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Creating System Architectures for Engineering Concepts: An introduction to Engineering Undergraduates

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Abstract:

In this paper, we explore the ability of engineering students to create architecture for engineering concepts. The conceptual design phase of the aerospace engineering capstone senior design course at North Carolina State university involves students' teams starting with an initial sizing of the high-level system, defining the system architecture to establish the main subsystems and functional block diagram, generating concepts for the different subcomponents, and finally selecting concepts for these subsystems via a qualitative method to define an initial design. To establish an initial design, students must make connections between the function of the subcomponent and the physical form that can achieve the desired function. A concept is selected when a function is mapped to a physical form from a selection of forms that perform similar functions. To explore their ability to create architecture (functional and physical form), a module is introduced at the midpoint of concept generation and selection of the design process. This module will be a precursor to using the Pugh matrix and conducting sensitivity analysis. The problem statement is open-ended where the student teams are required to select cleaning devices from a list based on their assumptions. They will create functional and form views of architectures for the selected device, map function to form of the different subcomponents, and identify aspects of distinction. The teams will further apply this knowledge to define architecture for their capstone projects. As an example, function and form view and one to one mapping of these architectures for the teams working on an inflatable lunar rover will be shown. Assessment rubric is via a project proposal to assess the teams and a pre and post project survey to assess individual students.

Keywords:

Concept Mapping, Function to Form, Aerospace Engineering, Mechanical Engineering, System Architecture, Systems Thinking

Introduction:

The aerospace engineering capstone design module at North Carolina State University is a two-semester course where students go through the design process in the fall semester to come up with a design solution, including phases like project definition, conceptual design, preliminary design, and critical design. In the spring semester they manufacture the prototype, conduct verification tests, conduct a system readiness review, and finally conduct flight tests. Concept selection is a critical part of the engineering design process usually preceded by concept generation [1]. There are several concept generation techniques like mind maps, brainstorming and concept maps. Typically, the project requirement defines the boundary for which these ideas can exist [2]. To move from generating these ideas to picking an idea(concept) can be daunting especially for the novice designer. Usually, at the undergraduate level, qualitative methods like the Pugh matrix [3] are used to simplify the process and facilitate a reasonable decision-making process. However, these qualitative methods are prone to subjectivity. In fact, the choice is based on the current knowledge of the team and their attitude towards the Pugh matrix process [3]. This can differ from team to team and can be detrimental if the team makes the wrong decision. Sometimes, they are far long in the project before they realize the error. To reduce the subjectivity involved, sensitivity analysis is carried out to increase the confidence level in the decision made. Using the Pugh matrix for example, something as fundamental as the choice of the reference concept can skew the decision-making process [3]. Concept generation and selection are aspects of the conceptual design phase in the design process where the design team establishes an initial design. The conceptual design phase of the aerospace engineering capstone senior design course at North Carolina State university involves students' teams starting with an initial sizing of the high-level system, defining the system architecture to establish the main subsystems and functional block diagram, generating concepts for the different subcomponents, and finally selecting concepts for these subsystems via a qualitative method to define an initial design. To select a concept, students must make connections between the function of the subcomponent and the physical form that can achieve the desired function. A concept is selected when a function is mapped to a physical form from a selection of forms that perform similar functions. Therefore, a functional and physical form view of the architectures of these subcomponents must be created prior to mapping. To introduce this, a "Unveiling Concept: A mapping of *function* to *form*" module is introduced at the midpoint of concept generation and selection of the design process. This module will be a precursor to using the Pugh matrix and conducting sensitivity analysis. The problem statement describes the student teams as the management of a cleaning company bidding for a contract with a rental property company. In their proposal, they are required to select cleaning devices from a list based on their assumptions, create functional views and physical form views of the architectures for the selected devices, and then map function to form of the different subcomponents. They also identify aspects of distinction, and eventually give a budget for the cost to clean an apartment.

