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WordTrees: A Method for Design-by-Analogy

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Abstract

Analogies to nature and other designs are recognized for its power in seeking innovative solutions. Currently available design methods provide little guidance for systematically identifying potential analogous solutions for a design problem. The typical guidance is that analogies are useful for seeking solutions and to look for analogies to other products and nature. Unfortunately the guidance provided ends here. This paper describes a new method for designing with analogies, called the WordTree Method. The WordTree Method provides designers with a systematic approach for re-representing their design problems and seeking potential analogies. This method is based on prior experimental results focused on understanding the cognitive processes involved during analogical reasoning and concept generation. The paper describes the method in detail and then presents results showing its effectiveness. The WordTree Method begins with the functions and customer needs of the problem. It then prescribes an approach to re-represent these functions and customer needs so that alternative retrieval cues can be developed. These retrieval cues are effective for both encouraging the engineers to retrieve other solutions from their memory and from databases. Alterative representations are developed both intuitively and through the use of databases readily available on the web. The alternative linguistic representations are then organized into WordTrees facilitating the identification of potential analogies and analogous domains. Analogies, along with analogous domains, are then researched. Concept generation can then be based on the new representations and analogies. A case study illustrates and evaluates the method. This method is appropriate for both professional and student engineers. The WordTree Method fills a gap in design class providing a tool for design-by-analogy.

1. Introduction

Engineering innovation is a highly sought after skill and needs to be taught to the next generation of engineers. Numerous idea generation techniques are available to assist the engineer in this process. Over one hundred formal idea generation techniques have been developed in areas such as psychology, business and engineering[1-3]. Techniques range from the well-known Brainstorming method developed by Osborn (1957)[4], to engineering specific methods, such as the Theory of Inventive Problem Solving (TIPS)[5]. Unfortunately, little empirical data exists to guide the use of these methods for engineering design.

One identified approach for innovation is analogy. Numerous examples of innovation based on analogy can be found in current technical magazines. One recent example of a design for a space suit partially based on a giraffe's legs is illustrated in Figure 1. The tight skins on a giraffe's legs assist in regulating its blood pressure. An ultra lightweight and easily maneuverable space suit uses a similar approach by using mechanical pressure rather than air pressure to support human life on mars. Analogy is recognized for its effectiveness, but limited formal method guidance is provided. This paper presents a new design method, the WordTree Method, for designing with analogies. The following sections discuss the current approaches for design-by-analogy and then present a new method, the WordTree Method. A case study is used to illustrate the WordTree Method followed by conclusions and future work.

Figure 1: The ultra maneuverable and lightweight space suit, partially inspired by the tight skin of a giraffe's legs which helps to regulate blood pressure, relies on mechanical pressure rather than gas pressure to support human life in a thin atmospheric environment like mars[6].

2. Formal Design-by-Analogy Methods

Currently, few formal methods exist to support design-by-analogy. Most methods either provide little guidance on identifying the analogies or require databases to be created to support the process. These include Synectics[7], French's work on inspiration from nature[8,9], Biomimetic concept generation[10,11] and analogous design through the usage of the Function and Flow Basis[12]. Synectics is a group idea generation method that uses four types of analogies to solve problems: personal (be the problem), direct (functional or natural), symbolic and fantasy[7]. Synectics gives little guidance to designers about how to find successful analogies. Synectics illustrates the usefulness of analogies and categorizes them.

Other methods also base analogies on the natural world. French[8,9], highlights the powerful examples nature provides for design but provides almost no guidance in seeking the analogies. Biomimetic concept generation provides a systematic tool to index biological phenomena[10,13,14]. In Biomimetic concept generation the functional requirements of the problem and the keywords are first derived. The keywords are then referenced to an introductory college textbook and relevant entries can be found.

