Proceedings of the ASME 2009 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2009
August 30 – September 2, 2009, San Diego, California, USA

DETC2009-86403

INCREASING INNOVATION IN MULTI-FUNCTION SYSTEMS: EVALUATION AND EXPERIMENTATION OF TWO IDEATION METHODS FOR DESIGN

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ABSTRACT

Many methods for design have been explored as the engineering community seeks to increase the efficiency, quality, and novelty of innovation. Some design methodologies are well equipped for use with any problem; others are best suited for specific domains or applications. Recent studies have developed two new independent methods for design. The first, WordTree Design-by-Analogy, uses a graphical structure of related words to help identify far-field analogies that have relevance to a given problem. The second method, Transformation Design, describes the mechanics and characteristics that drive the transformation of a reconfigurable mechanical system from one state to another. This paper presents a study of the effectiveness of these two methods in generating concepts for a specific problem statement requiring multiple sets of capabilities, i.e., tagging and tracking vehicles for military or civilian law enforcement purposes. Forty-one mechanical engineering students were assembled into groups and given specific guidelines to follow in generating concepts. A typical full-factorial experiment and ANOVA analysis was used to compare the effect of using the two design methods, as well as the interaction between them. Results from the design teams were evaluated quantitatively by the number concepts generated. Analysis of these results revealed that using the Transformation Design method increased the number of concepts developed by 25-30%. Use of the WordTree method was not judged to increase the number of concepts generated; however, the novelty and diversity of solutions were distinct for this method compared to Transformation Design or the control group.

KEYWORDS

Design Principles; Concept Generation; Transformation Design; Design by Analogy; WordNet; WordTrees; Design of Experiments; Reconfigurable Products

1. INTRODUCTION

In design, concept generation is an area that has undergone continuous development. Numerous portrayals of the design process have been described [1-4], with concept generation receiving considerable attention as a key part of any approach. Over time, concept generation has developed from vague ideas of brainstorming to fleshed-out formal methods such as morphological matrices [3], 6-3-5/C-Sketch [3], and TIPS/TRIZ [5].

For several years, we have pursued research on several different fronts related to concept generation and the design process in general. The first area of research examines Design-by-Analogy techniques and formulates a method for concept generation using a vocabulary of natural language verb terms. The second area deals specifically with systems that can transform between different configurations in order to perform multiple functions. A large number of analogous "transformers" are examined, and information gleaned from them can be used in the design of new systems. Both of these areas are described in more detail.

2. BACKGROUND

2.1 WORDTREE DESIGN-BY-ANALOGY

Designers frequently use analogies in the process of developing new ideas. In fact, a large portion of innovation is derived directly from analogy. However, much of this process is *ad hoc* or serendipitous. The challenge and purpose of a formal Design-by-Analogy method is to lead the designer to useful, but non-obvious analogies. This guiding process usually involves re-representing the problem from a different point of view. For example, some methods present the problem in terms of similar biological systems [6,7], while others describe its key functions and flows [8]. Synectics may challenge the designer "to be" the problem or look at it symbolically [9].

WordTree Design-by-Analogy is a recent development in design methodology [10-12]. In this method, key words such as functions or customer needs are used to seed a linguistic representation of the problem. This representation is developed both through an extended brainstorming approach and with the help of WordNet, a tool developed at Princeton University [13,14]. The WordNet database functions by returning a list of words related to a user-supplied seed word. WordNet works similarly to a thesaurus, but gives much more functionality and structure. For each input word, WordNet returns a set of *troponyms* (sub-types or more specific synonyms), *hypernyms* (overarching or more general synonyms), and *sister terms* (other words stemming from a common hypernym). An example WordNet entry for the verb "track" is shown in Fig. 1. The information retrieved from WordNet can easily be assembled into a graphical representation called a WordTree, with hypernyms and troponyms branching off of the seed term like roots and branches. An example WordTree based off of the same key word "track" is shown in Fig. 2.

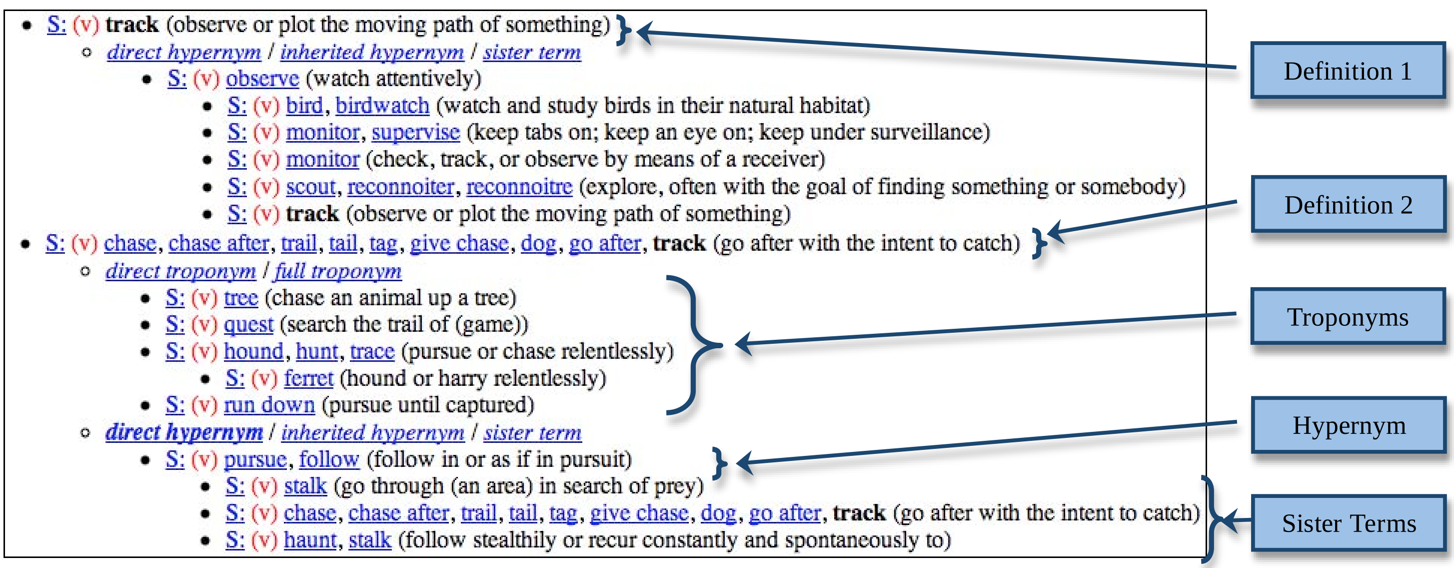

Figure 1: Sample from WordNet's online interface for seed word "track" [13].

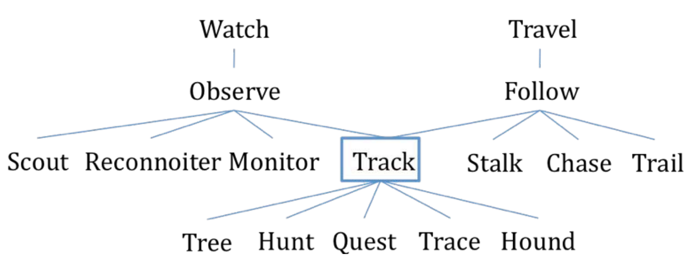

Figure 2: WordTree generated from seed word "track."

