Res Eng Design
DOI 10.1007/s00163-014-0186-4

ORIGINAL PAPER

Design-by-analogy: experimental evaluation of a functional analogy search methodology for concept generation improvement

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Received: 27 November 2013 / Revised: 20 October 2014 / Accepted: 5 November 2014

Abstract Design-by-analogy is a growing field of study and practice, due to its power to augment and extend traditional concept generation methods by expanding the set of generated ideas using similarity relationships from solutions to analogous problems. This paper presents the results of experimentally testing a new method for extracting functional analogies from general data sources, such as patent databases, to assist designers in systematically seeking and identifying analogies. In summary, the approach produces significantly improved results on the novelty of solutions generated and no significant change in the total quantity of solutions generated. Computationally, this design-by-analogy facilitation methodology uses a novel functional vector space representation to quantify the functional similarity between represented design problems and, in this case, patent descriptions of products. The mapping of the patents into the functional analogous words enables the generation of functionally relevant novel ideas that can be customized in various ways. Overall, this approach provides functionally relevant novel sources of design-by-analogy inspiration to designers and design teams.

Keywords Design-by-analogy · Function-based analogy · Design cognition

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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, or more generally, computer-based or computer-assisted synthesis (Chakrabarti et al. 2011). The goal was 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 nonobvious analogies. Through this approach, we seek to assist designers in developing innovative conceptual designs.

The functional vector space model-based (VSM) analogy search engine was developed in prior work by the authors (Murphy 2011; Murphy et al. 2014). The process begins with constructing a controlled and converged vocabulary of functions extracted from a patent database, building on the hierarchical structure of a *functional basis*, as inspired by the functional modeling approach of Pahl and Beitz (Hirtz et al. 2002; Otto and Wood 2001; Stone and Wood 2000; Pahl and Beitz 1996), and five categorical functions of which all functions are more specific instances. This approach provides a natural abstraction mechanism for analogies that is likely already familiar to an engineering designer. The patent documents are indexed against the functions listed in the patent documents, sorted by the functional basis. This creates a vector representation of the patent database based on functions. Query generation and similarity ranking tools are then used 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

Published online: 19 November 2014

details of the methodology can be found in (Murphy 2011; Murphy et al. 2014).

The purpose of this study was to evaluate the effectiveness of the patent-based functional analogy search methodology on a real-world design problem 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 functional analogy search algorithm embedded in a formalized patent based methodology, can lead to the identification of nonobvious analogies for design concept generation. Doing so within the conceptual design process will improve ideation as measured by quantity or novelty of ideas.

In the next sections, we review related works and concepts of functional modeling, analogical reasoning, and patent database research. Then, in Sect. 3, we present the major findings of our work on the efficacy of the patent-based functional analogy search methodology to improve conceptual design outcomes.

2 Background

2.1 Concept generation using design-by-analogy

Design-by-analogy has been shown to be an effective means in achieving innovation and novelty in design outcomes, where one such approach is the use of functional analogies (Chan et al. 2011; Linsey et al. 2008). The following sections review function representations and functional modeling and their roles in design-by-analogy. The related works in design-by-analogy will be discussed, followed by discussion of related work in patent analysis in conceptual design.

2.1.1 Functional modeling

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 (Otto and Wood 2001; Pahl and Beitz 1996; Chakrabarti and Bligh 2001). *Functional modeling,* or the process of developing functional representations 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 subfunctions, which are connected by flows of information, material, and/or energy, thereby creating a repeatable *function structure* representing the internal functionality of concept technical system (Kurfman et al. 2003). The functional model for a given system can take a number of different forms, depending on the choices made about inputs and underlying physical processes, such as the user interface and/or alternative representations of user activities associated with the problem/concept (Otto and Wood 2001). Otto and Wood provide a basic tutorial and guide on functional modeling in conceptual design (Otto and Wood 2001).