Background and Methodology:

<u>Systems Thinking and Systems Architecture:</u> Rarely taught at the undergraduate engineering level, these abstractions of function and physical form fall under the knowledge area of systems thinking. A good definition was given by Senge in [4] *Systems thinking is a discipline for seeing wholes. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static "snapshots*". In its broad sense, systems architecture design defines the behavior and structure characteristics in accordance with derived requirements. A systems architecture ensures that the system elements operate together in the applicable operating environment to satisfy Stakeholder needs [5]. The model-based systems architecture definition approach requires modeling languages like SysML and OPM to describe the three main systems architecture views (functional, logical and physical) which are beyond the scope of this paper. Functional Architectures defines what functions, and sub-functions exist within a system of interest (SoI), and the metaphorical "layout" or architecture which connects or otherwise relates

these functions. [5]. They do not describe the system design completely and are not independent standalone sub-unit of the systems architecture. [5]. A physical architecture view is an arrangement of physical elements, (system elements and physical interfaces) that provides the solution for a product, service, or enterprise [5].

<u>Function and Form Mapping:</u> Often, it is easy for the engineer to neglect the actual value creation source of a system, i.e. its function, and concentrate solely on the tangible elements that can be seen, i.e. physical form [6]. However, both are mutually connected and form the basis for defining a system's purpose and value. As noted by Haberfellner et. al [6], *function usually abstract, cannot be implemented without form* and *form usually tangible, without function creates no value* [6]. *In design, you know the functions you want and try to create the form to deliver the function(s)* [6]. The *function* should be neutral and conceived independently with respect to the solution. It is the *form* that determines how this *function* is realized [6]. This mapping of a neutral independent *function* to a tangible *form* is the concept. It is not just the attribute of *form* but the mapping. Therefore.

"To differentiate similar concepts, you must first identify their similar "desired functions/subfunctions" and then differentiate the "tangible forms" that is used to achieve these functions. These are their aspects of distinction."

<u>Unveiling Concepts: A mapping of *function* to *form*:</u> The module is based on the "Situated Framework" learning theory for engineering education practice [10]. Five main stages are involved; (1) pre-survey to assess current knowledge (individual), (2) lecture to pass on relevant knowledge, (3) assessment through proposal document by Team (4) feedback is given to the teams on their proposal, (5) post-survey to assess module contribution to state of knowledge (Individual). Furthermore, students will implement this in their capstone project which is an added form of assessment. The module encourages students to think about the value created through the *function* and the tangible *form* that is used to achieve them while making connections to differentiate similar concepts. The problem statement and proposal template are shown below with the typical XYZ floor and cleaning devices shown in figure 1.

<u>Module Objectives:</u> The following objectives are aspired for this module
Through the participation in the "unveiling concept" module students will be able to:

- Recognize the aspects of distinction between two similar concepts.
- Connect the functions to the tangible form of different parts that make up a system.
- Implement the skillset in the subsequent phases of the capstone project design process.
- Integrate subcomponent levels to create *form* and *function* view of the architecture for the different devices.
- Assess different concepts to select optimal combination while considering the cost that is best for business.
- Incorporate feedback to improve decisions made in the conceptual design phase and beyond for their capstone project.

Problem Statement

Your team are the managers of a cleaning company. You are trying to bid for a job with XYZ company to clean their apartments and their immediate environment. XYZ company owns a chain of rental properties that are very heavily patronized. They also are distributors of three cleaning devices which they can provide for cleaning services (see Figure 1: Typical XYZ floor and cleaning devices). They want you to select two of the three devices so they can make them available in the apartment storage for your company. You are in a bid for the contract with several other companies, so total cost is important. As part of the selection process XYZ company wants to know which two you've picked and the reasoning behind your selections. What functions do the different attributes/aspects of each device do that make it preferable?

