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Investigating the Effect of Functionality Level of Analogical Stimulation on Design Outcomes

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Abstract

Design-by-analogy is a growing field of study and practice, due to its power to augment traditional concept generation methods by expanding the set of generated ideas using similarity relationships from solutions to analogous problems. A new method for extracting functional analogies from data sources has been developed to assist designers in systematically seeking and identifying analogies from general data sources, databases, or repositories, such as patent databases. This search engine and design-by-analogy facilitation tool uses a functional vector space model to quantitatively evaluate the functional similarity between represented design problems and, in this case, patent descriptions of products. Document parsing algorithms are developed to reduce the patent text to key functions and solved conflicts using Zipf's law to reduce the words within the patents into the applicable functionally analogous terms, providing a mapping process for functional-based search. The mapping of the patents into the functional analogous words enables the generation of novel ideas that can be customized in various ways, providing potentially relevant sources of design-by-analogy inspiration. This paper presents a controlled experiment designed to evaluate the search engine efficacy during the conceptual ideation process. The two treatments explored are the effect of including analogous patents during ideation, and the effect of functionality level. The tool efficacy during concept generation is shown to increase novelty of generated solutions, while there is no significant change in the quantity of generated solutions.

Keywords: design-by-analogy, design cognition, functional analogy, computational design tools

1 Introduction

The findings reported here are part of a larger research effort to develop appropriate algorithms and tools to enable web-based search for design analogies (Braha et al., 2013; A. Chakrabarti et al., 2011). The goal is to enable a designer to methodically search the immense quantity of design information available online in data sources, such as patent archives, leading to analogous concepts that can be used to complement and enrich the concept generation process through the introduction of non-obvious analogies. Through this approach, we seek to assist designers resulting in developing innovative conceptual designs.

The Vector Space Model-based (VSM) analogy search engine developed in prior work by the authors (J. T. Murphy, 2011) consists of a five-step process shown in Figure 1. The process begins with constructing a controlled vocabulary of functions extracted from a patent database, building on the hierarchical structure of the *functional basis* (Hirtz, 2002; Otto & Wood, 2001; R. Stone & K. L. Wood, 2000). Once a complete set of function terms is compiled, the patent documents are indexed against the expanded functional basis to create a vector representation of the patent database. Query generation and similarity ranking tools are then developed to query and retrieve the patents with the highest degree of relevance to the functional description, or alternative functional descriptions, of a given design problem. Finally, the most relevant patent results are presented to the user. Further details of the tool can be found in (J. Murphy et al., 2013; J. T. Murphy, 2011).

The purpose of this study is to evaluate the effectiveness of the Patent Analogy Search Tool on a real-world design problem

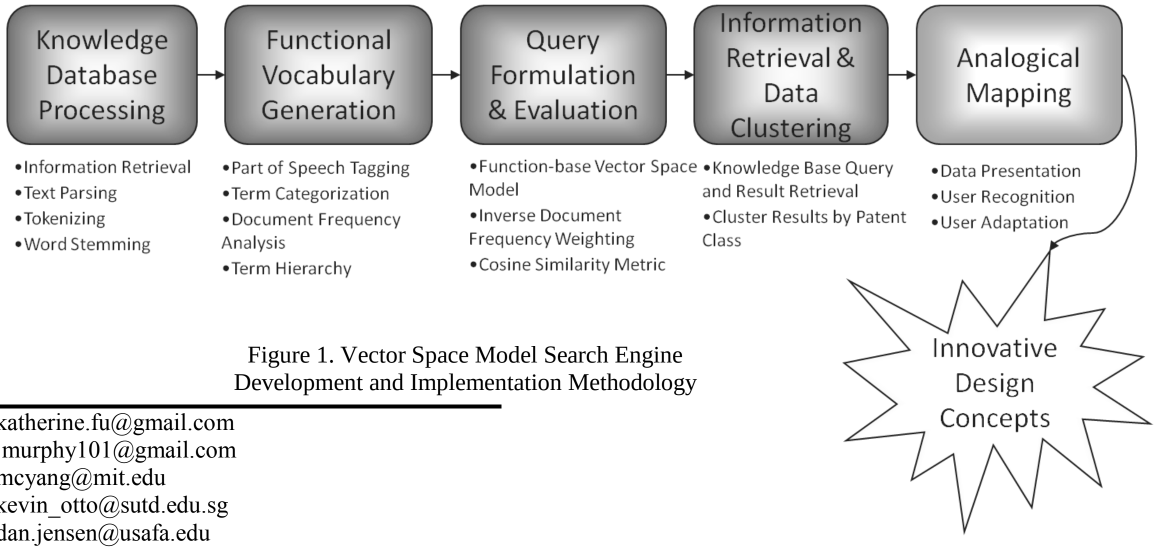

Figure 1. Vector Space Model Search Engine Development and Implementation Methodology

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when the analogical mapping is not known beforehand. The experiment presented in this paper is designed to elucidate the effects of presenting functionally analogous patents during concept generation on the quantity and novelty of design solutions.

The overall hypothesis is that, using a patent-based analogy search algorithm embedded in a formalized tool to identify non-obvious functional analogies for design concept generation, functional representations, rather than component form representations, of analogies can be used within the conceptual design process to improve the ideation result as measured by quantity or novelty of ideas.

2 Background

2.1 Concept Generation Using Design-by-Analogy

Design-by-analogy has been shown to be one effective means in achieving innovation and novelty in design outcomes, and rests upon the use of functional analogies (Chan et al., 2011; J. Linsey, Murphy, J., Markman, A., Wood, K. L., Kortoglu, T., 2006). The following sections review function representations and functional modeling and their roles in design-by-analogy, a brief summary of some existing design-by-analogy techniques, methods, and tools from prior research, and a description of some of the patent-based tools extant in the literature.