In order to standardize the language for the process of functional modeling and the representation of functions and flows that correspond to each subfunction, an extended *functional basis* approach from Pahl and Beitz's original five categorical functions is used here (Hirtz et al. 2002; Stone and Wood 2000; Pahl and Beitz 1996). All functions have been shown to be instances of abstract function classes, thereby providing a hierarchy of functions naturally intuitive to engineers. Function words and flow words combine to create verb–object couples, which describe the action conveyed on the input flows of each identified subfunction, 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, therefore, for our purposes here, 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 (Stone and Wood 2000), allowing for simplification of the model, and/or discovery of opportunities to improve manufacturability, maintainability, and reliability early in the design process through function sharing and proper interface design (Salonen et al. 2008). 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 (Szykman et al. 1999, 2000; Bohm et al. 2005, 2008). Computational design tools have been developed to use the design knowledge contained in these functional repositories for concept variant generation techniques (Terpenny and Mathew 2004; Potter et al. 2003; Hölttä-Otto et al. 2008; Van Wie et al. 2005; Kurtoglu et al. 2009).

A drawback of using the functional modeling approach of Otto and Wood (2001) is that it starts with flow variables. This requires process choices about the inputs and outputs be made early, which can be constraining and limiting. This limitation can lead to missed opportunities for innovation and novel designs. However, this issue can be remedied by approaching functional modeling from a broader perspective in terms of user and environmental functions and apply alternative process choices at higher levels of abstraction in a functional hierarchy (Otto and Wood 2001). It is therefore hypothesized that creating abstracted functional models of concepts that can be abstracted and detailed to permit comparison of the similarities between functionality can lead to the identification of analogous concepts that are vastly different in form.

2.1.2 Design-by-analogy

Facilitating design-by-analogy through computational aids is a diverse and well-explored area of research. Here, we review a subset from three areas: generalized semantic analysis-based tools, design-by-analogy tools, and methods that employ formal model bases.

On the semantic analysis front, Shu et al. developed a systematic process for identifying analogous biological phenomena and using biomimetic principles for generating concepts (Hacco and Shu 2002). Keywords were derived that relate 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. We take a similar approach here, but with function and patent concepts. In similar work by Yang et al. (2005), thesauri were developed using information retrieval from informal design documentation, for reuse in the design process This work was built on the DedalAI system to automatically index design concepts in electronic notebooks for retrieval and reuse (Yang et al. 2005). In both these cases, functionality is developed from documentation, similar to our work here, but it has not focused on patents as means to generate new concepts, and does not generate a hierarchical functional vocabulary from the underlying dataset.

On the design-by-analogy front, Linsey et al. (2012), Segers et al. (2005), and Verhaegen et al. (2011) develop approaches to analogical retrieval and reasoning through linguistic (semantic word) associations, problem re-representation, and mappings. Shai and Reich (Reich and Shai 2012; Shai and Reich 2004) developed approaches to analogical retrieval of knowledge structures and processes that allow the use of across domains. 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). A computational tool developed by Liu et al. (2000, 2003) called FunSION takes qualitative functional input and output requirements, and generates physical embodiments of design solutions. A Web-based tool was developed by Charlton and Wallace for finding preexisting engineering components for reuse in nonstandard applications in new designs to reduce manufacturing costs (Charlton and Wallace 2000). These works again do not focus on patents as a means of concept generation.

As for formal model-based tools, a system called KRITIK that was developed by Goel et al. (1997) autonomously generates new conceptual designs based on a case library of previously existing designs using functional modeling and functional indexing. IDeAL was created by Bhatta et al. which uses a structure–behavior–function model-based approach to design-by-analogy through pattern finding, constraint analysis, and problem reformulation (Goel and Bhatta 2004; Bhatta et al. 1994). A case-based reasoning tool called CADET was developed by Sycara et al. (1991) to better retrieve and synthesize case design components for more effective combination. An exploration medium for between-domain analogies using design function–behavior–structure design prototypes was created by Qian and Gero (1992). 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. (Chakrabarti et al. 2005; Chakrabarti 2000). These works do form a hierarchical functional vocabulary of varying depth and completeness, and they do consider an underlying set of design concepts. None compare with the breadth here covering the US Patent database.