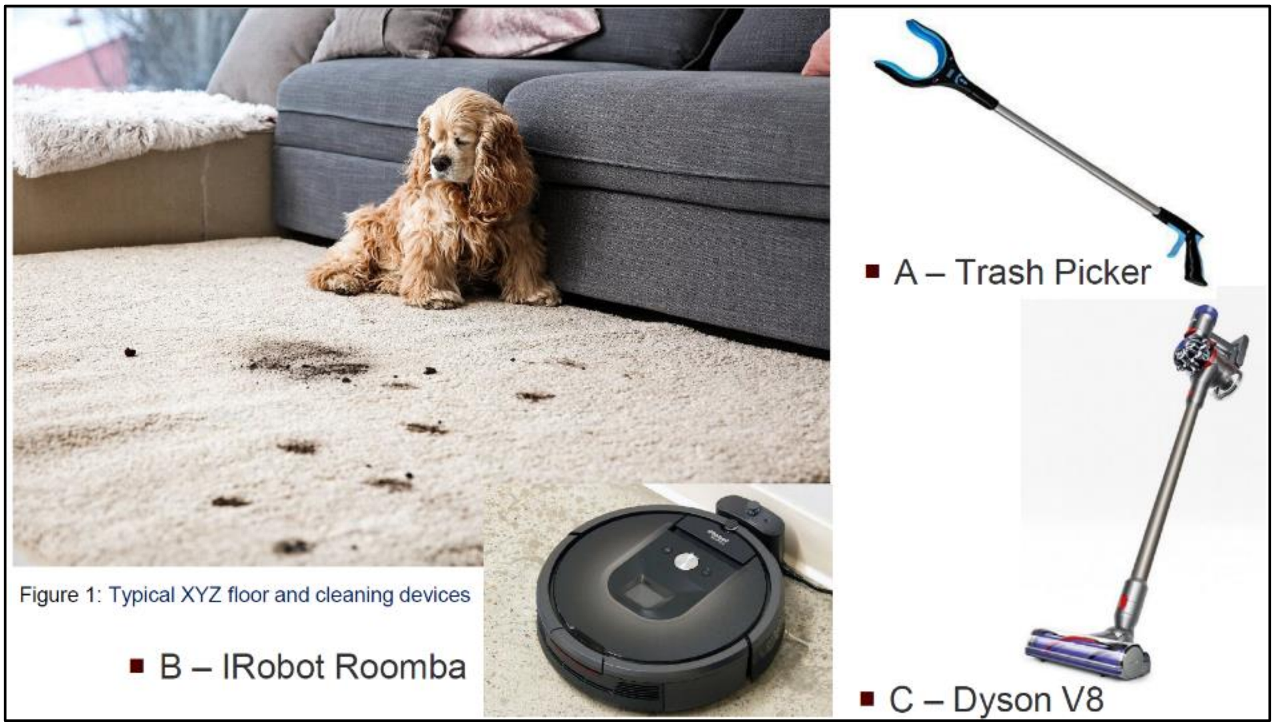

Figure 1: Typical XYZ floor and cleaning devices [7]

Results and Discussion:

Pre-Survey: The capstone class had ninety-four (94) students that made up fifteen (15) teams. The pre-survey was conducted using a Google form and a response rate of 95%. Three cleaning devices were presented, and the students were asked the following questions:

- Identify three (3) aspects of these cleaning devices that differentiate them?

This is an open-ended question that requires the respondent to use natural language to describe the aspects they can identify that differentiates the cleaning devices. The descriptions were generally about the aspects at the system level rather than the subcomponents. The word "function" was used or inferred to describe an aspect that differentiates the cleaning devices by only eight respondents, "form" by three respondents and "concept" was not inferred to at all in the responses. Their descriptions were about the physical form they see, like "size", "noise", "modularity of design", "number of parts (complexity)" and "requires a filter". Some were categorized as "Other" like "cost", "ease of use" and "lifetime".