More approaches requiring the creation of databases are currently exist or are under development. Analogous concepts can be also identified by creating abstracted functional models of concepts and comparing the similarities between their functionality. Analogous and non-obvious products can be explored using the functional and flow basis[12]. This method requires a database of products in order to find analogous solutions based on the customer needs and functions. Other database supported computation tools for design-by-analogy have been recently developed. An example of such a tool is the work by Chakrabarti, *et al.*[15,16]. They created an automated tool to provide inspiration to designers as part of idea generation process. Based on the function or behavior of a device, analogies from nature or other devices are provided as potential sources of inspiration to the designer. Chakrabarti, *et al.*, have tested the automated tool and its analogy representations with student participants as part of university design courses.

Anecdotally, the implementation of analogy is prolific. Unfortunately it tends to be an unstructured process with *ad hoc* approaches based on a designer's experience. The lack of applicable design methods causes the teaching of this influential technique to be limited to little more than interesting examples with accompanying direction to simply "try to find analogies." Simply trying to "think of" analogies and analogous domains is difficult even for experienced engineers. Yet this ability is clearly important and a critical path to innovation.

3. WordTree Design-by-Analogy Method

The WordTree Design-by-Analogy Method systematically re-represents a design problem, assisting the designer in identifying analogies and analogous domains. Figure 2 overviews the method's steps. The method begins by identifying the problem descriptors which are the key functions and customer needs. These are then linguistically re-represented in a diagram know as a WordTree (Figure 3). Next potential analogies and analogous domains are identified. The potential analogies are researched and the analogous domains are used to find solutions in distant domains. New problem statements ranging from very domain specific in multiple domains to very general statements are written. Finally the analogies, patents, analogous domains and new problem statement are implemented in a group idea generation session. This session further refines the method's results into conceptual solutions and provides additional inspiration for the designers. The following sections detail the WordTree method and illustrate it with the case study design problem of "developing a device to fold wash cloths, hand towels and small bath towels." The guidance from experimental data for the creation of this method is also described in parallel to explaining the method in detail.

One of the main principles for enhancing analogical retrieval provided by prior experimental work is the design problems need to be represented in multiple ways ranging from very domain specific to general, thereby providing a variety of retrieval cues. The effective retrieval cues depend on how the information was initially stores. Multiple representations which fall in the continuum between general and domain-specific assist in locate useful analogies stored in memory. The WordTree method focuses on creating multiple linguistic representations of the design problem though numerous other representations are likely to be effective including functional models. TRIZ, with a different approach, also linguistically re-represents the design problem as the conflict between two generalized engineering parameters[5,17]. Other possible re-representations and other linguistic approaches are possible.