All of these works are creative and useful developments in design-by-analogy. Our work lies at the cross section of the categories discussed above, as we combine the computational semantic analysis with the formal model-based techniques. Overall, unexplored in the previous work is the use of hierarchically abstracted functional modeling and terms to index and sort patent documents as a means of enhancing conceptual design. In the next section, we review patent analysis efforts that are more directly related to this opportunity.

2.1.3 Patent analysis

Patent databases are attractive sources of analogies and concepts that can lead to innovative solutions (Kang et al. 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 nonobvious 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 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 et al. 2007); similar 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 to overcome impasses in functional reasoning based on early studies of patents in terms of contradictions (Altshuller and Shapiro 1956; Altshuller et al. 1985), is the foundation of many of these design tools. For example, Zhang et al. (2007) created an axiomatic conceptual design model by combining TRIZ and the functional basis work. Cascini and Russo (2007) presented a way to automatically identify the contradiction underlying a given technical system using textual analysis of patents for use in TRIZ. Souili et al. developed a method using linguistic markers to identify relevant candidates for TRIZ automatically (Souili et al. 2011; Souili and Cavallucci 2012). Additionally, Nix et al. undertake the task of correlating the functional basis with the forty inventive design conflict resolution principles (Nix 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 preexisting knowledge within a domain, Souili et al. use patent citations in mining the data (Chakrabarti et al. 1993). Kasravi et al. and Indukuri et al. 2007 have aims in patent mining research to judge possible future market trends, identifying prolific inventors, and other business applications, using meta-data such as the number of citations, number of claims, average number of words per claim, and number of classes that the patent spans (Kasravi and Risov 2007).

Patent mapping is another area of research that attempts to extract information from the vast database. A method has been developed to extract inherent structure in textual patent data for both studying and supporting design-by-analogy (Fu 2012; Fu et al. 2013a, b). More generally, Szykman et al. (2000) have used design repositories (not specific to patents) to share and reuse elements of designs in the development of large scale or complex engineering systems. Koch et al. (2011) developed PatViz, which enables visual exploration of queries and complex patent searches using diverse types of patent data through user-created graph views (Koch et al. 2011). With the intention of patent infringement avoidance, Mukherjea et al. (2005) used a semantic Web to find semantic associations between important biological terms within biomedical patents. Chakrabarti et al. (1998) created a taxonomy/hierarchical structure using a topic model to analyze patent data. Work by Cascini and Zini (2008) uncovers patent similarity through comparison of their functional hierarchical trees, different from our work in that its motivation is driven by plagiarism detection and focuses on thesauri as its main driving computational foundation. Fantoni et al. (2013) base their patent similarity analysis on function–behavior–structure models and incorporate multiple parts of speech for syntactic analysis of the patent text. Goldfire by Invention Machine, a commercially available patent exploration tool, focuses on the goal of understanding competitive landscapes and new areas for technological development, as opposed to facilitating design-by-analogy through function-based cross-domain transfer of knowledge (Goldfire 2012). The main difference between these aforementioned research efforts and our work is our employment of Zipf's law and the functional basis to achieve a similarity and relevance evaluation that relies on a static, converged, computationally derived functional vocabulary for the patent database (Murphy et al. 2014). This approach allows for clearer disambiguation to distinguish the different meanings of polysemes. When compared to Zipf's law, three different regimes of function frequency distribution can be identified and 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 Law theory. These functions can be considered to lie above the upper cutoff chosen to be all terms that occur in more than 50 % of patents. Examples of these functions are provide, use, etc. The ubiquitous functions, which account for 50 of the 1,700 terms, are to be removed from the final function vocabulary index. This step removes highly ambiguous verbs.