Proposal Template

Title: Unveiling Concepts: a mapping of function to form

- **Introduction**
  - Introduce your company (name, company size, and what value you provide)
  - Selections and reasons for two devices selected.
  - Assumptions: Apartment size, cleaning surfaces, surroundings (grass, concrete), others.
- **System Architecture**
  - Show Form view of architecture.
  - Show Function view of architecture.
- **Mapping of function to form**
  - Do this for the two chosen concepts.
  - Map the function to form of the devices to establish their connections.
- **Aspects of distinction**
  - List the aspects (>5) of these two devices that make them different.
- **Budget**
  - How much do you expect to spend on cleaning one apartment?
  - Consider labor, devices, materials, and time per apartment.
- **Benefits and Recommendations (ROI)**

Function and Form View of Architecture: Using concept maps, the student team created these views for the two devices picked based on the proposal requirements. The function view and form view collectively define the systems architecture. Figures 2-5 show the systems architecture generated by one of the student teams – Wolfpack Inflatable Lunar Design: Team WILD. They picked Trash Picker and iRobot Roomba as their two devices. Figure 2 shows three levels of abstraction for the form view architecture of the Trash Picker while Figure 4 shows four levels for the iRobot Roomba. The device (system) itself is the zero level [1] and the first level are the main components that other subcomponents can be categorized under. The function view architecture is similar with the highest level being the system and the first level being high level functions that other subfunctions can be categorized under. Due to the open-ended nature of the problem statement, teams have the prerogative to define their levels of abstraction which introduces unique definitions of the architecture for same system. It should be noted that these images in Figures 2-5 are not exhaustive in their description of the system's architecture.

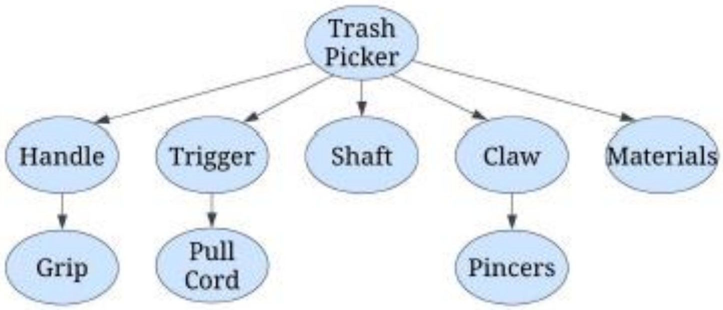

Figure 2: Trash Picker form view of architecture [8]

Figure 3 Trash Picker function view of architecture [8]

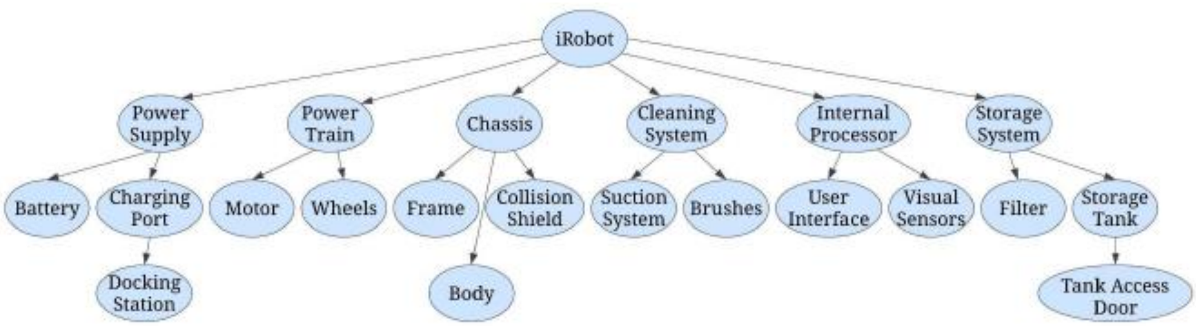

Figure 4: iRobot Roomba form view of architecture [8]

Figure 5: iRobot Roomba function view of architecture [8]

<u>Function to Form Mapping (First Level):</u> We unveil these concepts by mapping their functions to form. See sample of Team WILD's mapping in Figure 6 and Figure 7: This is a one-to-one mapping up to the first level of *function* to *form* view. There will be more complexity and one to multiple mapping at lower levels. Level zero is on top while the first level is connected and flows up to level zero.

