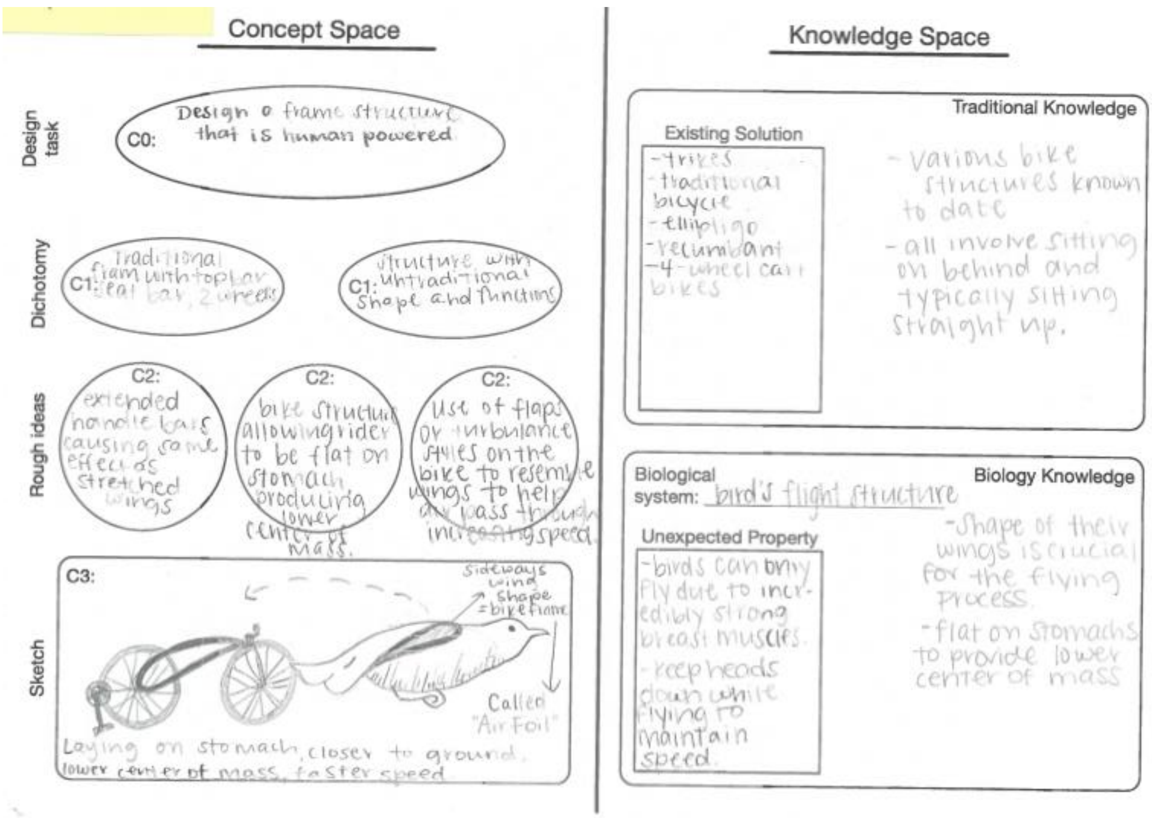

Figure 3. JMU student C-K mapping

3.2. Statistical analysis

Statistical analysis was carried out to investigate the relationship between biomimicry-based design engineering and design engineering attributes. Both JMU and UGA datasets were used as a pooled single dataset based on the two sample Kolmogorov-Smirnov test for the prediction of performance of design engineering attributes using the principle component analysis (PCA) method (Grace Raj et al., 2019). The number of principal components considered for PCA was decided based on the proportion of variance explained by them. Based on the principal component's scores of the first major principal components were used to map the relationship between biomimicry and design engineering attributes.

3.3. Performance assessment details

The number of students who participated in this project work from JMU and UGA were 53 and 48, respectively. They were instructed to record their bio-inspired design process in the C-K map with the connections between biological and engineering knowledge spaces to capture the evolution of design solutions from biological knowledge.

The students' performance on this design project work was evaluated based on their performance following the evaluation scheme described in Table 1.