Although the US patent database is fertile to support design-by-analogy, the magnitude and complexity make it very challenging to access in a top–down way. Theories like TRIZ and their resulting tools have attempted to address this (Altshuller and Shapiro 1956; Altshuller et al. 1985; Zhang et al. 2007; Nix 2011; Goldfire 2012; Duran-Novoa et al. 2011; Krasnoslobodtsev and Langevin 2005; Nakagawa 2012; Houssin and Coulibaly 2011; Mann et al. 2003; CREAX. (September 7, 2012); Hernandez et al. 2013; Liang et al. 2013), along with many more research-driven tools and methods (Verhaegen et al. 2011; Goel et al. 1997; Bhatta and Goel 1996; Vincent et al. 2006; Chiu and Shu 2007). However, much of this previous work often relies deeply on users/designers to create their own analogies, or search through large, unstructured quantities of results with little indication of relevance. We attempt to address this gap with the patent-based functional analogy methodology described next in Sect. 2.2. Testing the efficacy of this methodology in conceptual design is presented in Sect. 3.

2.2 Patent-based functional analogy search methodology

Figure 1 shows the overview of the five-part process that comprises the patent-based functional analogy search methodology, which is the 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 briefly describes each of these five steps to supply background on the selection of the external stimuli for the experiment described in this paper.

The first step of the five-part process involves retrieving the design document (patent) information in the form of text, parsing that text, and then implementing tokenizing, or breaking down passages of text into their individual words or "tokens," and word stemming, or reducing words to their base or root form. Sets of patents were randomly selected from the USPTO patent database of 4 million records until convergence of the functional vocabulary was reached (described below). After the third set was selected, the total number of indexed patents reached 65,000, and convergence of the functional vocabulary was achieved at 61,000 patents. The vector space model (VSM) of information retrieval is used, in which a document is represented as a vector of terms. The terms are words and/or phrases extracted from the documents themselves using natural language processing techniques (van Rijsbergen 1979; Rindflesch 1996). To represent a document as a vector of terms, each term in the vocabulary becomes an independent dimension in an n-dimensional space, where n is the number of vocabulary terms. All of the documents in the database are mapped onto the vector space using