2.1.1 Function and Design-by-Analogy

In order to effectively apply design-by-analogy techniques during concept generation, it is helpful to decompose the design problem at hand into a set of solution-neutral functions, thereby minimizing design fixation and greatly expanding the number of concepts to be considered (A. Chakrabarti & Bligh, 2001; Otto & Wood, 2001; Pahl & Beitz, 1996). *Functional modeling*, or the process of developing a functional representation of a concept or design problem, often begins with an abstracted "black box" formulation of the overall product/concept function. This simplified conception can then be decomposed into sub-functions, which are connected by flows of information, material, or energy, thereby creating a repeatable *function structure* representing the internal functionality of that concept (Kurfman, Rajan, Stone, & Wood, 2001, 2003). The functional model for a given concept can take a number of different forms, depending on the process choices (choices/assumptions made initially about what kind of inputs will go into the system on the user side), and/or alternative representations of user activities or functions associated with the problem/concept (Otto & Wood, 2001). Figure 2 illustrates an exemplified functional model of a Jigsaw system.

In order to standardize the language for the process of functional modeling and the representation of functions and flows that correspond to each sub-function, a standard language has been developed called the *functional basis* (Hirtz, 2002; R. Stone & K. L. Wood, 2000). Function words and flow words combine to create verb-object couples, which describe the action conveyed on the input flows of each identified sub-function, achieving a level of abstraction broad enough to cover a large function and flow space. This functional basis enables design concepts to be characterized using a standard taxonomy, and facilitates the direct representation and comparison of physical systems, concepts or products.

Identification of modules and interface boundaries within functional models may be achieved through additional refinement of the functional model (R. Stone & K. Wood, 2000), allowing for simplification the model, and/or discover of opportunities to improve manufacturability, maintainability, and reliability early in the design process through function sharing and proper interface design. In Figure 2, an example of modules within a functional model can be seen, signified by the colored boxes encompassing sections of the function chains of the Jigsaw. Another benefit of functional models is the ability to standardize, allowing for the archiving and retrieval of design knowledge, for which a number of systems have been developed (M. Bohm & Stone, 2004a, 2004b; M. R. Bohm, Vucovich, & Stone, 2005; Szykman, Sriram, Bochenek, & Racz, 1999; Szykman, Sriram, Bochenek, & Senfaute, 2000). Computational design tools have been developed to use the design knowledge contained in these functional repositories for concept variant generation techniques (Bryant, Stone, McAdams, Kurtoglu, & Campbell, 2005a, 2005b; Potter, Culley, Darlington, & Chawdhry, 2003; Terpenny & Mathew, 2004). A drawback of using functional modeling during the design process is that it requires process choices, or assumptions about the inputs/outputs of the system on the user side, be made early on, which can be constraining and limiting (Otto & Wood, 2001). For example, with the jigsaw show in Figure 2, the choice to use a battery (stored electrical energy) as the power source, while a potentially obvious choice for a portable device, prohibits the designer from considering other options for power sources, like fuel cells, solar cells, or pneumatically powered devices. This limitation can lead to missed opportunities for innovation and novel designs. However, this issue can be remedied by approaching functional modeling from a more broad perspective in terms of user and environmental activities and functions and to apply alternative process choices or levels of abstraction that lead to multiple alternative functional models (Otto & Wood, 2001). Appropriate functional representation of design concepts is as critical to the successful implementation of design-by-analogy as is developing a systematic approach to search for and evaluate the utility of functionally similar concepts. Creating abstracted functional models of concepts and comparing the similarities between their

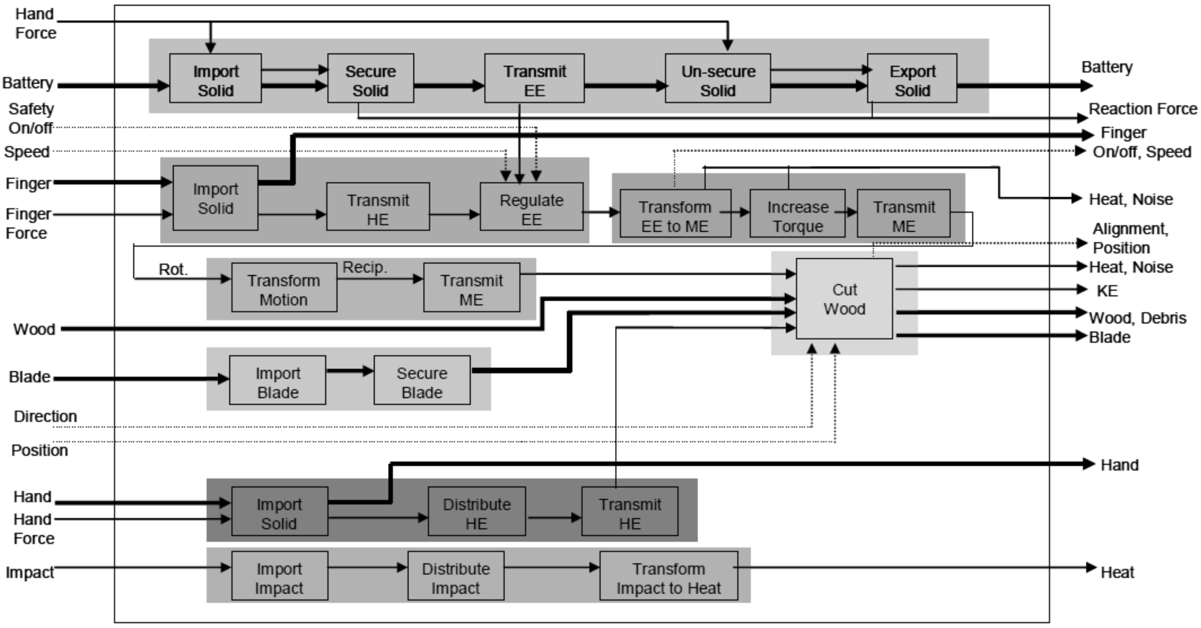


Figure 2. Functional Model for the Black and Decker Jigsaw

functionality can lead to the identification of analogous concepts.