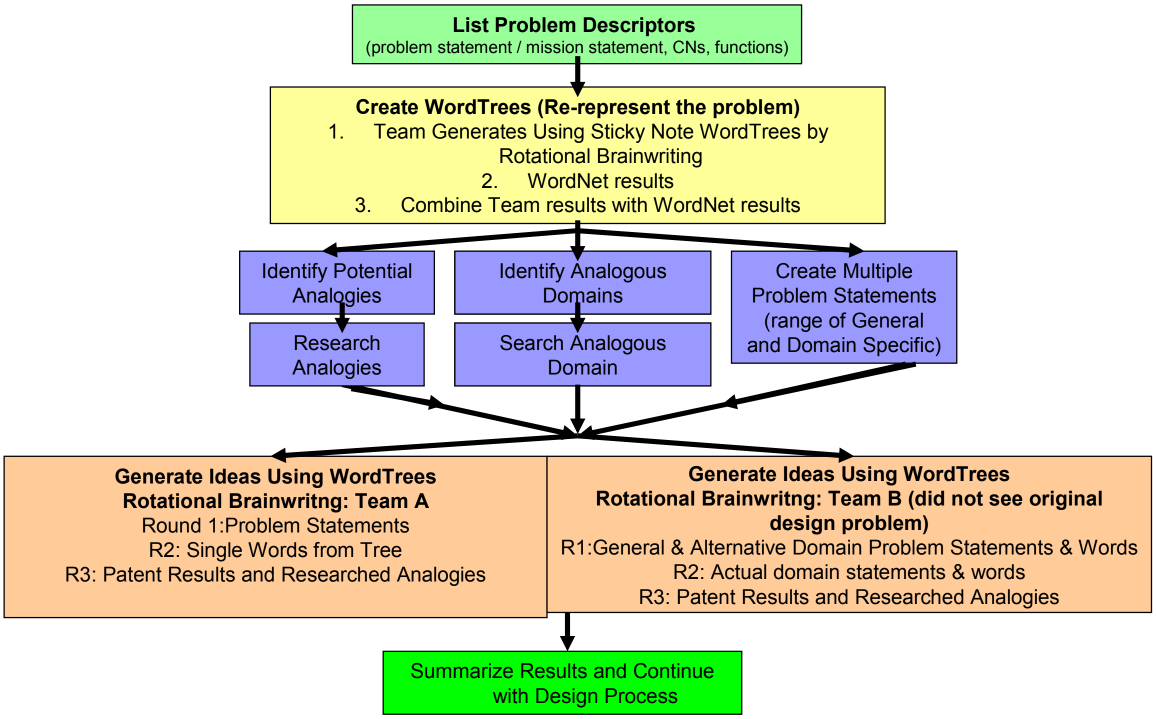

Figure 2: Overview of the WordTree Design-by-Analogy Method.

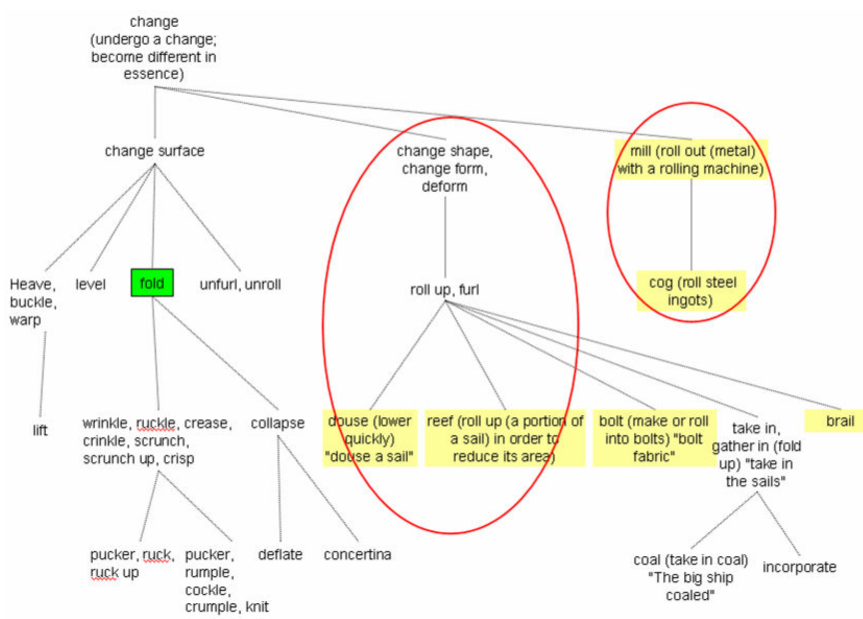

Figure 3: Partial WordTree for the function of "Fold". Analogous domains for folding include sailing (douse a sail, reef a sail) and machining processes (cog: roll steel ingots).