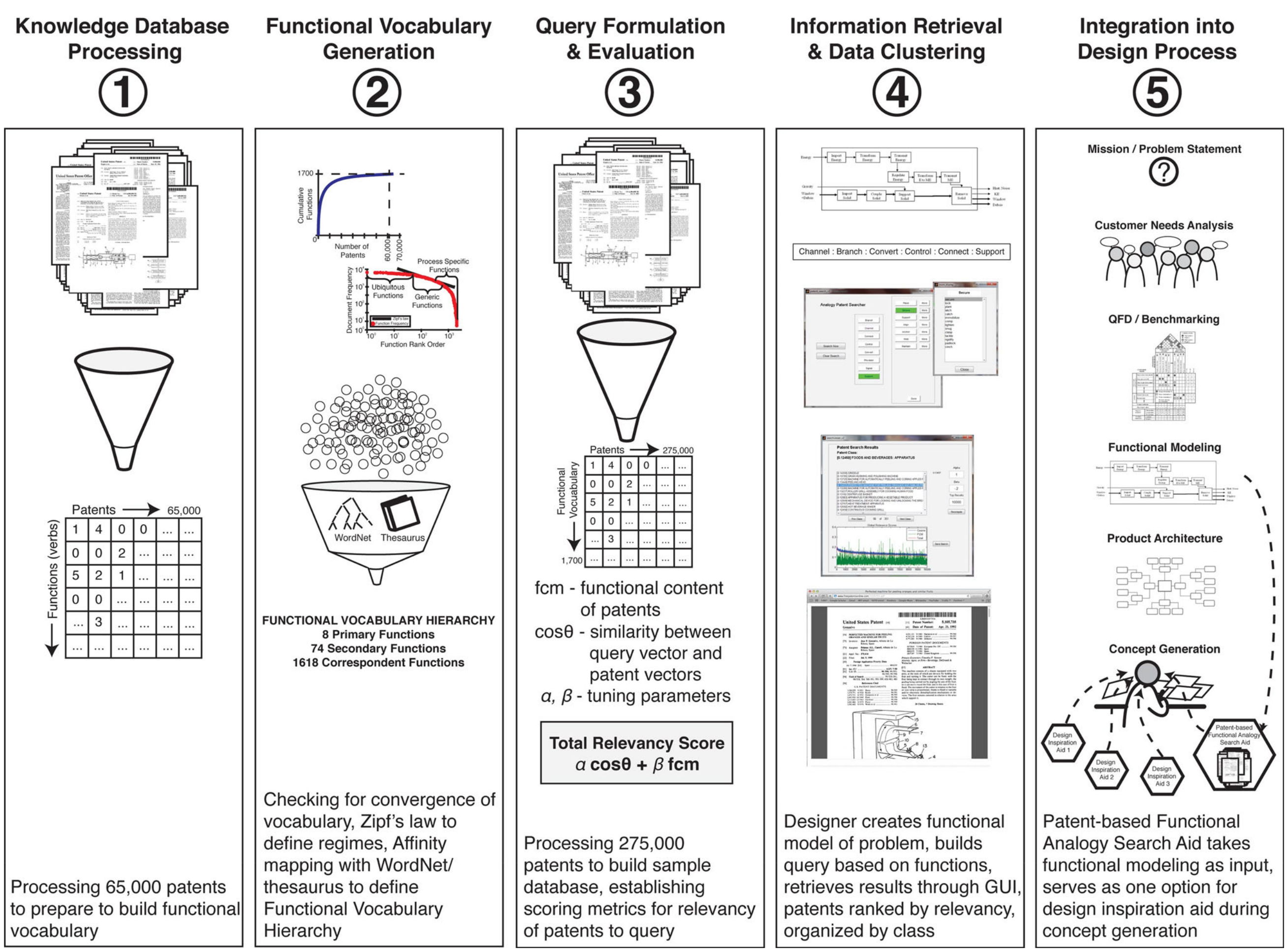

Fig. 1 Overview of the patent-based functional analogy search development

indexing algorithms. Issues of polysemy, where a word has multiple meanings, and synonymy, where multiple words have the same meaning, are overcome through query mapping heuristics using one-to-many term mapping; in other words, query mapping rules are devised such that a single query term is mapped to multiple document terms, allowing for a simplified query to capture a range of patents that possess the same general functionality.

After indexing the set of 65,000 patents, the second step in the development of methodology is the functional vocabulary generation, in which we identified and extracted 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*. *Cumulative functions* plotted versus *number of patents indexed* illustrates that the metric reached a horizontal asymptote of 1,700 functions, and furthermore, convergence was reached at approximately 61,000 patents. This asymptote provides a verification that the function vocabulary does in fact converge to a finite set. The set of 1,700 functions are then sorted using affinity mapping with WordNet (Fellbaum 1998; Miller 1995) and a thesaurus, into a functional vocabulary hierarchy of 8 primary functions, 74 secondary functions with <50 correspondent functions associated with each secondary function.

The third step of the methodology was to formulate the means to query the database of patents and functions. Query formulation and evaluation involves creating a sample patent database of 275,000 patents—the whole of the patent database was not indexed, as this was an example implementation of the methodology; next, the definition of how to build query vectors for chosen primary and secondary functions with a graphical user interface is established; then, a relevancy scoring for any patent in the database to a given functional query based on two calculated components: (1) the *functional content metric (fcm)*, which measures how functionally rich (how many functions/subfunctions are addressed relative to the entire database) a given patent is, and (2) the *inverse document frequency (idf) weighted cosine similarity* between the user-specified query vector and the patent document vectors in the sample database.

Once the query construction is complete, the fourth step is the information retrieval and clustering task. Information retrieval and data clustering involves entering desired primary and secondary functions into the query generator as abstracted and specified by the designer from their given design problem; next, it involves exploring the top 500 patents (a value that can be changed and was chosen here as a reasonable cutoff for number of results to retrieve) identified by the patent-based functional analogy search methodology in a search result viewer as clustered by USPTO patent class; and finally, it requires viewing the patents of interest in PDF format using an online patent database Web site.