2.1.2 Design Cognition and Design-by-Analogy Techniques

Research efforts attempting to improve the conceptual design process and develop tools or methods for design-by analogy must be founded upon an understanding of the cognitive process involved with forming analogies. Analogy may be viewed as a mapping of knowledge from one situation (source) to another (target) enabled by a supporting system of relations or representations between situations (M. Chiu, 2003; Falkenhainer, Forbus, & Gentner, 1989; Gentner, 1983). Analogical comparison can lead to new implications and promote new insightful problem representations, often most noticeable when situation domains are very different (Chan et al., 2011; Gentner & Markman, 1997). Design-by-analogy, as a structured methodology, has the potential to diminish the effects of the experiential gap between novice and expert, has been shown to mitigate the effects of design fixation (J. Linsey, I. Tseng, K. Fu, J. Cagan, K. Wood, and C. Schunn, 2010), and can enable the identification of innovative solutions from both experiences and similar solutions from a range of sources. A robust design-by-analogy methodology enables designers to identify non-obvious analogous solutions even in cases where the mapping between concepts is tenuous and/or the concepts occupy different domains. The cognitive processes that underlie design-by-analogy, as we understand it, are based upon the representation and processing of information, opening up the possibility for the mechanism/method to be implemented systematically given an appropriate representation of the information and information processing tools (Goldschmidt & Weil, 1998; Kryssanov, Tamaki, & Kitamura, 2001).

Some structured approaches to design-by-analogy methodologies and tools are reviewed next. A systematic process for identifying analogous biological phenomena and using biomimetic principles for generating concepts was developed in one structured approach (Hacco, 2002). Keywords are derived that relate the function to biological processes using a semantic representation of the functional requirements problem, followed by a search using a biology textbook as the reference database. A system called KRITIK was developed by Goel et al. that autonomously generates new conceptual designs based on a case library of previously existing designs using functional modeling and functional indexing (Goel, Bhatta, & Stroulia, 1997; Goel & Chandrasekaran, 1989). IDeAL was created by Bhatta et al., which uses a function-behavior-structure model-based approach to design-by-analogy through pattern finding, constraint analysis, and problem reformulation (Bhatta, Goel, & Prabhakar, 1994; Goel & Bhatta, 2004). A case based reasoning tool called CADET was developed by Navinchandra et al. to better retrieve and synthesize case design components for more effective combination (Navinchandra, Sycara, & Narasimhan, 1991). An exploration medium for between-domain analogies using design function-behavior-structure design prototypes was created by Qian and Gero (Qian & Gero, 1992). A web-based tool was developed by Charlton and Wallace for finding pre-existing engineering components for reuse in non-standard applications in new designs to reduce manufacturing costs (Charlton & Wallace, 2000). A computational tool developed by Liu et al. called FunSION takes qualitative functional input and output requirements, and generates physical embodiments of design solutions (Liu, Bligh, & Chakrabarti, 2003; Liu, Chakrabarti, & Bligh, 2000). Idea-Inspire, a database and software tool that automates analogical search in a natural and artificial systems database to provide inspiration in the design process, was created by Chakrabarti et al. (A. Chakrabarti, 2009; A. Chakrabarti, Sarkar, Leelavathamma, & Nataraju, 2005). Thesauri using information retrieval from informal design documentation for reuse in the design process were developed by Yang et al. (Wood, Yang, Cutkosky, & Agogino, 1998; Yang, Wood, & Cutkosky, 2005), in addition to creating the DedalAI system to automatically index design concepts in electronic notebooks for retrieval and reuse (Yang & Cutkosky, 1997). A system was developed by Ahmed for helping designers to index and build a knowledge network based on engineering designer queries, which generates associations between concepts, with the end goal of aiding in the search for information, reformulation of a query, and prompting design tasks (Ahmed, 2005). Linsey et al. (J. Linsey, Markman, & Wood, 2008; J. Linsey, Markman, & Wood, 2012; J. S. Linsey, Wood, & Markman, 2008), Seger et al. (N. Segers & De Vries, 2003; N. M. Segers, De Vries, & Achten, 2005), and Verhaegen et al. (Verhaegen, D'hondt, Vandevenne, Dewulf, & Duflou, 2011) develop approaches to analogical retrieval and reasoning through linguistic (semantic word) associations, problem re-representation, and mappings.

2.1.3 Patent-based Tools

Patent databases are attractive sources of analogies and concepts that can lead to innovative solutions (Kang, Na, Kim, & Lee, 2007), due to the fact that all the concepts within the database must be both useful and novel, where “useful” is defined as being functional and operable. “Novel” is defined as being non-obvious and having not previously existed in the public domain (Kang et al., 2007). In addition, the Patent Classification structure, which includes approximately 450 well-defined primary classification categories organizing and grouping patents according to the field of invention, is a valuable feature of the database for design information retrieval for its enabling of data clustering for more efficient presentation and organization of search results (Kang et al., 2007). The anatomy of a patent includes distinct partitions, and the sections that contain the embedded design information are the abstract, claims and description, a regularity in structure that facilitates the processing of patent documents through natural language processing techniques to extract the desired functional information.

The majority of the literature touching on patent search and information extraction, and specifically function extraction and concept generation from patents, is related to the topics of patent invalidity searches and patent informatics (Trippe, 2003; Tseng, Lin, & Lin, 2007), but the same information extraction principles are applied in this work for deriving the patent functionality. A significant focus of the literature has been computational design aids using the patent database. TRIZ, a theory which presents heuristic rules, or principles, to assist designers overcome impasses in functional reasoning by searching through patents in terms of contradictions (Altshuller & Shapiro, 1956), is the foundation of many of these design tools. For example, an axiomatic conceptual design model was created by combing TRIZ and the functional basis work (Zhang, Cha, & Lu, 2007). Cascini and Russo presented a way to automatically identifying the contradiction underlying a given technical system using textual analysis of patents for use in TRIZ (Cascini & Russo, 2007). Souilli et al. developed a method using linguistic markers to identify relevant candidates for TRIZ automatically (Souili & Cavallucci, 2012; Souili, Cavallucci, Rousselot, & Zanni, 2011).

Another large section of the literature employs patent mining techniques, which use meta-data to identify or understand large sets of patents. For example, to understand the interrelatedness between patent technologies and the benefits of understanding the pre-existing knowledge within a domain, patent citations have been used in mining the data (A. K. Chakrabarti, Dror, & Nopphdol, 1993). Some aims of patent mining research include judging possible future market trends, identifying prolific inventors, and other business applications, using meta-data like the number of citations, number of claims, average number of words per claim, number of classes that the patent spans, etc. (Indukuri, Ambekar, & Sureka, 2007; Kasravi & Risov, 2007).