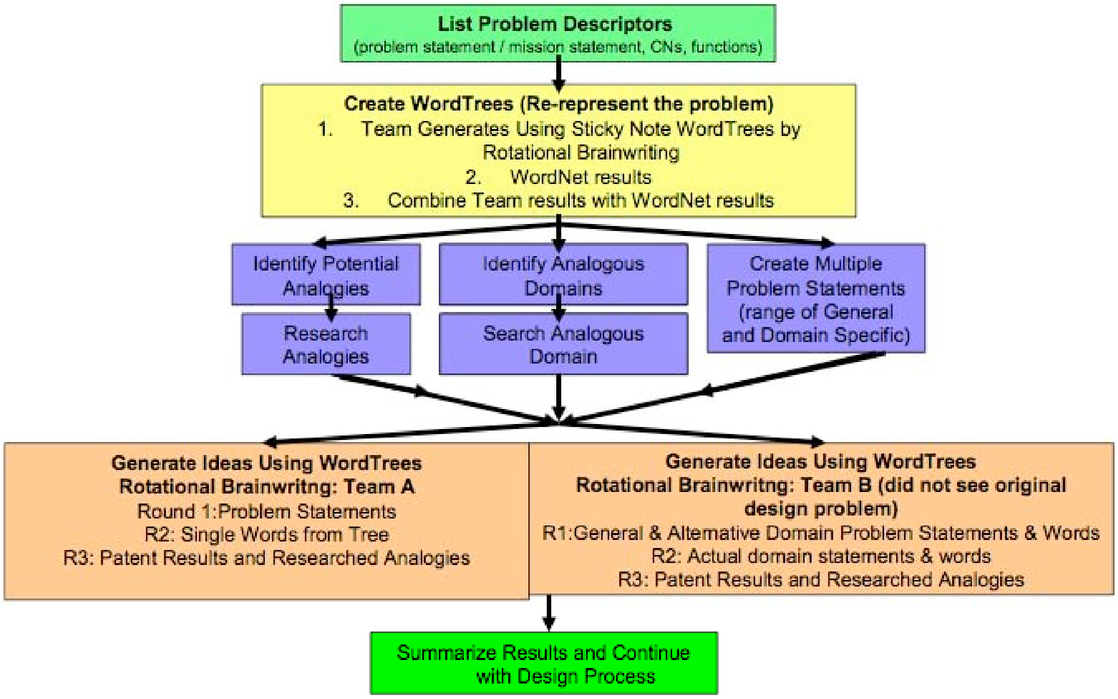

Figure 3: Complete WordTree Design-by-Analogy Methodology [12].

Figure 4: Laundry storage resulting from WordTrees [12].

The information in a WordTree can be used to branch out from known functions and customer needs into far-field applications. For example, a sample design problem may require the function "track," as in Fig. 1. The associated WordTree terms may lead the designer to explore current applications of "hunt" (perhaps hunting animals or *using* animals to hunt). It would also lead to ways to "scout" or "reconnoiter" (methods and skills used by soldiers, boy scouts, or outdoorsmen), and tools to "monitor" or "trace" (perhaps through electronics). These trains of thought would reveal specific, real-world examples that might have otherwise gone unnoticed. By exploring multiple WordTrees, the designer is led towards a wide swath of related concepts and applications far-removed from the initial problem, i.e., design-by-analogy.

Figure 3 shows a more extensive and complete form of the WordTree Design-by-Analogy method. Notice that the method provides systematic guidance to a designer or design team through the exploration of analogous verb terms and analogous domains. An exemplar design result using this method is also shown (Fig. 4), providing design concepts for the problem of storing towels and washcloths for distribution in hotels. The term "douse," as in dousing a sail for a boat, motivated this design concept through the re-representation of "change," "roll up," and "gather in."

2.2 TRANSFORMATION DESIGN

Transformation, in a mechanical sense, can be defined as changing state (or configuration) in order to provide new functionality [15,16,17]. Transforming, or reconfigurable systems occur frequently in design, ranging from vehicles to furniture to toys and tools. A basic example of a transformer is shown in Fig. 5. Here, a chair transforms into a stepstool by folding half of the structure about a hinge.

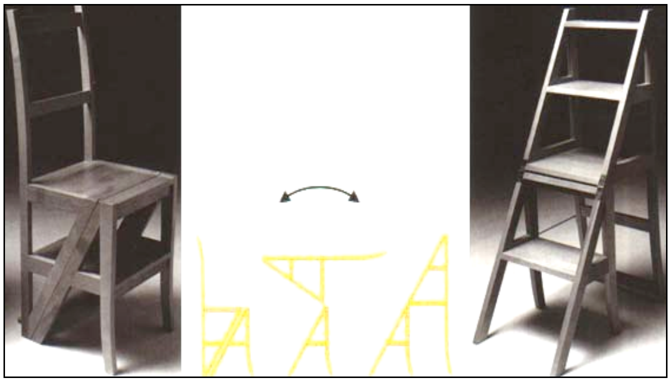

Figure 5: Transforming chair/stepstool [18].

Table 1: Transformation principles and facilitators [16].

Principles					
Expand/Collapse  [19]		Expose/Cover  [18]		Fuse/Divide  [20]	
Facilitators					
Conform with Structural Interface	Flip	Interchange Working Organ	Roll/Wrap/Coil	Share Power Transmission	Utilize Composites
Enclose	Furcate	Modularize	Share Core Structure	Shell	Utilize Generic Connections
Fan	Inflate	Nest	Share Functions	Telescope	

Transformers can be complex and difficult to execute, yet their design is mostly *ad hoc*, relying on serendipitous analogies and previous experience to create smooth, functional transformation processes. Over the past three years, extensive research has been conducted to better understand how transformation works, how it is currently designed, and how a better, more formalized design process could be applied. Over the course of this research, a theory of transformation design has been developed which identifies a set of principles and facilitators relevant to the process of transformation (Table 1).

Analysis of over 200 assorted transforming systems indicates that these three principles and 20 facilitators form a common basis that can be used to describe most, if not all, mechanical transformers [16]. Transformation principles describe the general form of the process, and the facilitators are specific characteristics or actions that enable the transformation. At their most basic level, transformation principles and facilitators can be used as seeds for ideation, such as at the center of a mind-map. Discretizing a mind-map into the three principles can be useful in studying possible solutions from multiple angles.

Additional research shows that these principles and facilitators occur in consistent, predictable patterns [16,17]. These trends and interrelationships can be utilized to assemble transformation processes that operate smoothly and robustly, while still having the freedom to pursue unconventional match-ups among the principles and facilitators.

2.3 OTHER CONCEPT GENERATION METHODS

The study in this paper evaluates the usefulness of the WordTree Design-by-Analogy method and the Transformation Design method when used in conjunction with two more common ideation methods: mind-maps and 6-3-5 (C-Sketch).

2.3.1 MIND-MAPS

Mind-mapping [3] is a frequently used method for organizing and facilitating the generation of ideas through the approach of categorization. One or more key words or design problems are placed in the center of a page, and then additional concepts are added around the periphery, with lines connecting related concepts. By identifying and recognizing categories of ideas as the process unfolds, a greater quantity of ideas may be developed. This categorization process may be viewed as identification of "meta-analogies," fostering the generation of concepts through piggybacking and leap-frogging ideas as concepts are generated.

The end result of mind-mapping is a web, or network, with ideas moving from general to specific as the web is traced outward. The example mind-map shown in Fig. 6 uses the three transformation principles to study the possibilities for transforming a motorcycle into a four-wheeled ATV. Figure 7 shows an example instantiation of a concept for a motorcycle/ATV transformer developed from this approach.

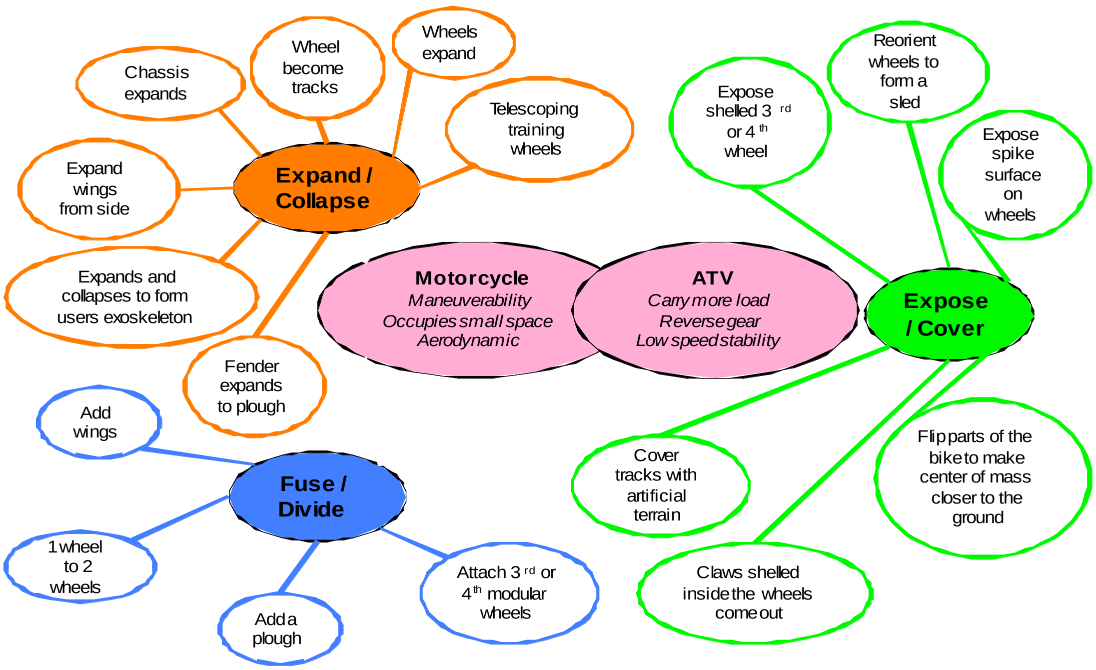

Figure 6: Mind-map for transforming motorcycle into ATV [15].