The last step of the research is to make use of the resulting patents presented as a design inspiration aid within the design process. Integration into the design process, depicted in Fig. 2, involves input from designer-generated functional modeling of design problem into the patent-based functional analogy search. The identified patent-based functional analogies can be used as one of many possible design inspiration methods/aids during the concept generation phase of the design process. The analogy search method outlined in this section is now applied to choose analogical stimuli for the experiment presented in this paper. For further technical details of this tool, see (Murphy 2011).

Given this background and literature, we focus here on studying how functional modeling and patent data analysis can be effectively combined into a novel analogy based, computationally supported concept generation support methodology. In the next section, we present the details of our comparison and efficacy testing.

3 Experimental method

An experiment is conducted to evaluate the efficacy of the patent-based functional analogy search methodology to complement the concept generation phase of the design process. The hypothesis to be tested is whether the approach improves the ideation result as measured by novelty or quantity of ideas. More specifically, the process shown in Fig. 2 is compared with and without the analogical search steps. A control group executed the process with a distraction activity of reading an unrelated article between two phases of ideation on the design problem; this activity was meant to dissuade or prevent control group participants from continuing to solve the design problem actively during this time. An analogy group examined identified functional analogies between two phases of ideation.

The 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 subfunction versus all subfunctions. Three levels of functionality are chosen for the analogy groups as shown in Table 1. Further description of the design problem used in the experiment, as well as the specific subfunctions chosen for each condition, is described next in Sects. 3.2 and 3.3.

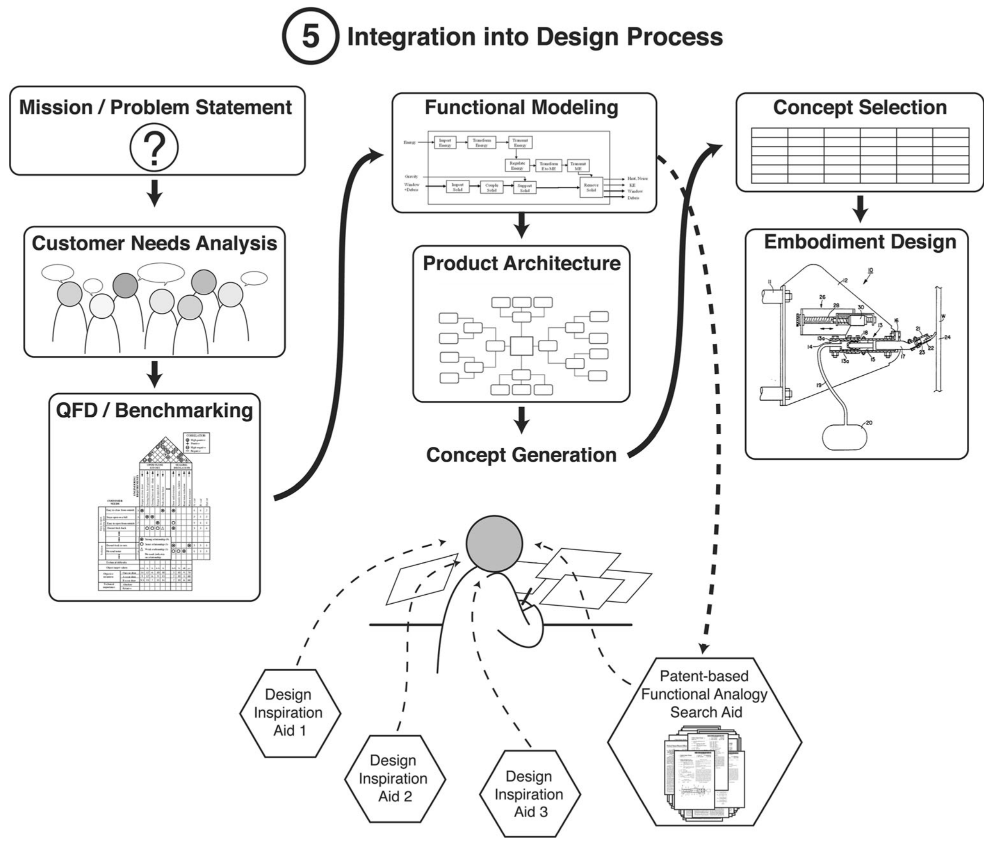

Fig. 2 Integration into design process involves input from user-generated functional modeling of design problem into patent analogy search, use as one of many possible design inspiration methods/aids during concept generation