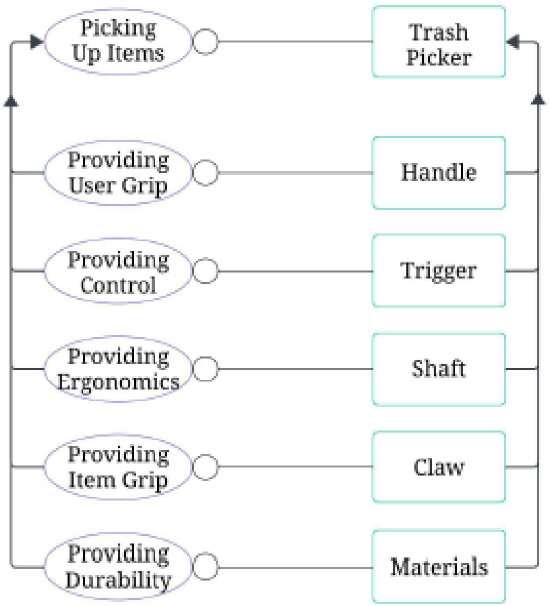

Figure 6: Trash Picker Function to Form Map (First Level) [8]

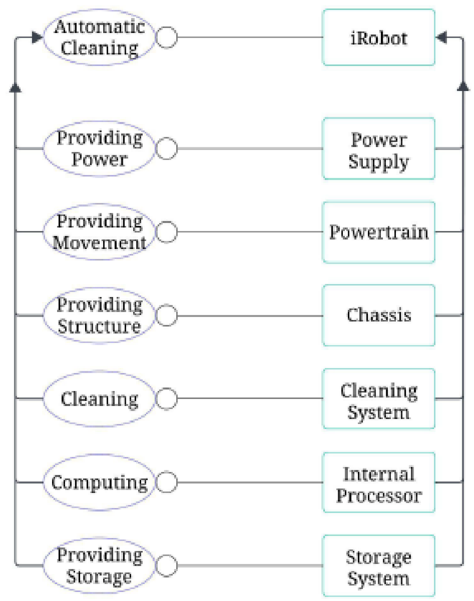

Figure 7: iRobot Roomba Function to Form Map (First Level) [8]

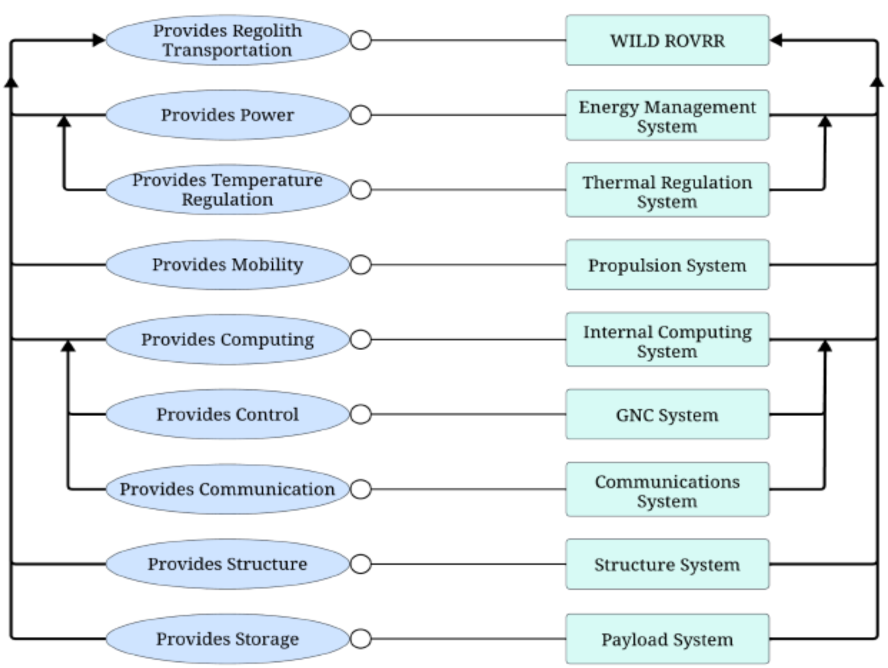

Figure 8: WILD ROVRR Function to Form Map (First Level) [9]