Figure 7: Concept for transforming motorcycle/ATV [15].

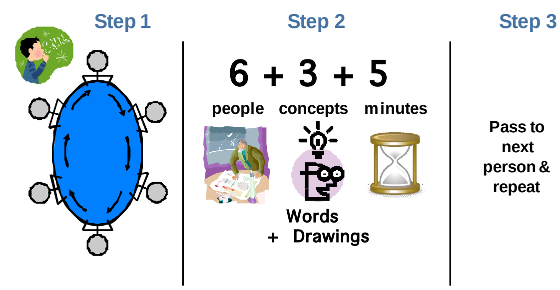

Figure 8: 6-3-5 concept generation technique.

2.3.2 6-3-5/C-SKETCH

Another concept generation technique that has become popular is known as rotational brain-writing, C-Sketch, or 6-3-5 [3]. This method provides structure that enables team members to build off of each other's ideas. In essence, each member of a small team (about six people) draws three concepts that pertain to the design problem on a large sheet of butcher paper. After spending 5-15 minutes to flesh out their ideas, focusing on a certain number of functions, members pass their papers to the adjacent person. In this second stage, members add additional ideas or clarification to the drawings they receive. This stage lasts 5-10 minutes, after which the papers are rotated again. The process continues until each member has contributed to all of the papers. No verbal communication is allowed during the process, which allows members to innovate on the concepts as they appear on the page without the previous member transferring fixation or limiting how the drawing could be interpreted. An outline of the process is shown in Fig. 8.

2.4 USING FACTORIAL EXPERIMENTS

For completeness, we briefly review the basic foundations of factorial experiments [21]. A factorial experiment examines the effects of several different control factors at once. For two-level factorial experiments, each factor is set to two discrete levels (labeled + and -). The factors are varied in a prescribed manner, and a specific output is observed (or measured). For a full factorial experiment with m factors being measured at n levels, a total of n^m experiments are needed. Thus, a two-level experiment with two factors requires $2^2 = 4$ trials. Such an experiment could vary the levels of the factors as shown in Table 2.

Table 2: Sample 2^2 factorial experiment

Trial	Factor 1	Factor 2	Measured Output
1	-	-	p_1
2	+	-	p_2
3	-	+	p_3
4	+	+	p_4

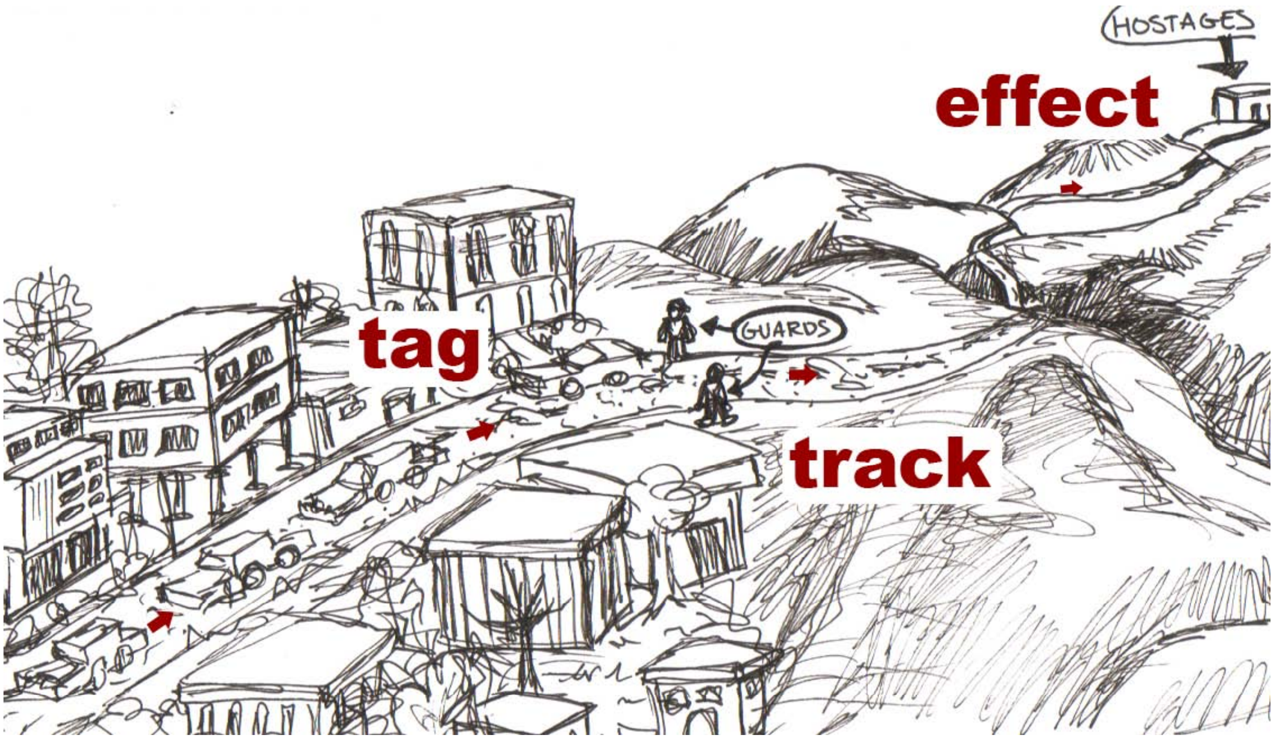

Figure 9: Example scenario involving "tag, track, and effect" design problem.

The order in which the four trials are actually conducted should generally be randomized to minimize bias intrinsic in the order or other hidden variables. Conducting multiple instances of each trial, i.e., replicate trials, may also be useful to determine error, variance, and other information. After the experiment has been run, tools such as basic t-tests or ANOVA can be used to determine the effects, interactions, and significance of the factors with respect to experimental or random variation.

3. RESEARCH EXPERIMENT

A controlled experiment was designed with the aim of comparing the effect of using WordTrees and/or Transformation Design methods in the concept generation process. To focus on these two methods, other parts of the process were controlled as much as possible.

Design teams of three to six members generated concepts for a design problem; specifically to create a system that can tag and track a vehicle for military purposes, then perform an effect on the target when desired. An illustration of this scenario is shown in Fig. 9. Team members followed a script outlining the methods to be used and recorded all concepts for subsequent analysis.

3.1 SOURCE OF PARTICIPANTS

Forty-one participants were assembled into nine teams of three to six people for this study. All participants were volunteer undergraduate students at The University of Texas at Austin, where the motivation to participate in the study was extra credit in the senior-level engineering design class from which they were recruited. Approximately 75% of them were male, 25% were female. The volunteers' ages ranged from 21-27. In their capstone design class, they had previously learned common concept generation techniques such as mind-mapping and 6-3-5. The volunteers had experience typical to undergraduate engineering students, with some receiving additional training through internships, co-ops, previous jobs, and research opportunities. Because of their general engineering experience and common level of understanding of design as taught in the class, it was assumed that they would have comparable backgrounds coming into the test study.

3.2 FACTORIAL ORGANIZATION

The study was formulated as a simple 2^2 factorial experiment with four different conditions. The two controlled variables were the use of the WordTree Design-by-Analogy method and the use of the Transformation Design method.

In the first trial (- -), neither WordTrees nor transformation heuristics were used. This condition corresponds to a control. After a brief introduction, a design problem was given, after which the randomly assigned participants spent 25 minutes brainstorming with a mind-map. This stage was followed by 30 minutes of 6-3-5. In the final stage of the process (20 minutes), each participant searched the Internet (through patents, images, videos, and design websites) for additional information on analogies uncovered during the earlier stages. A research assistant introduced each step of the process, using a script for consistency in language and timing. The complete outline for this "control" variation is given in the next section.