The WordTree method begins by defining the *Key Problem Descriptors*. The key problem descriptors are *single word action verbs* derived from the functions and customer needs for the design problem. The Key Problem Descriptors are defined from the customer needs, mission statement, function structure and black box model. Key Problem Descriptors fall into a few categories. One set describes the overall function of the device with a single word. The next category is the critical or difficult functions to solve, and the final category is the important customer needs transformed into single action verbs. Normally the customer needs are a combination of an adjective and a noun. To be used in the WordTree Method, customer needs must be converted to equivalent verbs. For example, the verb form of the customer need of "easy to repair" is "repair". Figures 4-6 illustrate the mission statement, partial functional model and black box model for a device to fold laundry[18]. The laundry folding device is intended for students with very limited fine motor skills. This design project was originally completed without the WordTree Method presented in this paper and then the design problem was revisited with the WordTree Method at a later time. The first author of this paper was both a member of the original graduate design team and the individual who created the additional solutions by implementing the WordTree Design-by-Analogy Method. Some of the customer needs for this device are to smooth the laundry, to be rugged, to be easy to use and to be easily portable. Some of the key problem descriptor for this device are fold, prepare [laundry for storage], store and smooth.

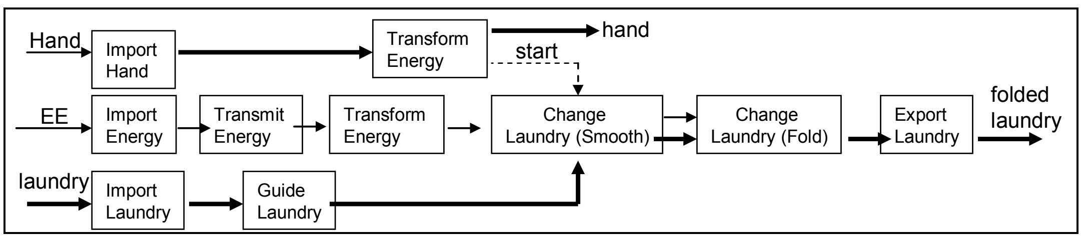

Figure 4: Partial functional model for the laundry folding device.

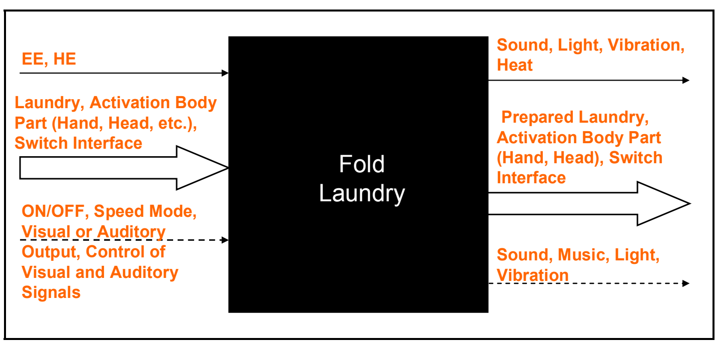

Figure 5: Black box model for the laundry folding device.

Figure 6: Partial mission statement for the laundry folding device.

The next step is to re-represent the key problem descriptors using WordTrees. This step facilitates the identification of analogies and analogous domains. First, the design teams use rotational brainstorming to create sticky note WordTrees (Figure 7). Rotational brainstorming is very similar to 6-3-5 except that each team member receives three separate sheets of paper and develops one WordTree on each sheet (Figure 8). The set of key problem descriptors should be divided evenly between team members. Each person begins with a set of three different problem descriptors and spends ten minutes creating the WordTrees. The WordTrees are then rotated clockwise around the table and the next person spends five minutes adding to the WordTrees. The sticky notes allow for additional layers to be added and words to be rearranged. Verbs within the English language tend to be hierarchically structured with more general verbs and more specific verbs. More specific verbs for a given word are known as troponyms, and more general instances are known as hypernyms. For example, some of the troponyms for the word "fold" are "wrinkle, tuck, ruffle, pleat and crease." More general verbs are placed above and more specific are placed at lower levels (Figure 7). A rotational brainwriting method was chosen since a prior group idea generation experiment showed this type of approach results in a greater number of ideas[19].