Table 1. Criteria for assignment of score value to each engineering design attribute

Scale Value	Criteria
4	For well-defined/described concepts with higher order of creativity and well-defined design path
3	For moderate explanation of concepts with moderately defined design path
2	For lower level explanation of concepts with roughly defined design path
1	For poor explanation of concepts with unclear design path

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3.4. Student reflection 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 was given, as well as an assignment related to the course project, which are briefly described as follows.

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 map 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.

4. Results and discussion

Assessment of student work performance was completed using PCA, while qualitative content analysis was used to identify themes in student reflection statements.

4.1. Results

From the statistical analysis through Pareto chart and PCA, it was found that the JMU data, 57% of the variance was addressed by the first principal component and 7.7% of the data variance was addressed by second principal component. Similarly, for the UGA data, 44.4% of variance was addressed by first principal component and 9.9% of variance was addressed by second principal component. Hence, the principal component's scores of the first two principal components were used to identify the best representative design engineering attributes of the students' design performance. It was observed from the biplots (Grace Raj et al., 2019) that the design engineering attributes "Innovation" and "Imagination" had the highest magnitude in the positive quadrant for the pooled dataset. The results of student performance shown in Table 2 using the criteria given in Table 1 demonstrated that "innovation" and "imagination" are the best attributes of student's design performance. Table 3 provides the emergent themes from the reflection questions that resulted from qualitative content analysis of student reflections of adopting C-K theory in the conceptual design process.

Table 2. Design engineering attributes

Design Attribute	UGA Score	JMU Score
Innovation	4	4
Imagination	4	4
Decision making	3	4
Active participation	4	4
Redesign and Improvement	3	4

Some typical student reflection comments include:

> *"I learned a great deal about how nature has inspired design, and am beginning to see it the everyday items that I use."*

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"I learned that the process is not leaner not is it concreate or clear-cut. There's much room for creative expansion and many ways to achieve the same solution to a problem."

"After completing the process, I plan to continue using it to find other subsystems that could potentially benefit from bio inspired design. Bio inspiration has opened up endless amounts of possibilities."

"During this assignment I gained more background knowledge on the subsystem of steering on the bicycle and on a biological system of a bird. For the bicycle I learned that the handlebars undergo a counter rotating motion to achieve steering. On the bird I learned that the tail feathers actually contribute to not only the turning, but the braking and the upward and downward motion a bird can undergo."

Table 3. 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

4.2. Discussion

It was evident from the analysis on student performance presented in Table 2 that the students were able to obtain necessary knowledge, to search for alternatives and to experience collaborative creativity thinking to result with innovative design solutions. It can also be concluded based on the classification of students' performance on each attribute of the bio-inspired design process, mapped in C-K space that the knowledge generated and accessed during the design process for the evolution of innovative design solutions from the concepts and problem definition were effectively controlled by students' design thinking. This is due to the fact that the design thinking stimulated by the C-K theory based bio-inspired process was obtained due to the systematic thought process stimulated by the organized scientific information/knowledge search in broad scope of solution space for the definition of problem and concepts and by the relational out of box thinking of the students for the generation of knowledge and design concepts. The relational mapping by reasoning led to the design process evolution and to the generation of innovative design solutions.

The reflection questions and the associated themes reveal 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.

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All students in both institutions (UGA and JMU) indicated in reflections that the experience of C-K theory knowledge and interdisciplinary problem-solving into bio-inspired design projects provided them with invaluable design experiences. End-of-course student reflections recognized the importance of bio-inspired design projects and innovation in the project conceptual design phase.

5. Concluding remarks

The student training in design innovation through bio-inspired projects and concept–knowledge (C-K) space model, presented in this paper is unique in its focus to bridge design innovation from an interdisciplinary perspective. The statistical analysis of the student data from UGA and JMU revealed that the C-K theory based design process had significant capability to produce innovative design solutions and could be integrated into the engineering curriculum to train students in conceptual design process. There was clear understanding that bio-inspired design is another way to perform concept generation during the design process. Based on the assessment results from student reflection responses, these students demonstrated engagement in learning, an ability to recognize and formulate interrelationships across disciplinary boundaries, as well as bring innovation to the design solutions. One limitation of this study is the sample size (due to one semester course at UGA and JMU) and possibly constrain the generalization of the trends. However, the approach has a potential for future research with more studies and sample size in several design courses.

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