In the second trial (+ -), a WordTree Design-by-Analogy method was inserted before the mind-mapping. This method is also outlined in the next section. The third trial (- +) inserted an introduction to transformation principles and facilitators, with information on how to use them. The fourth trial (+ +) used both WordTrees and transformation heuristics.

3.3 OUTLINE OF EXPERIMENT

Each instance of the experiment followed the outline shown below. The control (- -) trial follows the steps as listed, excluding 3A and 3B (shown in italics). The other variations inserted steps 3A (for WordTrees) and/or 3B (for Transformation Design) as appropriate. The assistant leading the session was given a script to read to the participants, and each stage was given a set time period, with the total session lasting two hours. Supporting documents given to the groups are located in the appendices.

1. **Introduction to "transformers" (3 minutes) –** The students are given a definition and brief explanation of transformation, and they are invited to give examples of transformers to demonstrate understanding.
2. **Introduction to analogies (2 minutes)** – The students are given a brief explanation of how analogies are often used cognitively in design and how actively searching for analogies can lead to benefits in the design process. They are invited to give examples of products easily linked to specific analogies.
3. **Design statement (10 minutes)** – A specific design statement is given to the group (Appendix A). In this case, the participants were given a problem to create a system for the US Air Force that builds upon unmanned air vehicle (UAV) technology to "tag," "track," and cause an "effect" of some sort on a target vehicle (Fig. 9). Novelty and the use of transformation and analogies are specifically encouraged.

3A. (For Transformation Design)

Introduction to principles and facilitators (15 minutes) – Explain each principle and facilitator, and pass out papers with definitions and examples (Appendix B). Explain that research has shown common groupings of principles and facilitators, and pass out papers with tables of groupings.

3B. (For WordTree Design-by-Analogy)

Introduction to WordTrees (15 minutes) – Explain that the purpose of Design-by-Analogy is to re-represent the problem, and one way to do this is through relationships in terminology. Demonstrate a sample WordTree and instruct the members to create their own WordTrees (Each person chooses a seed word, preferably "tag," "track," "effect," transformation principles, or other appropriate descriptors). Have the team members switch WordTrees with each other several times and add onto them. Pass out WordTrees compiled from WordNet on the same key words (Appendix C).

4. **Brainstorm with mind-map (15-25 minutes depending on the trial) –** The participants are instructed to generate concepts for the design problem and record them on a mind-map. Each member uses a different color on a dry-erase board so that individual contributions can be recorded. The participants are free to organize their mind-map however they want. If WordTrees or transformation heuristics are used, they are suggested as possible center nodes for the mind-map. The papers passed out on WordTrees/transformation heuristics may be used as references during the process. The members are also asked to make note of any useful analogies they discover and how they were identified.
5. **6-3-5 brain-writing (30 minutes)** – One round of conventional 6-3-5 is followed. Each member draws three concepts on paper, based on the brainstorming session. After 10 minutes to develop their own ideas, members rotate papers and add to their teammates ideas for 5 minutes. Each member uses a different color ink to differentiate contributions. Rotations continue every 5 minutes until the papers have rotated completely around the table, allowing each member to enhance the original concepts or add new ones.
6. **External analogy search (20 minutes) –** The participants are asked to identify concepts, key words, or ideas that may lead to existing analogous products or systems. Each participant is assigned a computer and is given a list of useful websites and tools, such as web searches (Google, Yahoo), patent searches (Google Patents, FreePatentsOnline.com) and Industrial Design websites (YankoDesign.com, Coolest-Gadgets.com). They are allowed 20 minutes to freely search the Internet, "leap-frogging" and "piggybacking" from concept to concept and recording what they find.
7. **Exit survey (10 minutes) –** The participants are asked to fill out a one-page survey asking how innovative they feel their concepts are, how well they fulfill the design problem, what their favorite concepts are, what analogies they found useful, which concept generation method they preferred, and how completely they feel they covered the design space. All papers are collected, and results from the mind-map, 6-3-5, and external analogy search are recorded.

4. RESULTS

A sample result from the 6-3-5 portion of the study is shown in Fig. 10. Note the extensive use of both analogies (spiders, drills, etc) and transformation processes.

The effectiveness of the four conditions was assessed on the quantity of concepts developed in each session. Research has shown that innovation significantly improves when a concept generation method increases the number of concepts developed [22-24]. The experiment was quantitatively evaluated by conventional Design-of-Experiments using Yates standard form of the factorial set-up [21], analyzing several different organizations of the data.

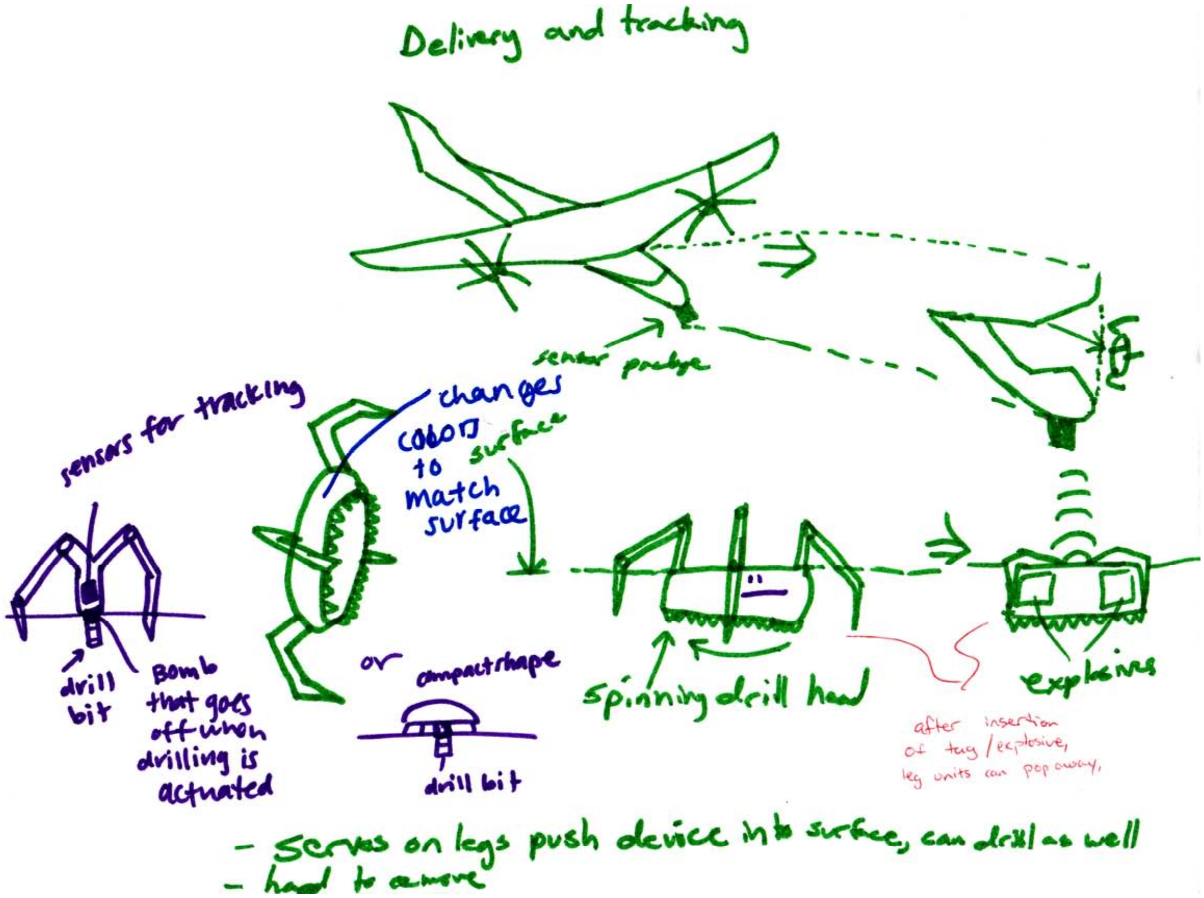

Figure 10: Sample 6-3-5 result showing burrowing tag

4.1 MEANS OF ANALYSIS

The mind-map, 6-3-5, and external analogy search results for each individual and team were compiled in a spreadsheet, detailing each unique concept generated, who contributed it, and during which stage it was generated. A concept was characterized as a solution/embodiment of a function or a specific form/configuration. For example some generated concepts that fulfill the function "track" were the use of satellite or GPS, leaving chemical traces that could be tracked by a dog, tracking credit card purchases, using a radio beacon, and using a high frequency sound to make flocks of birds or bats follow the target. Because of the wide scope of the design problem (no specifications on the target or the mission objectives) the solutions returned were similarly of wide variety in application and feasibility. A concept was judged "unique" if it had not been presented in the same form by a different member of the group. If the same concept was listed twice in the same stage (e.g. mind-mapping), only one contribution was recorded. If a different team member significantly developed the concept at a later stage (such as 6-3-5), this contribution was also recorded, but was not considered unique. Thus, the data as a whole can be examined by the total number of concepts generated or the number of unique concepts generated.