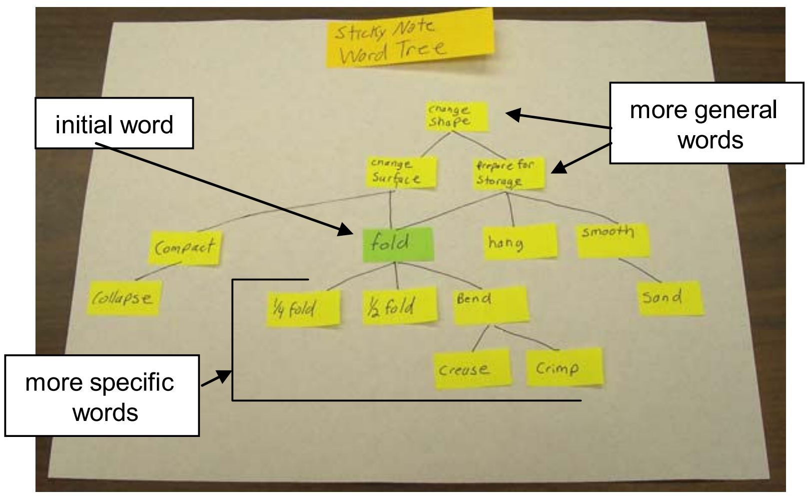

Figure 7: Sticky Note WordTree.

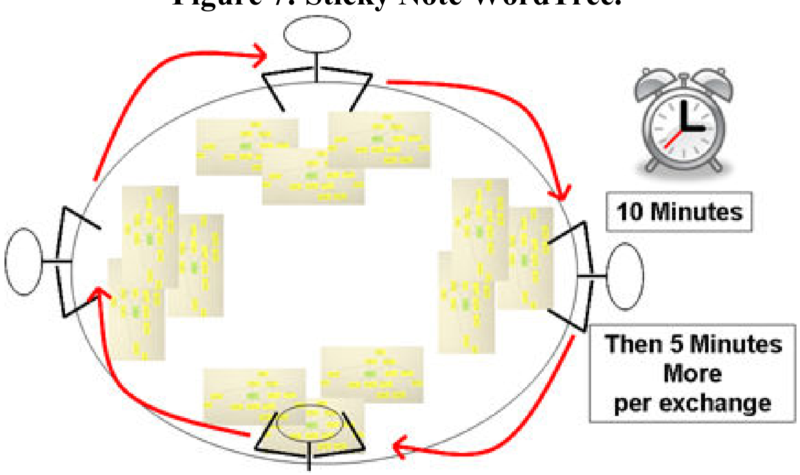

Figure 8: Rotational Brainwriting

After the team generates the sticky note WordTrees using rotational brainwriting, WordNet (http://wordnet.princeton.edu/perl/webwn) is used to find additional results. WordNet was originally developed as a database to support natural language processing and computational linguistics[20]. It is similar to a thesaurus since it gives synonyms for words, but it is far more sophisticated. WordNet structures words in the same manner in which they are used within the

English language with some having very broad general meaning and others being much more domain specific. WordNet often gives brief usages and definitions for words, for example "douse a sail" (lower quickly). If the words are unusual or unfamiliar, it is useful to include these in the WordTree since they are frequently very domain specific verbs (functions) in distant but analogous domains.

The WordNet and sticky note WordTrees are then combined. Next the team reviews the WordTrees looking for potential analogies and analogous domains. Analogies can occur anywhere in the WordTree and many of the words will trigger new ideas. Analogies frequently occur as words that are both nouns and verbs. These are often unusual words whose meaning as verbs is unfamiliar, for example "brail, to hail up sails" (Figure 3). Many of the analogies occur at the ends of the branches or on the "leaves of the tree." Analogous domains frequently occur on parallel branches which contain multiple potential analogies. For example in Figure 3, "douse a sail" and "reef a sail" indicate that sailing is an analogous domain. The analogous domains and general terms are categorizes of possible solutions. The WordTree structure highlight the general terms.