Patent mapping is another area of research that attempts to extract information from the vast database. Fu et al. implemented a method of extracting inherent structure in textual patent data for both studying and supporting design-by-analogy (K. Fu, 2012; Fu, Cagan, Kotovsky, & Wood, 2013; Fu, Chan, et al., 2013). Patent mapping has been applied to gauge overlap in mergers and acquisitions (Moehrle & Geritz, 2004), and more generally, design repositories (not specific to patents) have been used to share and reuse elements of designs in the development of large scale or complex engineering systems (Szykman, Sriram, Bochenek, Racz, & Senfaute, 2000). PatViz enables visual exploration of queries and complex patent searches using diverse types of patent data through user-created graph views (Koch, Bosch, Giereth, & Ertl, 2009). With the intention of patent infringement avoidance, Mukherjea et al. used a Semantic Web to find semantic associations between important biological terms within biomedical patents (Mukherjea, Bhuvan, & Kankar, 2005). Chakrabarti et al. created a taxonomy/hierarchical structure using a topic model to analyze patent data (S. Chakrabarti, Dom, Agrawal, & Raghavan, 1998).

Although the U.S. patent database is fertile to support design-by-analogy, the magnitude and complexity make it very challenging to access in a top down way. This has been attempted to be addressed by theories like TRIZ and their resulting tools (Altshuller & Shapiro, 1956; Duran-Novoa, Leon-Rovira, Aguayo-Tellez, & Said, 2011; Hernandez, Schmidt, & Okudan, 2012a, 2012b; Houssin & Coulibaly, 2011; Krasnoslobodtsev & Langevin, 2005; Liang, Tan, & Ma, 2008; Nakagawa, 2012; Nix, Sherret, & Stone, 2011; Zhang et al., 2007), and commercially marketed computational “innovation support tools” (CREAX; Goldfire), along with many more research driven tools and methods (Bhatta & Goel, 1996; I. Chiu & Shu, 2005; Goel et al., 1997; Verhaegen et al., 2011; Vincent, Bogatyreva, Bogatyreva, Bowyer, & Pahl, 2006). However, much of this previous work most often relies deeply on users/designers to create their own analogies, or search through large quantities of results. We attempt to address this gap with the patent-based design-by-analogy tool described next in Section 2.2, which is tested in the experiment presented later in this paper.

2.2 Patent Analogy Search Tool

Figure 1 shows the overview of the five part process that comprises the Patent Analogy Search Tool, which is the prior foundational research that this experiment is testing: (1) knowledge database processing, (2) functional vocabulary generation, (3) query formulation and evaluation, (4) information retrieval and data clustering, and (5) analogical mapping. This section will briefly describe each of these five steps to supply background on the selection of the external stimuli for the experiment described in this paper. Further detail on the Patent Analogy Search Tool and its development can be found in (J. T. Murphy, 2011).

2.2.1 Knowledge Database Processing

The five-part process begins with retrieving the design document (patent) information in the form of text, parsing that text, then implementing tokenizing and word stemming. The basis of the analogy search engine developed in this work is the Vector Space Model (VSM) of information retrieval (Salton, 1971; Salton, Wong, & Yang, 1975), in which a document is represented as a vector of terms. Natural language processing techniques are used to extract the terms, which are words and/or phrases extracted from the patents (Rindflesch, 1996; van Rijsbergen, 1979).

The HTML patent text is parsed to extract information, such as the title, abstract, description, claims, and patent class. Articles, prepositions, and other unnecessary terms are eliminated using stop words lists (Salton & Waldstein, 1978). Word-stemming algorithms are applied to the retrieved text to further consolidate terms, and a modified prefix-stripping algorithm was created to extract root functions. Part-of-speech (POS) tagging is a major component of automated indexing of the patents. TreeTagger was used, which is an open-source POS tagging program chosen based on high accuracy of tagging in natural language documents (Schmid, 1994). Validation of automated indexing was achieved with manual verification.

2.2.2 Functional Vocabulary Generation

A primary goal of this research is to identify and extract a complete set of functions covering the entirety of the patent database. Completeness of the function vocabulary is evaluated using two metrics: *cumulative functions versus number of patents indexed* and *function document frequency versus term chronological order*. A set of approximately 1,700 functions are identified after indexing 65,000 patents. Cumulative functions plotted versus patents showed that the metric reached a horizontal asymptote, and furthermore convergence was reached at approximately 61,000 patents, providing verification that the function vocabulary does in fact converge to a finite set.

The function vocabulary identified in the indexing process, with a theoretical Zipf distribution fit to the data reveals three different regimes of function frequency distribution that can be identified, which are label as: ubiquitous, generic and process-specific. Ubiquitous functions occur so frequently across all patents that they offer little value for determining similarity or relevance, per Zipf’s theory. These functions (i.e. *provide*, *use*, etc.), which can be considered to lie above the upper cut-off chosen to be all terms that occur in more than 50% of patents, account for 50 of the 1,700 terms and are to be removed from the final function vocabulary index. Generic functions (i.e. *shape*, *rotate*, etc.) enable better distinction between patent vectors within a cosine similarity metric, as they have a good balance between frequency and specificity. Process-specific functions occur in very few patents and would be below the chosen lower cut-off region.

After the final set of functions is vetted per the process described, a hierarchical structure for the functional vocabulary, modeled after the functional basis, is created using affinity diagramming and thesaurus construction techniques (Hirtz, 2002; Otto & Wood, 2001). The affinity diagram technique is used to group like-terms together into sub-groups of hypernyms and synonyms, an iterative process that leads to secondary functions with similar numbers of correspondent sub-functions. The structure of the expanded functional basis vocabulary is 1,700 unique functions organized into 74 groups of secondary functions, with the secondary functions and associated correspondents mapped into the eight (8) primary function classes.

The patent search database is then constructed by indexing additional patents against the completed function vocabulary, using this expanded functional basis vocabulary structure. A representative sample of the USPTO database is constructed with three continuous selections of 100,000 patents. After omitting repealed or missing patents, the sample database consists of approximately 275,000 patents mapped into document vectors resulting in an approximately 275,000 x 1,700 patent vector matrix.