Because the number of participants varied among different groups from three to six, it is useful to approach the aggregate data from several different angles. We chose to evaluate the experiment using three different aspects of the data:

1. The total number of concepts generated by each group (including multiple instances).
2. The number of *unique* concepts generated by each group.
3. The number of concepts generated by each *individual* (identified by different color pens).

In this way, we avoided several issues with the data. If we only analyze totals for the groups, the results may be skewed because of differences in group size. By analyzing data for both groups and individuals, we can make full use of a larger population size but still observe group-specific trends.

4.2 STATISTICAL ANALYSIS OF DATA BY GROUP

The first analysis of the data examines the total number of concepts generated by each group. Of the nine groups, eight are included here, with two groups at each data point. The last group is a third case of using WordTree, and was omitted because it is the only group with 6 people. The results can be organized for Design-of-Experiments as shown in Table 3.

Table 3: Factorial results using total number of concepts per group

Trial	Mean	d_1(WordTree)	d_2 (Transformation)	d_1 d_2	p_1	p_2	Average	Variance
1	+1	-1	-1	+1	77	93	85	128
2	+1	+1	-1	-1	60	76	68	128
3	+1	-1	+1	-1	108	106	107	2
4	+1	+1	+1	+1	109	99	104	50
$\Sigma \cdot \Pi$:	364	-20.00	58.00	14.00			S_p:	8.77
Effect:	**91.00**	**-10.00**	**29.00**	**7.00**			S_e:	6.2
t_E:	**14.67**	**-1.61**	**4.67**	**1.13**			$t^*_{95}(4)$:	**2.78**
							$t^*_{99}(4)$:	**4.60**

ANOVA	Sum of Squares	DOF	Mean Square	F	Significance
Transformation	1653.13	1	1653.13	20.38	0.01
WordTree	210.13	1	210.13	2.59	0.18
WordTree*Transformation	105.13	1	105.13	1.30	0.32
Error	324.50	4	81.13		

Design-of-Experiments provides a least-squares estimate for the effect of each factor and interaction in the experiment. In Table 3, the numbers of concepts generated by each of the eight included groups are listed under p_1 and p_2. The effects of the variables d_1 (WordTrees) and d_2 (Transformation Design), as well as the interaction between them are determined by subtracting the average for all "-1" runs from the average for all "+1" runs. We see that, on average, using WordTrees tended to produce 10 *less* concepts than not using it, while using transformation principles and facilitators led to 29 more concepts than not using them. The interaction between the two methods gave an effect of 7 more ideas.

However, it is important to determine how much of this information is due to actual trends and how much is due to error and random variation. Because we have two replicates at each data point, we can compute the variance for each run. From this approach, we can determine the pooled variance (S_p^2= average of variances) and the standard deviation of the effects ($S_e = 2S_p/\sqrt{m}$ where m = number of groups). A t-value for each factor effect is also determined by dividing the estimated effect by S_e. These t-values can then be compared to required t-values for four runs and confidence levels of 95% and 99%.

As shown in Table 3, the use of Transformation Design (d_2) has a t-value of 4.7, which indicates with a 99% confidence level that the effect of using Transformation Design is statistically significant. The use of WordTrees did not prove to be significant in this instance, nor did the interaction between the two methods. ANOVA calculations confirm the relative significance of the effects.

Table 4 shows the results of the second analysis of the data. Here, only the number of unique concepts is included for each group; instances where a concept is developed further later in the process are not recounted. This analysis shows that once again, the use of Transformation Design (d_2) was the only significant factor, with a confidence level of 99%. This result is also confirmed with ANOVA calculations.

As stated previously, a third replicate for WordTree (+ -) was also run, but not included in these results, since only eight trials were needed for the factorial. This 6-person group developed 90 concepts, of which 73 were unique. Substituting this team's results for one of the other WordTree teams results in similar effects and levels of significance as the original analysis for both total and unique concepts.

4.3 STATISTICAL ANALYSIS OF DATA BY INDIVIDUAL

One challenge of interpreting this study by group is the relatively small sample size. With only two replicates for each of the four trials, uncertainty exists about the true characteristics of the population, even though the results are statistically significant. Different group sizes, personalities and interactions in the groups, and even time of day may affect the studied factors. We can increase the effective sample size if we also examine the results by individual. Now, instead of eight (or nine) samples, there are 35 (or 41) independent samples. The additional unknowns that result from different group dynamics can be controlled by using blocks to separate the individuals of different groups. Hence, the results can be arranged as shown in Table 5 (once again leaving out the 6-person group to even out the distribution of replicates throughout the experiment).

Table 4: Factorial results using total unique concepts per group

Trial	Mean	d_1(WordTree)	d_2 (Transformation)	d_1 d_2	p_1	p_2	Average	Variance
1	+1	-1	-1	+1	75	86	80.5	60.5
2	+1	+1	-1	-1	56	74	65	162
3	+1	-1	+1	-1	95	102	98.5	24.5
4	+1	+1	+1	+1	101	98	99.5	4.5
$\Sigma \cdot \Pi$:	343.5	-14.50	52.50	16.50			S_p:	7.9
Effect:	**85.88**	**-7.25**	**26.25**	**8.25**			S_e:	5.6
t_E:	**15.32**	**-1.29**	**4.68**	**1.47**			$t^*_{95}(4)$:	**2.78**
							$t^*_{99}(4)$:	**4.60**

ANOVA	Sum of Squares	DOF	Mean Square	F	Significance
Transformation	1352.00	1	1352.00	20.56	0.01
WordTree	112.50	1	112.50	1.71	0.26
WordTree*Transformation	144.50	1	144.50	2.20	0.21
Error	263.00	4	65.75		

Table 5: Factorial results using number of concepts per individual, blocked by group

Trial	Mean	d_1(WT)	d_2 (Trans.)	d_3 (Block)	d_1 d_2	d_1 d_3	$d_2 d_3$	p_1	p_2	p_3	p_4	p_5	Average	Variance
1	+1	-1	-1	-1	+1	+1	+1	16	25	15	21		19.3	21.6
2	+1	+1	-1	-1	-1	+1	-1	14	16	18	12		15	6.7
3	+1	-1	+1	-1	-1	-1	+1	28	34	20	26		27	33.3
4	+1	+1	+1	-1	+1	-1	-1	41	32	36			36.3	20.3
5	+1	-1	-1	+1	+1	-1	-1	17	15	20	15	27	18.8	25.2
6	+1	+1	-1	+1	-1	-1	+1	19	15	13	17	12	15.2	8.2
7	+1	-1	+1	+1	-1	+1	-1	32	22	26	14	12	21.2	69.2
8	+1	+1	+1	+1	+1	+1	+1	15	19	21	21	23	19.8	9.2
$\Sigma \cdot \Pi$:	172.6	0.08	36.08	-22.58	15.78	-22.08	-10.08						S_p:	4.9
Effect:	**21.57**	**0.02**	**9.02**	**-5.65**	**3.95**	**-5.52**	**-2.52**						S_e:	1.7
t_E:	**12.84**	**0.01**	**5.37**	**-3.36**	**2.35**	**-3.28**	**-1.50**						$t^*_{95}(8)$:	**2.31**
													$t^*_{99}(8)$:	**3.36**

ANOVA	Sum of Squares	DOF	Mean Square	F	Significance
Transformation	663.95	1	663.95	12.99	0.001
WordTree	0.03	1	0.03	0.00	0.98
WordTree*Transformation	40.97	1	40.97	0.80	0.38
Error	1584.00	31	51.10		

Similar to the group results, this analysis indicates that using the transformation principles and facilitators has a statistically significant positive effect on the design process (confidence level of 99%). The greater sample size also results in eliminating most of the effect due to the use of WordTrees. In addition, the effect of the block (members of different groups) was also found to be significant (confidence level of 99%).