After potential analogies and analogous domain have been identified, the analogies are researched along with searching for solutions in analogous domains. Google Image© is an effective and efficient tool for finding information about a potential analogy. Patents in analogous domains should be searched for also. The analogies and patents will usually be solutions are not the common solutions to the problem and not the solutions people typically think of. The initial solutions presented to a design team and the first solutions they think of have the potential to cause them to fixate leaving them unable to obtain additional concepts. Searching for analogies and patents in analogous domains can be completed prior to the teams attempting idea generation because it has been shown that uncommon solution, which is the type of solutions analogies should provide, tend to increase the number of ideas generated and not cause fixation[21,22].

Finally the teams use the results to generate more ideas. Two separate teams of designers are recommended to base their idea generation sessions on the results from the WordTree Method. The first team is the original team who generated the WordTree and knows the details of the design problem. The second team is unfamiliar with the problem and is given the general and alternative domain problem statements along with general and alternative domain words. When using analogies, individuals tend to focus too much on the surface and unimportant features of the problem rather than the causal structure[23,24]. It is believed, the second team will be less likely to focus on unimportant features of the original design problem since they will be shown a series or analogous problems which will tend to focus them on the deep structure and not the surface information. After team idea generation, the results are summarized and the team continues with the design process. The WordTree Method is further illustrated and evaluated below using a case study.

4. Abbreviate WordTree Design-by-Analogy Method (WordTree Lite)

Acknowledging limited class time for teaching the various design methods and the desire for a less complex method, a reduce version of the original WordTree Method (WordTree Lite) was derived (Figure 9). This simplified version maintains the steps which maximize outcomes for minimal time but some of the potential for innovation is lost. The WordTree Lite Method begins with listing the single verb problem descriptors. From the problem descriptors, WordTrees are created based on the team's knowledge and also employing WordNet. The next step is the identification of analogies and analogous domain which are then researched. Finally, the WordTrees, analogies and analogous domains are used as starting points for idea generation. This version has not been empirically evaluated.

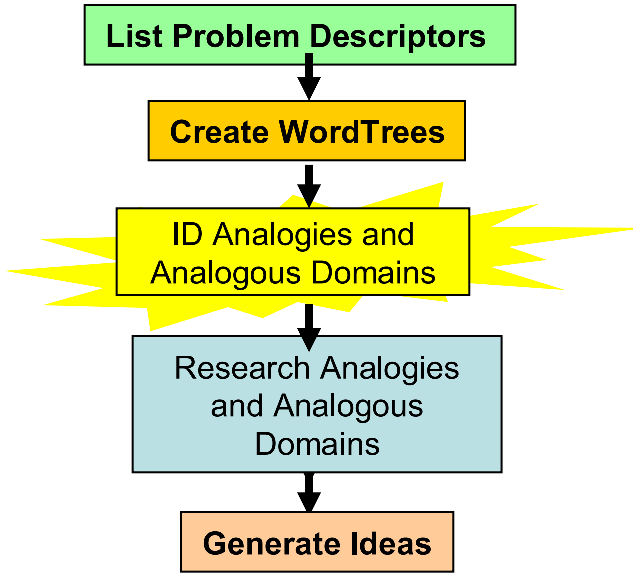

Figure 9: Abbreviated WordTree Design-by-Analogy Method

5. Evaluation of the WordTree Method

The WordTree Method has been evaluated using a case study, controlled experiment and on team redesign projects[25,26]. The controlled experiment showed participants who used the WordTree Method were able to identify more analogies and searched electronic databases in analogous domains. The evaluation on team redesign projects produced unexpected analogies. For example, a team redesigning an automatic cat litter box identified the analogies of panning for gold, a dump tuck tailgate and dredging as analogies for cleaning. The case study described below further evaluates and illustrates the WordTree Method. The case study compares the solution developed by the original design team to the solutions found implementing the WordTree Method.