Capstone Project: An example of the implementation of the module to the capstone project is shown in Figure 8, Figure 9, and Figure 10. Team WILD worked on an inflatable lunar rover (WILD ROVRR) for their capstone project in the space section of the aerospace engineering capstone course. The function and form view of the architecture are up to level 5 (Figure 9 and Figure 10) and the one-on-one mapping of the first level function to form architecture is shown in Figure 8. This architecture definition is helpful not only in the design process but during the manufacturing and verification tests conducted in the spring semester.

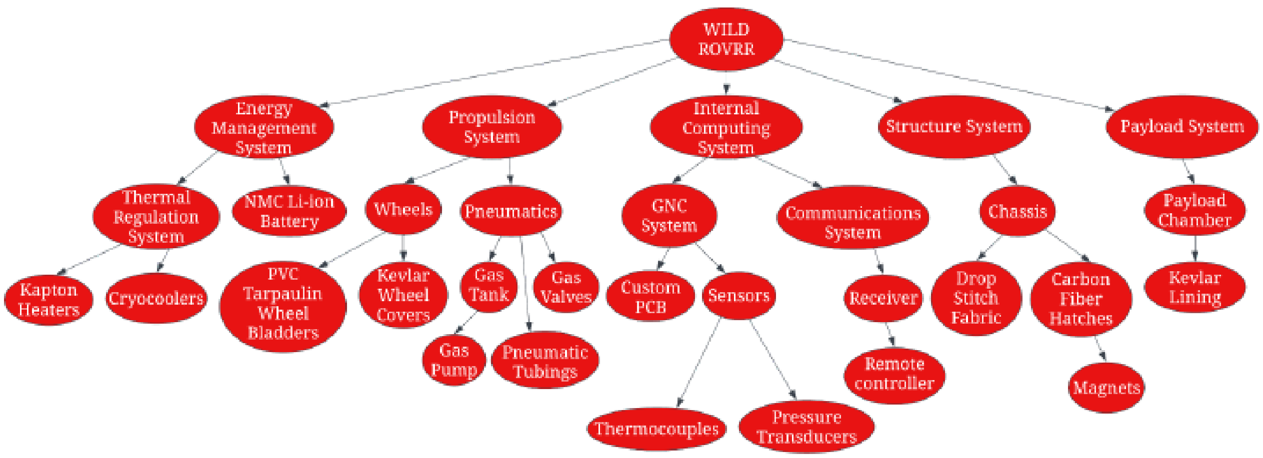

Figure 9: WILD ROVRR Form View of architecture [9]