Another insight resulting from this analysis of individual contributions is that there may be a statistically significant interaction between the use of WordTrees and Transformation Design. Even though WordTrees by themselves did not contribute to a rise in quantity, the t-test shows an interaction between the two design methods resulting in a slight increase in the number of concepts, above and beyond the effect of Transformation Design alone (confidence level of 95%). However, this interaction was not shown in the ANOVA calculations.

4.4 DIVERSITY AND NOVELTY OF SOLUTIONS

The data indicate a large degree of variation between teams in the concepts that were generated. Almost 500 different concepts were generated between the nine groups, with an average of 90 concepts per team over a two-hour period. Out of the 500 concepts, 352 concepts were unique to single teams, with the remaining 150 being generated by multiple teams. In fact, although a few concepts were proposed as many as 12 times, the average number of times any given concept was generated over the course of the experiment was only 1.66, showing a wide spread of diversity.

The concepts generated may be classified into several general categories. The majority of the concepts fulfilled the main functions of “tag, track, and effect” from the design statement. In addition, some concepts addressed the overall form of the system, such as resembling a bird, insect, seedpod, helicopter, or animal droppings. Other concepts developed general methods of power or transportation (e.g. hovering, insect legs, digging underground), as well as transformation issues (folding wings, changing shape for camouflage, break-away modules for tagging, etc.). An example concept is shown in Fig. 11, where a bird-like UAV drops a tag embedded in a substance disguised as bird droppings.

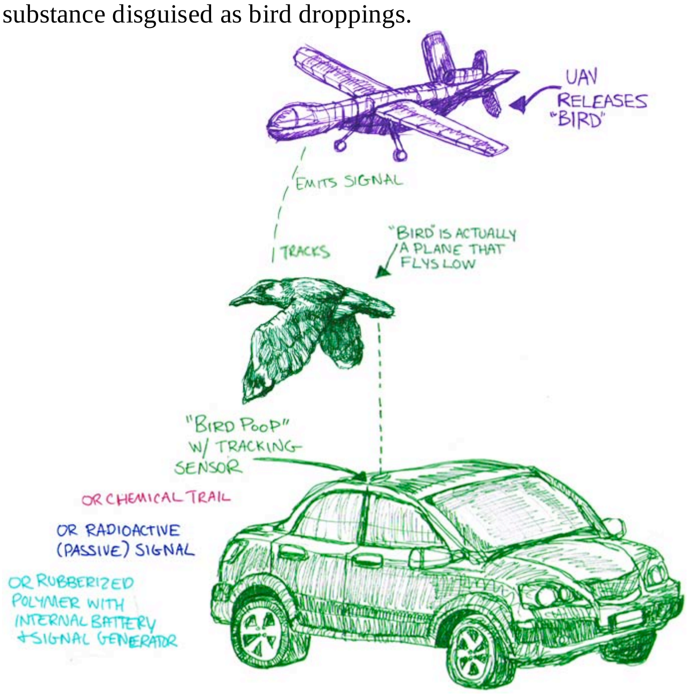

Figure 11: Exemplar concept from 6-3-5.

5. DISCUSSION OF FINDINGS

To evaluate the outcome of this experiment, we will first look at the participants’ response to the transformation principles and facilitators, and then to the WordTree method.

5.1 TRANSFORMATION RESULTS

The analysis of the data above indicates that teaching the participants about transformation principles and facilitators and encouraging them to use the information did indeed result in a noticeable increase in the number of generated concepts. Table 6 summarizes this effect.

Table 6: Increase in concepts generated due to using Transformation Design method

	Total Concepts	Total Unique Concepts	Concepts Per Person
Without Trans.	79.2	72.8	17.1
With Trans.	105.5	99	24.8
Difference	26.3	26.2	7.8
% Increase	**24.9%**	**26.5%**	**31.3%**

Depending on which method of parsing the data is used, using Transformation Design led to an increase in concepts of 25-31% compared to design processes not using the method. This result is of course limited to the specific design statement given and other parameters of the test problem. However, it is an encouraging sign that describing systems in terms of transformation heuristics can often be beneficial to the design process.

In speaking with participants and reviewing their exit surveys, we found insights into possible improvements and applications. In particular, many of the participants felt that using transformation principles and facilitators would be more effective when applied to design problems that are more process-specific. When asked to design a “system that can tag, track, and cause an effect on a target” based loosely on a UAV, participants were sometimes confused about how to attack such a broad problem and how to best apply what they had learned about transformation. If, instead, they were asked to design a “UAV that can stealthily approach a target, attach itself and remain hidden while relaying information back to a base, and then puncture the target’s tires,” the participants used specific trends in transformation to determine *how* to accomplish this particular scenario. This may indicate that a separate step would be useful, where the designer determines what functions or processes they would like to focus on, before examining specific opportunities for transformation. Even those who did not directly use the principles and facilitators to create transforming concepts did find the words useful as mental cues to viewing the problem differently.

5.2 WORDTREE RESULTS

This experiment did not find any significant change in output correlated to the use of the WordTree Design-by-Analogy method alone. In fact, the analysis above looking at group totals (Fig. 6 and 7) showed a slight decrease in number of concepts, although the change was not statistically significant. However, it did seem to contribute slightly to an additional increase in quantity when used in conjunction with the Transformation Design method. Other recent studies [11] also showed no noticeable effect on the number of concepts produced, although they did find that participants used considerably more analogies and made better use of analogies outside the original domain. Initial evaluation of the current study supports this conclusion, as the groups that consciously tried to use Design-by-Analogy returned results more focused on analogies to animals and natural phenomena than did the other groups. However, it is not known how significant this effect may be, nor whether it is due to the specific WordTree method or to a focus on analogies in general. Further testing is needed to determine the specific benefits of the WordTree method, as well as the simplest and most efficient use of WordTrees.

Participants in this study were often unsure how to make full and effective use of the WordTree method. A large part of this difficulty was most likely due to how the method was introduced. In the previous studies, students were exposed to the multi-part methodology over the course of a one-hour lecture in their senior design class, with examples and step-by-step explanation. Due to time constraints, introduction to the WordTree portion of the method in this study was limited to a short overview of why Design-by-Analogy can be useful and a short explanation of how to assemble WordTrees. The participants had only a few minutes to digest this information and review WordTrees of relevant key words before transitioning into the mind-mapping phase of the method. Because of this limitation, the participants tended to think of the tool as a static piece of reference information instead of a more important and central part of the design process. Its effectiveness was largely hit-and-miss: one team commented that they found it very useful and attempted to incorporate analogies into their mind-map; other teams either ignored the tool or commented that they thought it was interesting, but could not completely figure out how to apply the information to the remainder of the design process.

6. FUTURE WORK

Both the areas addressed in this study show promise as methods to assist in design. Understanding how similar systems work and how they have been designed in the past can help current innovators improve the functionality, usability, and novelty of future products. The concept generation methods for transformation design and WordTree Design-by-Analogy can both be refined to make them simpler, easier to learn and follow, and more effective in drawing out untapped potential from the design process.

Research in transformation design thus far has yielded a wealth of information on how transformation behaves and ways to categorize it. The challenge remains how to best apply this information to a directed, formalized design method. Using the results of this experiment and other feedback from participants, we will continue to revise the current method detailed in this paper and run further experiments and test studies to judge under what conditions it is most useful. We will also pursue alternative methods that may use the underlying theories in wholly different ways.

The WordTree method as it now stands can be difficult for first-time users to execute successfully. Additional work will be carried out to simplify and streamline the process so that less time can be used explaining and more can be used to dive into the innovation process. Additional experimentation may also be needed to further quantify how WordTrees benefit concept generation results.