The WordTree Design-by-Analogy Method was applied to the design problem of "creating a laundry folding device for students with serve physical and mental disabilities." A local Austin school does their laundry at the school and wanted to involve their students in the process. The goal was to be able to fold wash cloths, hand towels and small bath towels. Folding an item requires fine motor skills that the students do not possess. The author was a member of the six-person design team that created a solution to this problem[18]. This project was completed as part of a graduate product development class, and the final solution won a design competition award from RESNA (Rehabilitation Engineering & Assistive Technology Society of North America).

The initial team created an effective solution and spent considerable time on the project. This case study illustrates an innovative solution found using the WordTree Method that was not identified by the original team. The team, who found a solution to this problem initially, developed over 40 concepts for the function of folding and actively sought analogies. At the time when the first solution was being sought, it was known that the representation of the design problem influenced the analogies and solutions developed. One of the phrasing used by the team was a "device to prepare laundry for storage". The school ultimately needed to be able to store the laundry items. They had no preferences for how the items were folded as long as they were capable of being stored. This lead the design team to consider a number of different approaches to folding, see examples in Figure 10. The final solution used a quarter fold and is shown in Figure 11.

Figure 10: Different approaches to folding.

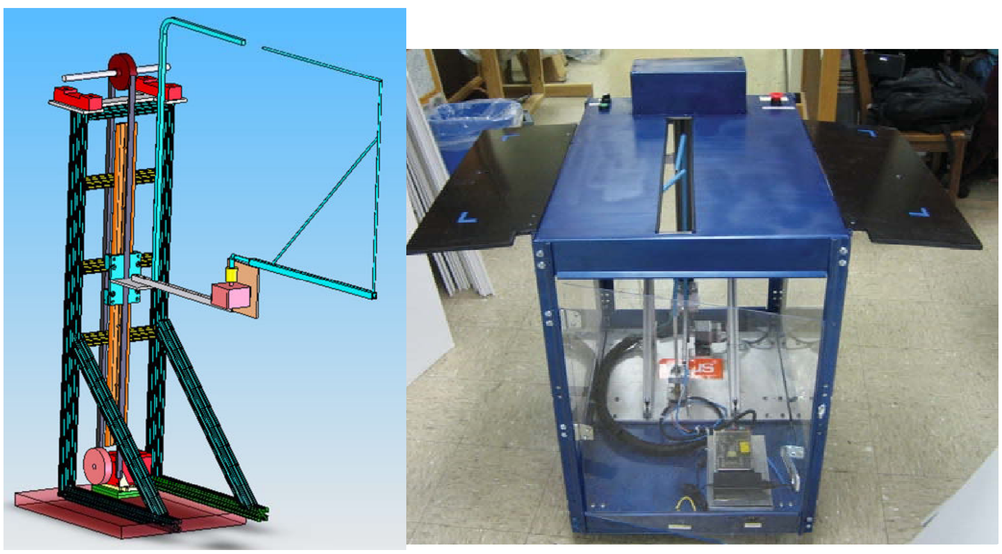

Figure 11: Original team's award winning solution to the laundry folding problem. The image on the right shows the final solution and the left image is the internal mechanism. The towel or wash cloth is spread out on the top surface of the device. A bar rises in the center causing the item to fold in half. Half of the bar rotates around causing another half fold in the towel.

Application of the WordTree Method to this problem results in the WordTree shown in Figure 3 and a number of analogies and analogous domains not considered by the original design team (Table 1). Unusual words or unusual senses of words shown by WordNet are frequently very domain specific terms. Stickle is one example from the fold WordTree. A stickle is a device used to smooth the inner and outer surface of a bell when it is being built (Figure 12). An interesting analogous domain presented by the WordTree is the domain of sailing, with specific analogies of dousing a sail and reefing a sail. A quick search using Google image provides the two analogous solutions for dousing a sail shown in Figure 13.