2.2.3 Query Formulation and Evaluation

The document vector matrix contains both the functional content information for each patent and the term-document frequencies across all indexed patents, both of which are used to derive the similarity metric for ranking the search results. *Inverse document frequency* (*idf*) is used to weight rare terms higher than common terms (Manning, Raghavan, & Schutz, 2009; Salton & Waldstein, 1978). Previous research has shown more specific function verbs can yield more novel solutions (J. Linsey, Clauss, E. F., Kurtoglu, T., Murphy, J. T., Wood, K. L., Markman, A. B. , 2011), thus the *idf* weighting yields a higher cosine similarity score for patents that contain process-specific functions, and each element of the document vector matrix is scaled according to the calculated weight for that term.

Furthermore, each document vector is normalized in order to simplify the cosine similarity calculation, generating a patent document unit vector matrix. The *patent functional content* (*fcm*) metric is a normalized measure of the total functional content with a specific patent. The *fcm* metric increases the weighting of patents with high functional content. The reasoning for including this metric is a hypothesis that functionally rich patents contain more information, which can be mapped as analogies. The *total relevancy score* is then defined as a linear combination of the two components: the *idf*-weighted cosine similarity metric and the *patent functional content* metric.

The linear combination within the *total relevancy score* is weighted with two coefficients, alpha, α, and beta, β, which are tuning parameters used to bias the relevancy ranking towards a higher weighting on either the cosine similarity or the functional content metric. These parameters can be explored by running multiple patent searches through a parametric evaluation process.

The process of constructing the patent query vector is automated with the Query Generator tool. The Graphical User Interface (GUI) builds the query using the expanded functional basis vocabulary hierarchical structure, described in Section 2.2.2. The query is built using the following steps:

1. User selects primary function corresponding to high-level functionality derived from functional model of their design problem.
2. User selects secondary function corresponding to specific functionality to be retrieved. Selecting "More" button will display all correspondent functions organized under the secondary function.
3. Interface populates query vector with all correspondent terms associated with secondary function.
4. Additional secondary functions can be selected to further populate query vector for a particular primary function.
5. "Done" button is selected to save new query vector once all secondary functions are chosen.
6. Process can be repeated for additional primary functions.

2.2.4 Information Retrieval and Data Clustering

After the query construction is complete, the "Search Now" button will launch the Search Result Viewer. The viewer performs multiple functions including calculating the cosine similarity, *fcm*, and *total relevancy score*, extracting the top results and clustering the results by patent class. The cosine similarity is calculated for all documents simultaneously by first normalizing the query vector to form the query unit vector and then calculating the dot product of the unit query vector with the document vector unit matrix.

The top *n* results as specified by the user are retrieved, sorted by *total relevancy score* and clustered by primary patent classification, which can be quickly scrolled through using the "Previous" and "Next Class" button. The first column of the results list clearly indicates the similarity scores for the individual patents. To help the user quickly identify patent classes with high potential for identifying functionally relevant patents, the average relevancy score for the patent class is given before the title. The search results can be explored by selecting results of interest, automatically opening a web browser window with a PDF version of the selected patent, using Freepatentsonline.com as the web interface.

2.2.5 Analogical Mapping

Sections 2.2.1-2.2.4 describe a structured methodology for identifying analogous patents, meant to be a supplemental technique to traditional concept generation methods such as brainstorming, brainsketching, and the C-Sketch/6-3-5 method (Markman, 2009; Osborn, 1957; Otto & Wood, 2001; Vangundy, 1988). The desired functionality described during the functional modeling phase of the design process is used directly to create functional semantic representations of the design problem, which are independent of the flow domain. The functional semantic representations are mapped to the expanded functional basis vocabulary, and the Query Generation tool creates the query function vector. The Search Result Viewer identifies the functionally similar patents where analogies to the design problem may exist. The final step in the process is mapping useful patents back into the original problem domain. Analogous patent search fits into the product design workflow after benchmarking and functional modeling, but before or in parallel with ideation methods. The analogy search method outlined in Section 2.2 is applied to choose analogical stimuli for the experiment presented in this paper. For further technical details of this tool, see (J. T. Murphy, 2011).

3 Experimental Method

An experiment is conducted to evaluate the efficacy of the Patent Analogy Search Tool to complement the concept generation phase of the design process. The first factor that is investigated is the overall effect of augmenting brainstorming, or other ideation methods, by presenting functionally analogous patents derived from the search engine, on the quantity and novelty of ideas. The second factor that is investigated is the effect within the analogy groups of searches derived from different levels of functionality, for example focusing on a single sub-function versus all sub-functions. Three levels of functionality are chosen for the analogy groups as shown in Table 1. Further description of design problem used in the experiment, as well as the specific subfunctions chosen for each condition are described next, in Sections 3.2 and 3.3.

The analogy and control groups all executed a three-phase ideation process. Phase 1 consisted of a 10-minute concept generation process, which was common for all experimental groups. The differentiation between the analogy and control groups occurs during Phase 2 of the experiment. During this phase, the analogy groups are presented with the analogous patents according to the assigned functionality levels. During the same phase, the control group is given an article to review that is unrelated to the design problem to serve as a distracter. A primary purpose of this study is to test the cognitive effect of introducing analogous patents versus the unrelated distracter document on the concept generation process. Phase 2 was followed by a second 10-minute concept generation phase to record any additional unique solutions. The experimental

Table 1. Functionality Level of Analogy Distribution Among Experimental Groups

Group	Functionality Level of Analogies
Control	None
Analogy Group 1	Single Sub-Function
Analogy Group 2	Sub-Function Pair
Analogy Group 3	All ns

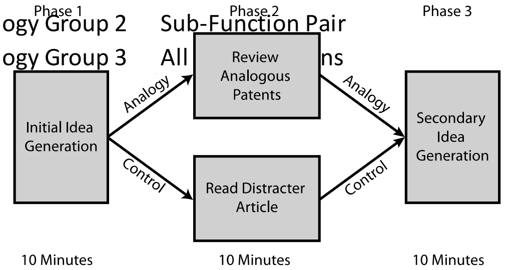


Figure 3. Experimental Workflow Comparison for Analogy vs. Control Groups

workflow for all groups is illustrated in Figure 3. All groups are given the same total length of time for concept generation.