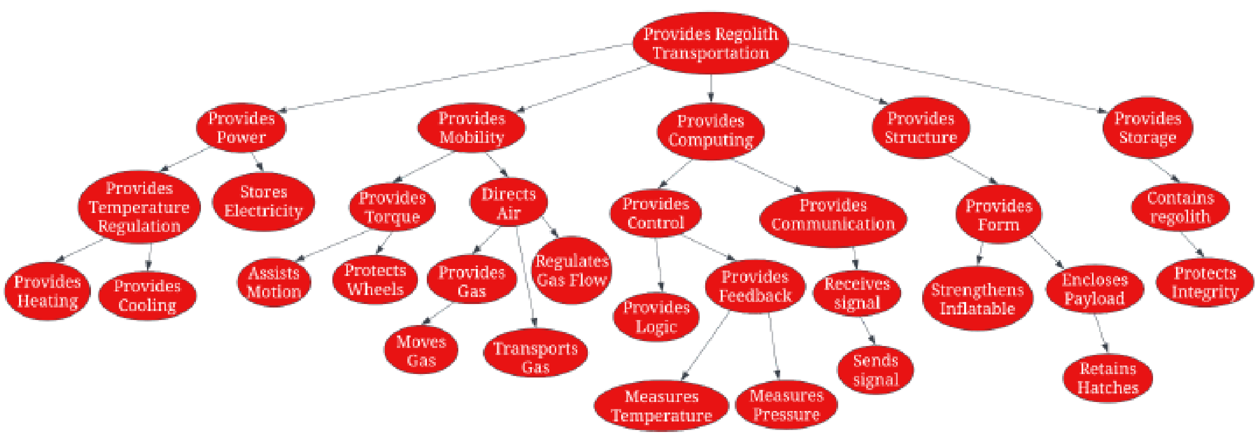

Figure 10: WILD ROVRR Function View of architecture [9]

Budget (ROI): Figure 11 shows the selections made by the teams for their two devices. Trash Picker and Dyson V8 combo is the most popular as it was selected by 60% of the teams. The open-ended nature of the problem statement is also evident in the budget proposed by the teams, it was very diverse. Overall, the budget was based on the number of workers per apartment, the number of apartments, and the cost of the selected devices. The average cost was lower for the Trash Picker and Dyson V8 and the highest was for iRobot Roomba and Dyson V8.

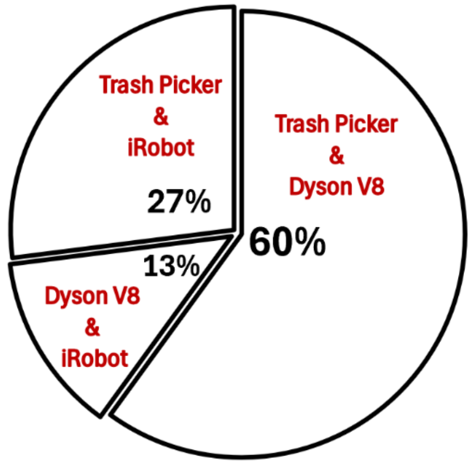

Figure 11: Teams' Cleaning Devices Selection

Post-Survey: The post project survey was also given through a Google form with a 78% response rate. The question of interest was:

- Currently, how would you rate your ability to differentiate two similar concepts?

About 72% of the respondents perceived that participation in the module improved or very improved their ability to differentiate similar concepts (Figure 12).

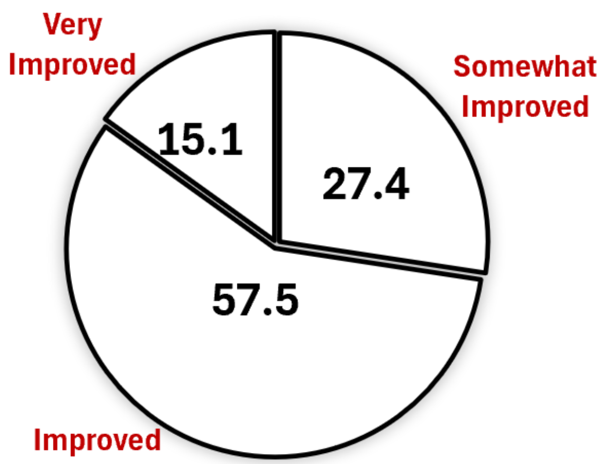

Figure 12: Rate your ability to differentiate similar concepts

Conclusion:

In this paper, undergraduate engineering students were introduced to creating system architectures. Using concept maps the functional view and form view of the architecture of similar cleaning devices were defined by students as part of the "Unveiling Concepts: a mapping of function to form" module. A first level mapping of the function view and form view architecture is shown, however, these mapping are more intricate at lower levels. Furthermore, the student teams practiced being part of the management of a company and made business decisions considering risk and profit. The feedback and knowledge gathered from the module was successfully implemented in their capstone project. Future work includes exploring describing similar concepts using natural language only, collecting similar data sets from future seniors' class, gathering more quantitative metrics beyond surveys, and collaborating with faculty from other departments to gauge their student's reception of this module.

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