The original design team did not focus on the fact that the laundry items needed to be prepared for storage but not necessarily folded. They did not evaluate various approaches to storage. Later, it was realized an effective solution for the problem of "storing laundry" was the shopping bag storage tube (Figure 14). Examples of storage devices for another design project had been collected and the shopping bag storage tube was a rather unique example that had been identified. The shopping bag storage tube is a very effective solution to the laundry storage problem. The need for an easy and effective method to store washcloths also plagues the many homes. The wash clothes generally exist in a unstable pile on a shelf. A solution was developed based on the analogy (Figure 14). The wash cloth storage tube shown in Figure 14 could be scaled up to hold larger items such as small bath towels.

Table 1: Analogies and analogous domains for the laundry folder.

Analogies & Analogous Domains Identified using the WordTree Method	Original Team's Analogies & Analogous Domains
cogging	sheet metal design (metal folding)
douse (douse a sail)	napkin folding
raking	origami
sandblasting	industrial laundry machines
stickle	

Figure 12: A stickle is used in the process of creating a bell. A stickle smoothes the inner and outer surface of a bell[27].

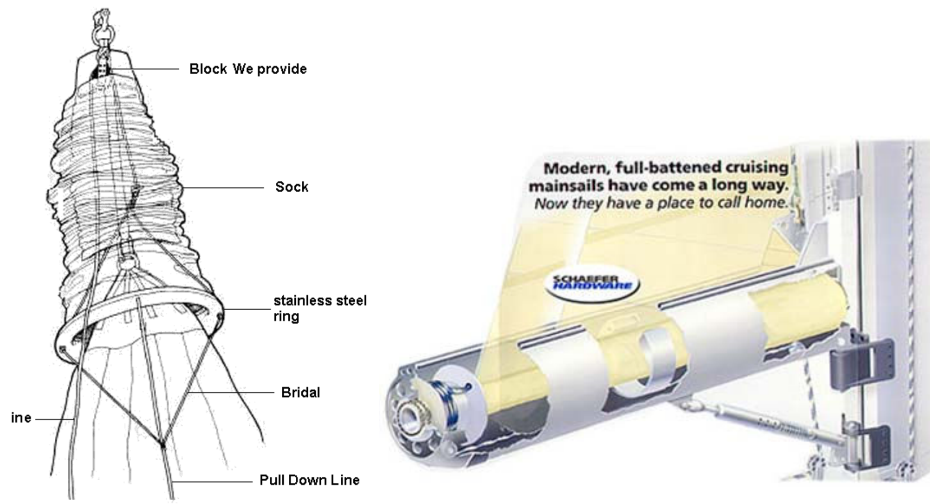

Figure 13: Two solutions for dousing a sail[28].

Figure 14: A solution for the laundry storage problem. Two versions of the wash cloth storage device are shown. One has a circular cross-section and the other a square.

6. Conclusions and Future Work

Designing based on analogies to nature and other distant domains is a powerful tool for innovation. The WordTree Design-by-Analogy Method provides designers with a systematic approach for identifying analogies and analogous domains. Most available design-by-analogy methods either provide little guidance on how to identify analogies or require extensive databases to be created. The WordTree Method linguistically re-represents the design problems such that other analogies are retrieved from the designer's memory and from readily available databases (patent, Google©, etc.). The method was illustrated and evaluated with a case study. The case study was to designing a device to fold laundry for students with serve disabilities. The WordTree Method outcomes were compared to the designs created by a team of graduate students who built a device for this problem. The application of WordTree Method produced unexpected analogies including to the domain of sailing and additional analogies that resulted in a efficient, much simpler solution. The WordTree Method produced a significant number of analogies not evaluated by the original design team.

The WordTree Method is one effective approach for enhancing design-by-analogy. There are many other representations including linguistics ones that need to be explored. Functional models are one potential representation that justifies investigation. Much more evaluation of the WordTree Method needs to be completed partially with experience very effective designers. Further refinements will be made to the method and additional approaches for re-representing the design problems will be sought.

7. Acknowledgements

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