> **Design Problem Statement**
> Design a device to collect energy from human motion for use in developing and impoverished rural communities in places like India and many African countries. Our goal is to build a low-cost, easy to manufacture device targeted at individuals and small households to provide energy to be stored in a battery. The energy is intended to be used by small, low power draw electrics, such as a radio or lighting device, hopefully leading to an increase in the quality of life of the communities by increasing productivity, connection to the outside world, etc.
>
> **Phase 1**
> Generate as many solution concepts to the design problem as you can. Record all concepts, including novel and experimental ones. You may use words and/or sketches to describe your ideas. Please record each distinct solution concept in the separate boxes provided. Additional pages are available upon request.

Figure 4. Design Problem Statement and Concept Recording Instructions

3.1 Participants

The participants were senior mechanical engineering students enrolled in the design methods course at The University of Texas at Austin. Senior students were chosen because they are of similar educational and experiential backgrounds. They have also had exposure to a wide variety of mechanical engineering theory and practical experience through design projects, internships, coops, etc. The relative uniformity across education and knowledge will minimize the variation between individuals during concept generation due to prior experience. As a result, main and secondary effects of the experimental conditions will be more readily identifiable. The total number of participants in the experiment was 68 students, who were randomly assigned to one of the experimental groups discussed above, resulting in 4 groups of 17 students each.

All participants were given the design problem described in the next section and worked individually to generate concepts. The students were instructed to record all concepts using both words and sketches, with distinct solutions recorded individually, similar to the Brainsketching process (Vangundy, 1988).

3.2 Design Problem Description

The design problem is to design a device to collect energy from human motion. The mechanical energy from human motion must then be converted to electrical energy and stored for later use to power small devices such as a radio or lighting device. Additional constraints on the design are that it should strive to be:

- Low cost
- Easy to manufacture
- Portable

The complete problem statement is given in Figure 4. No further constraints or clarification regarding the design embodiment was given. This problem was chosen because it is a real-world, need driven problem with great breadth of possible solutions that a mechanical engineer with the participants' knowledge base would feel comfortable attempting to solve. This problem was originally developed and used in similar studies by Fu et al. (Chan et al., 2011; K. Fu, 2012; Fu, Cagan, et al., 2013; K. Fu, Cagan, J., Kotovsky, K., Wood, K., 2012; Fu, Chan, et al., 2013).

3.3 Description of Analogous Patents Selection

Table 2. Functions Searched for Each Analogy Group

Group	Functionality Level of Analogies	Search Functions
Analogy Group 1	Single Sub-Function	Import
Analogy Group 2	Sub-Function Pair	Import, Convert
Analogy Group 3	All Sub-Functions	Import, Convert/Transform, Transport, Move/Rotate/Oscillate, Produce, Collect, Export/Supply

The analogous patents utilized by the experimental analogy groups were found using the patent search methodology described in Section 2. The sub-functions used in each search were derived from the sub-functions required to fulfill the design problem functional requirements and constraints. The complete list of the design problem sub-functions is:

- Import
- Convert/Transform
- Transport
- Move/Rotate/Oscillate
- Collect
- Produce
- Export/Supply

where the functions are grouped by alternate functions, which represent different flow domains. Acceptable solutions and analogies include any and/or all combinations of alternate sub-functions. The specific sub-functions utilized in the patent searches for each analogy group are shown in Table 2.

In order to minimize the time burden and cognitive demand on the participants within analogy group conditions, the searches for the analogous patents were completed prior to executing the experiment. Selections of four (4) patents were chosen from each set of search results based on both near-field and far-field analogies to the design problem as given in Table 3 (Chan et al., 2011; Fu, Chan, et al., 2013). The patents are selected from the search engine results based on both the relevancy score as well as the analogical distance as evaluated by a subject-matter expert.

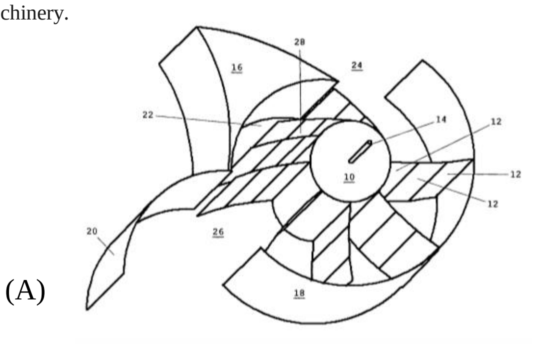
Table 3. Analogous Patents Determined Using Patent Search Tool

Group	Functionality Level of Analogies	Patent Title	Patent Number
Analogy Group 1	Single Sub-Function	Fuel injection apparatus having fuel pressurizing pump	5080079
		Inflating/deflating device for an inflatable air mattress	7571500
		Wireless communication device and signal receiving/transmitting method	7542009
		Paper guiding arrangement for a business machine	3567143
Analogy Group 2	Sub-Function Pair	Photovoltaic cell powered magnetic coil for operation of fluidic circuit flapper	3584636
		Virtual-wheeled vehicle	7588105
		Gray water interface valve systems and methods	7533426
		Air-blower tidal power generation device	7511386
Analogy Group 3	All Sub-Functions	Wave operated power apparatus	3603804
		System for recovering wasted energy from IC engine	7549412
		Method and device for capture, storage, and recirculation of heat energy	7549418
		Water current powered motor	7521816

Water Current Powered Motor

Abstract:

A water powered motor for extracting raw energy from a water current and converting it to kinetic energy. The water powered motor is generally rectangular in shape with a generally round water wheel consisting of foldable vanes. The vanes receive raw energy produced by water current transforming that raw energy into usable energy for powering a pump, electric generator or as a general power source to power other equipment such as desalinization machinery.



Virtual-Wheeled Vehicle

Abstract:

A virtual wheel provides a leg pair as a conveyance mechanism for a land vehicle. The virtual wheel propels the vehicle across a surface using a repetitive motion of the legs that contact the ground as would a wheel, due to their geometry. Vehicle embodiments include at least two-, three-, four- and six-wheeled vehicles, both transverse and in-line. Additionally, the invention provides a bipedal walking robot. One embodiment provides a robotic mule—a payload-carrying vehicle. The invention combines the flexible mobility of bipedal vehicles with the stability and functionality of very large-wheeled vehicles. Additionally, a bimodal conveyance mechanism readily converts between walking and rolling modes.