The interaction between transformation heuristics and WordTrees will also be further explored. These two methods have a logical link that may lead to a more complete, robust approach when combined effectively. Transformation design gives the designer a wealth of information on how different words (principles & facilitators) are related to each other. However, it gives little specific direction of how to apply this information. WordTrees, on the other hand, take user-inputted words and direct the designer to specific analogies and applications from beyond the original domain. A proper combination of these two methods could potentially lead to concept generation for transforming systems that identifies useful analogies and solutions from both near- and far-field in a step-by-step, formalized method.

This paper examines the quantitative implications of the research experiment. However, other aspects should also be analyzed. Future work will evaluate how the diversity, novelty, and quality of concepts vary between the WordTree and Transformation Design methods. We will also look for insights into when in the processes these concepts tended to appear – during mind-maps, 6-3-5, or external analogy search.

7. CONCLUSIONS

A controlled experiment was conducted using a sample of 41 senior-level mechanical engineering students divided over nine teams. These teams each followed one of four formal concept generation approaches, incorporating two recently developed design methods: WordTree Design-by-Analogy and Transformation Design. The four conditions tested were a conventional concept generation process with mind-mapping and 6-3-5, Transformation Design combined with mind-mapping and 6-3-5, WordTrees with mind-mapping and 6-3-5, and both Transformation Design and WordTrees with mind-mapping and 6-3-5. The average number of concepts generated in each 2-hour trial was 91 per group, or 22 per person. Design-of-Experiments analysis revealed that while using the WordTree method had no noticeable effect on the number of concepts generated, using the Transformation Design method yielded a consistent increase of 25-31% more concepts across all groups and individuals.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support provided from the Cullen Endowed Professorship in Engineering, The University of Texas at Austin, the National Science Foundation under grant number CMMI-0555851, and grants from the Air Force Research Laboratory Munitions Directorate (AFRL/MN) at Eglin, Florida and the Air Force Office of Scientific Research (AFOSR). The authors would also like to thank the Department of Engineering Mechanics at the U.S. Air Force Academy for their support and guidance, as well as the Thrust 2000/Cockrell Engineering Fellowship for additional support. Any opinions, findings, or conclusions found in this paper are those of the authors and do not necessarily reflect the views of the sponsors.

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APPENDIX A: DESIGN STATEMENT FOR EXPERIMENT

Design Problem: Tag, Track, and Effect

The Air Force wants to increase the functionality of their Unmanned Air Vehicle technology by using transformation to move between states that are suited to tagging, tracking, and performing and effect on targets of interest.

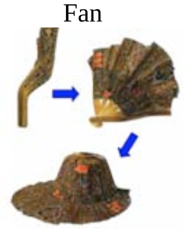
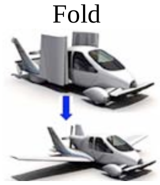
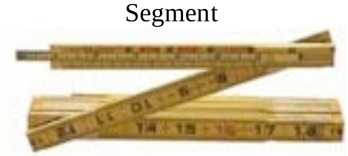
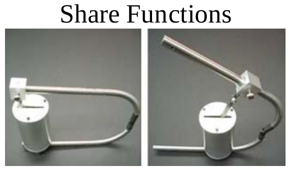
Tag: Physically mark or create a way to easily find and identify a target, even after direct contact has been lost. Possible means include, but are not limited to physically attaching, chemically marking, using energy or radiation, biological means, and visual or other sensory marking.

Track: Be able to continuously or sporadically determine certain characteristics of the target, such as position, velocity, size, strength, etc. Be able to lose direct visual contact but still reacquire and positively identify target when it reappears.

Effect: Be able to remotely trigger a desired effect on the target when desired. Destruction or disablement are possible effects, but options for non-destructive actions specific to the mission are desirable.

APPENDIX B: TRANSFORMATION PRINCIPLES AND FACILITATORS GIVEN TO DESIGN TEAMS

Transformation Principles		
Expand/Collapse  (Folding Chair)	Expose/Cover  (Library Chair/Stepladder)	Fuse/Divide  (Drill/Sander/Jigsaw)

Transformation Facilitators			
Conform with Structural Interfaces  (Cardboard Box)	Enclose  (Stuffed Animal/ Pouch/Ball)	Fan  (Fan/Hat)	Flip  (Rocking Horse/Chair)
Fold  (Airplane/Automobile)	Furcate  (Slap Bracelet)	Inflate  (Balloon)	Interchange Working Organ  (Snowmobile/Motorcycle)
Modularize  (Power Tool Set)	Nest  (Nesting Paper Cups)	Roll/Wrap/Coil  (Sleeping Bag)	Segment  (Folding Ruler)
Share Core Structure  (ATV/Jetski)	Share Functions  (Bicycle Lock/Pump)	Share Power Transmission  (Helicopter/Airplane)	Shell  (Cane/Sword)
Telescope  (Telescoping Cup)	Utilize Composite  (DNA)	Utilize Flexible Material  (Roll-Up Shoe)	Utilize Generic Connections  (Quick-Connect Poles)

Principles	Expand / Collapse	Change physical dimensions of an object to bring about an increase/decrease in occupied volume primarily along an axis, in a plane, or in three dimensions
	Expose / Cover	Reveal or conceal a new surface to alter functionality
	Fuse / Divide	Make a single functional device become two or more devices (discretization), at least one of which has its own distinct functionality defined by the state of the transformer, or vice versa
Facilitators	Conform with Structural Interfaces	Statically or dynamically constrain the motion of a component using structural interfaces
	Enclose	Manipulate object in three dimensions in order to enclose a three-dimensional space
	Fan	Manipulate object in two dimensions to create an elongation, planar spread, or enclosed space to alter its function
	Flip	Perform different functions based on the orientation of the object
	Fold	Create relative motion between parts or surfaces by hinging, bending or creasing
	Furcate	Change between two or more discrete, stable states determined by the boundary conditions
	Inflate	Fill an enclosed space, constructed of flexible material, with fluid media to change geometry and function
	Interchange Working Organ	Interchange working organ to produce a different end effect
	Modularize	Localize related functions into product modules
	Nest	Place an object inside another object, wholly or partially, wherein the internal geometry of the containing object is similar to the external geometry of the contained object
	Roll/Wrap/Coil	Bring about a change in an object's functionality by manipulating its geometrical surfaces around an axis to create or enhance spheroidality and curvature
	Segment	Divide single contiguous part into two or more parts
	Share Core Structure	Device's core structure remains the same, while the periphery reconfigures to alter the function of the device
	Share Functions	Perform two or more discrete functions
	Share Power Transmission	Transmit power from a common source to perform different functions in different configurations
	Shell	Embed an element in a device, where the element performs a different function
	Telescope	Manipulate an object along an axis to create elongation, planar spread or enclosure to alter its function
	Utilize Composite	Form a functional part from two or more non-functional parts
	Utilize Flexible Material	Change object dimensions with change in boundary conditions
	Utilize Generic Connections	Employ internal or external connections (structural, power) that can be used by different modules to perform different functions or perform the same function in a different way

Principles	Most Common Facilitators With This Principle	Facilitators Occurring Only With This Principle
Expand/Collapse	• Conform w/ Structural Interfaces • Nest • Shell • Segment	• Inflate • Furcate • Utilize Flexible Material • Nest
Expose/Cover	• Shell • Share Functions • Flip • Fold	• Flip
Fuse/Divide	• Segment • Conform w/ Structural Interfaces • Modularize • Share Functions	• Utilize Generic Connect. • Interchange Working Organ

Common Facilitator Groups:

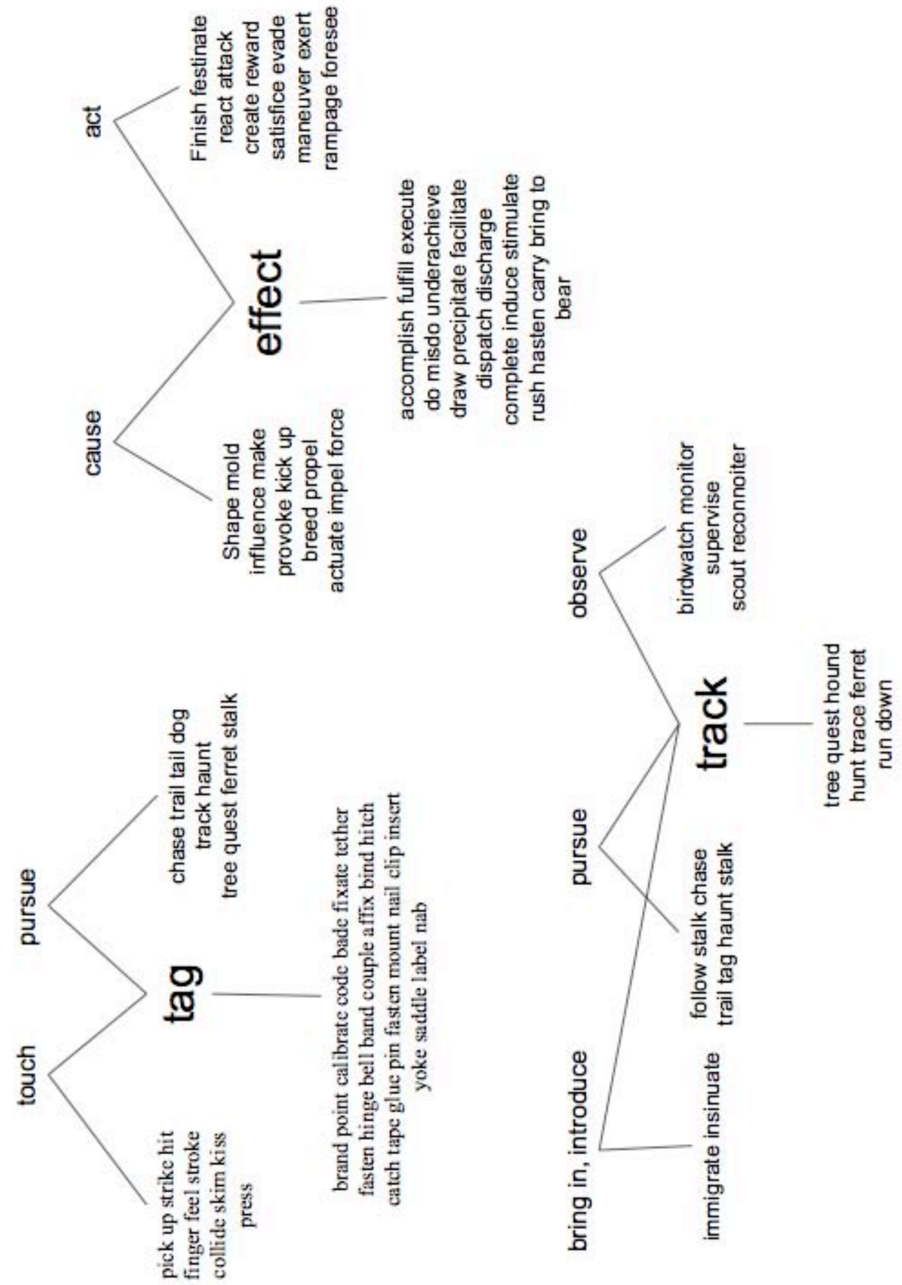
Fan / Fold / Shell / Segment / Nest

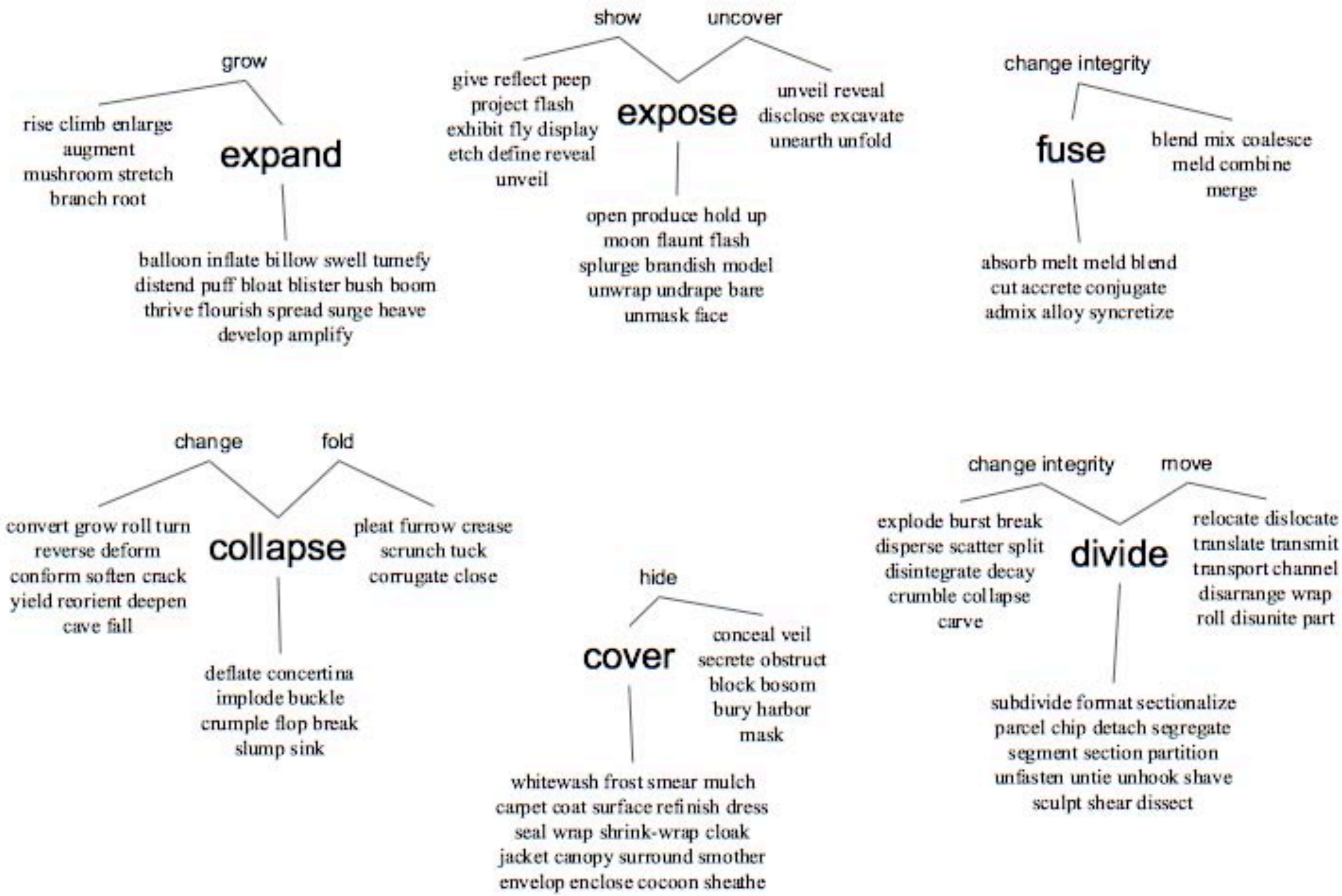
Furcate / Conform w/ Structural Interfaces / Fold / Segment / Shell / Nest

Inflate / Utilize Flexible Material / Shell / Nest

Interchange Working Organ / Share Power Transmission / Share Core Structure / Modularize / Utilize Generic Connections / Segment / Share Functions

APPENDIX C: WORDTREES GIVEN TO DESIGN TEAMS




grow
rise climb enlarge augment mushroom stretch branch root
expand
balloon inflate billow swell tumefy distend puff bloat blister bush boom thrive flourish spread surge heave develop amplify
show
uncover
give reflect peep project flash exhibit fly display etch define reveal unveil
expose
unveil reveal disclose excavate unearth unfold
open produce hold up moon flaunt flash splurge brandish model unwrap undrape bare unmask face
change integrity
fuse
blend mix coalesce meld combine merge
absorb melt meld blend cut accrete conjugate admix alloy syncretize
change
fold
convert grow roll turn reverse deform conform soften crack yield reorient deepen cave fall
collapse
pleat furrow crease scrunch tuck corrugate close
deflate concertina implode buckle crumple flop break slump sink
hide
cover
conceal veil secrete obstruct block bosom bury harbor mask
whitewash frost smear mulch carpet coat surface refinish dress seal wrap shrink-wrap cloak jacket canopy surround smother envelop enclose cocoon sheathe
change integrity
move
explode burst break disperse scatter split disintegrate decay crumble collapse carve
divide
relocate dislocate translate transmit transport channel disarrange wrap roll disunite part
subdivide format sectionalize parcel chip detach segregate segment section partition unfasten untie unhook shave sculpt shear dissect