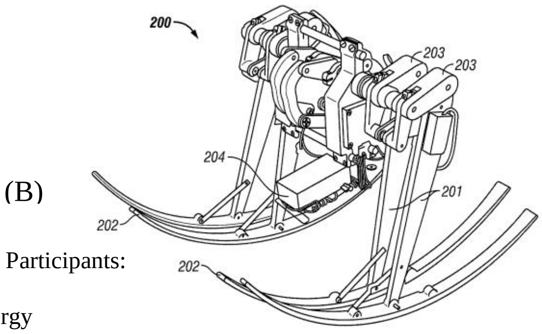


Figure 5. Example of Analogous Patent Presented to Analogy Group Participants:
A) Near-Field Analogy of Power Generator,
B) Far-Field Analogy of Mechanism to Import Human Energy

During Phase 2 of the experiment, the analogy groups were presented the 4 patents corresponding to their respective group and given 10 minutes to study the patents (Chan et al., 2011). They were given the patent abstract as well as a representative figure from the patent. The textual description and pictorial descriptions were intentionally given together to mitigate the influence of representation (J. Linsey, Clauss, E. F., Kurtoglu, T., Murphy, J. T., Wood, K. L., Markman, A. B. , 2011). An example of an analogous patent as presented to the analogy group participants is shown in Figure 5.

3.4 Metrics for Evaluation

Goals of the concept generation process include the generation of as many unique ideas as possible, and the discovery of novel concepts within the theoretical space of ideas. A great breadth of potential solutions spanning as much of the design space as possible increases the potential for successfully determining the "best" solution per a given set of selection criteria (Otto & Wood, 2001; Ullman, 2003; Ulrich & Eppinger, 2004). Although a single concept can readily be identified as a comprehensive solution to the given design problem, determining what constitutes a single idea is more difficult to define. Previous literature has established rules or heuristics for defining what constitutes an independent idea (J. S. Linsey, Green, M. G., Murphy, J. T., Wood, K. L., Markman, A. B. , 2005; J. J. Shah, Kulkarni, & Vargas-Hernández, 2000). Building on this knowledge base, the definition of an independent idea utilized in this study is a physical embodiment that solves one of the sub-functions listed previously. Furthermore, the solution must consist of a *how* and *what* couple, which satisfies the functional requirement of the corresponding sub-function, as well as defines the solution *flow* domain per the Functional basis framework (Hirtz, 2002). The *how* specifies the component of the solution that acts upon the flow, and the *what* defines the flow that is acted upon. For example, a solution for the flow independent function "Collect" would be "*air pressure* with *tank*" where the *how* is the "tank" collecting the "air pressure," and the air pressure is the *what* defining the specific flow domain as pneumatic potential energy. Following this definition scheme, the *Quantity of Ideas* metric is simply the sum total of unique ideas across all sub-functions for each participant.

The *Novelty of Ideas* metric was established as a measure of the rarity of a particular solution within each sub-function's design space. A complete design space for a particular function would be difficult to properly establish *a priori*, so an approximation was used which was defined as the initial set of solutions generated in Phase 1 for all participants. Novelty scores were computed for each sub-function solution using a formula utilized by Shah, et al. (J. J. Shah, Vargas-Hernandez, N., Smith, S. M. , 2003) and Chan, et al. (Chan et al., 2011):

$$N_i = \frac{T_i - C_i}{T_i} \qquad (1)$$

where T_i is the total number of unique solutions generated for sub-function i in Phase 1 across all participants, and C_i is the total number of solution tokens of the each solution in the first phase of ideation. The novelty score is a normalized value ranging from 0 to 1 for each idea. An example of the novelty scoring is given in Figure 6 for clarification.

Solutions generated in Phase 3 of the ideation process that did not occur in Phase 1 were given a novelty score of 1 since these concepts occurred outside the design space established prior to introduction of the patents in Phase 2. The final *Novelty of Ideas* score for each participant is the average of their sub-function novelty scores.

	Sub-Function 1			
	Solution 1	Solution 2	Solution 3	Solution 4
Participant 1	●		●	●
Participant 2	●	●		
Participant 3	●		●	
Novelty Score (N_1)	$\frac{7-3}{7} = 0.57$	$\frac{7-1}{7} = 0.86$	$\frac{7-2}{7} = 0.71$	$\frac{7-1}{7} = 0.86$

Figure 6. Example of Novelty Scoring Evaluation

4 Results

The experimental results for both the *Quantity of Ideas* and *Novelty of Ideas* are presented and discussed in the following sections. The statistical significance and implications of these results are reviewed with regard to the efficacy of the analogous patents on these metrics. The functionality level effects are reviewed to determine recommendations for analogy search strategies utilizing the Patent Analogy Search Tool.

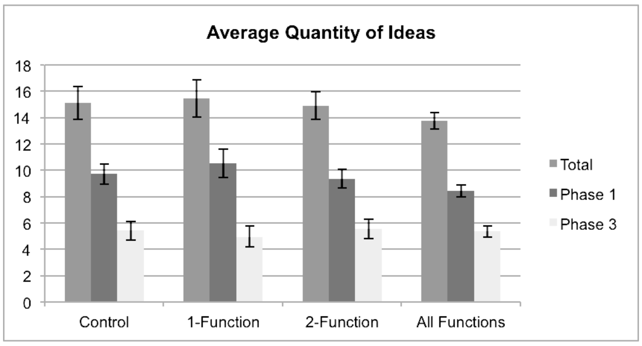


Figure 7. Average Quantity of Ideas Generated for Each Group, Error Bars Show +/- 1 Standard Error

The quality of the sketches and descriptors was fairly consistent across all participants with few exceptions of both higher and poorer quality. The poor quality sketches were difficult to score due to unclear intent, therefore a conservative approach was taken for all scoring to ensure only explicit solutions were counted, not interpreted solutions.

4.1 Quantity of Ideas

The average *Quantity of Ideas* for Phase 1 and Phase 3 combined was evaluated for each of the four experimental groups per the metric discussed in the previous section. The results for each ideation phase and the total *Quantity of Ideas* are given in Figure 7. The overall high number of ideas generated by the participants can be attributed to previous training in ideation techniques through their design methodology courses.

There is a consistent fall-off in the *Quantity of Ideas* generated from ideation Phases 1 and 3 across all groups. This result is in line with previous experimental data on ideation over time (J.S. Linsey, 2007). The total *Quantity of Ideas* was also remarkably consistent across all groups. The Student's t-test for difference in means between the control group and the analogy groups in Table 4 shows that there is no statistically significant difference between the groups.

Table 4. Quantity of Ideas Student's T-Test Results for Each Analogy Group Compared to Control Group

	Control	*1-Function*	*2-Functions*	*All Functions*
Mean	15.12	15.47	14.88	13.76
Variance	26.99	34.39	19.11	6.94
P(T<=t)		0.427	0.444	0.174

This result implies that the sets of patents and level of functionality of those sets of patents had no positive or negative effect on the *Quantity of Ideas* generated. Although the analogous patents do not increase the quantity of ideas, they also do not have a negative impact, such as reinforcing design fixation or unmanageably increased cognitive load, which would have a detrimental effect on the concept generation process.

4.2 Novelty of Ideas

The average novelty for each participant's ideas over the ideation Phases 1 and 3 was calculated per the *Novelty of Ideas* metric discussed in Section 3.4. The mean *Novelty of Ideas* and standard errors for each experimental group are derived as shown in Figure 8.

Upon initial inspection, the "All Functions" experimental group appears to have a larger mean and tighter distribution. The Student's t-test for difference in means was again used to determine whether a statistically significant difference in the mean group novelty score exists with respect to the control group. The results are given in Table 5.

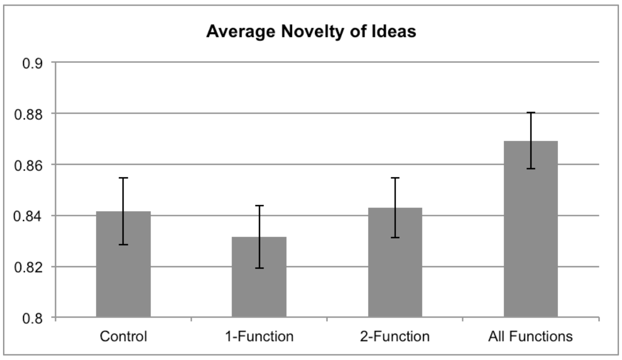


Figure 8. Average Novelty of Ideas Generated for Each Group across Phases 1 and 3, Error Bars Show +/- 1 Standard Error

Table 5. Novelty of Ideas Student T-Test Results for Each Analogy Group Compared to Control Group

	Control	*1-Function*	*2-Functions*	*All Functions*
Mean	0.8416	0.8316	0.8429	0.8892
Variance	0.0029	0.0025	0.0023	0.0021
P(T<=t)		0.291	0.470	0.048

The "All Functions" experimental group does have a statistically significant higher average *Novelty of Ideas* than the control group at the 95% confidence level. The other analogy groups do not have a statistically significant difference in means. This result tends to confirm the analogous patents can improve the *Novelty of Ideas* generated during concept generation, but this effect appears to be dependent on the functionality level of the analogy. To confirm this insight, the t-test was performed on the mean *Novelty of Ideas* between the analogy groups by comparing both the "1-Function" and "2-Functions" experimental groups to the "All Functions" group as shown in Table 6.

The "All Functions" experimental group has a statistically significant higher average *Novelty of Ideas* than the "2-Functions" experimental group at the 94% confidence level, and a statistically significant higher average *Novelty of Ideas* than the "1-Function" experimental group at the 98% confidence level.

Table 6. Novelty of Ideas Student T-Test Results within the Analogy Groups Compared with All Functions Group

	All Functions	*1-Function*	*2-Functions*
Mean	0.8892	0.8316	0.8429
Variance	0.0021	0.0025	0.0023
P(T<=t)		0.014	0.051

5 Discussion

The strong significant effect on novelty due to the functionality level of the analogies was not expected. This effect could be attributed to a number of possibilities, including: 1) the narrow focus of the 1- and 2-function analogies causes design fixation within the constricted design space of those sub-functions or 2) the participants have a greater difficulty mapping the analogies at the narrowly focused functional level and the analogies are more apparent at the higher functional level. The design fixation cause is contradicted by the quantity of ideas result which showed the overall number of unique ideas to be the same across all groups. That contradiction lends support for the analogy mapping difficulty theory, but additional experiments would be required to verify the phenomenon.

6 Conclusions

The experiment presented in this paper examines the efficacy of the Patent Analogy Search Tool for augmenting concept generation methods, specifically testing the effect of different levels of functionality of analogical stimuli given to designers and their effect on design outcomes. Level of functionality is defined to be how many sub-functions of the design problem at hand are addressed by the analogical stimuli, either from 1, 2, or 7 (all) subfunctions, with a control condition that receives no analogical stimuli, but instead a distracter newspaper article. The results of the experiment garnered several significant insights. The first insight is that analogical patents have no impact on the total quantity of unique ideas generated. The significance of this finding is that the introduction of analogous patent examples does not have a detrimental effect on concept generation through the phenomenon of design fixation.

The most important result supporting the efficacy of the Patent Analogy Search Tool is the significant effect of increased average *Novelty of Ideas* for the high functionality level analogy group. The “All Functions” group had a 5% higher average *Novelty of Ideas* rating than either the control group or the other analogy groups. This level of performance increase could justify the inclusion of the Patent Analogy Search Tool into the toolbox for concept generation processes. Further experimentation should be conducted as part of the future work to identify the root cause of the functionality level effect. In the meantime, a high level, multi-function representation of the design problem should be used for search query generation to obtain the best possible performance from the search tool. This finding is in agreement with the results of the case studies presented in Murphy’s work (J. T. Murphy, 2011), which concluded that using multiple searches rather than using multiple secondary functions maximizes the functional relevancy resolution. The next phase of experimental studies will investigate the performance of the Patent Analogy Search Engine compared to alternative Design-by-Analogy methods, such as the Wordnet procedure (J.S. Linsey, 2007).

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