Table 1 Functionality level of analogy distribution among treatment groups and control

Group	Functionality level of analogies
Control	None
Analogy Group 1	Single subfunction
Analogy Group 2	Subfunction pair
Analogy Group 3	All subfunction

The analogy and control groups participated in a three-phase ideation process. Phase 1 consists of a 10-min concept generation process, which is common to all treatment groups and the control group. This initial ideation phase was included to establish "open goals" in the participants' minds with respect to the given design problem, which has been shown by Moss et al. (2007) to allow them to more easily and aptly apply potentially useful external information that may be relevant to solving the design problem. 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. The primary purpose of this study, in addition to the validation of the computational methodology described in Sect. 2.2, was to test the cognitive effect of introducing analogous patents versus the unrelated distracter document on the concept generation process. Phase 2 is followed by a second 10-min concept generation phase to record any additional unique solutions. The experimental workflow is illustrated in Fig. 3. All groups are given the same total length of time for concept generation.

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, co-ops, etc. The relative uniformity across education and

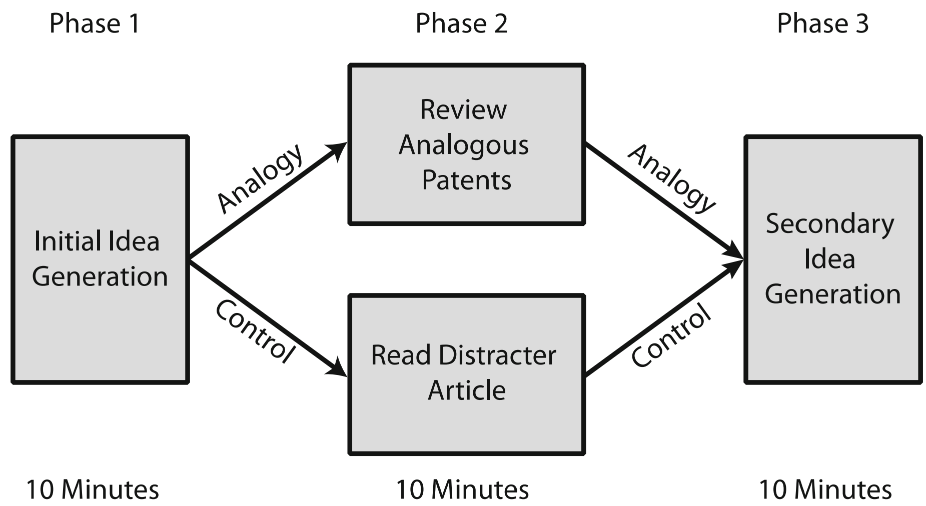

Fig. 3 Experimental workflow comparison for treatment versus control groups

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.

Fig. 4 Design problem statement and concept recording instructions

knowledge will minimize the variation between individuals during concept generation due to prior experience. As a result, main and secondary effects of the treatment 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 treatment groups or the control group 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 or C-Sketch process (Vangundy 1988).

3.2 Design problem description

The design problem provided 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 Fig. 4. No further constraints or clarification regarding the design embodiment were 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 has been used in similar earlier studies (Chan et al. 2011; Fu et al. 2013a, b).

3.3 Description of analogous patents selection

The analogous patents utilized by the treatment analogy groups were found using the patent search methodology described in Sect. 2. The subfunctions used in each search were derived from the subfunctions required to fulfill the design problem functional requirements and constraints. The list of the design problem subfunctions is

- Import
- Convert/transform
- Transport
- Move/rotate/oscillate
- Collect
- Produce
- Export/supply

Acceptable solutions and analogies include any and/or all combinations of alternate subfunctions. The specific subfunctions 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 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 2 Functions searched for each analogy group

Group	Functionality level of analogies	Search function
Analogy Group 1	Single subfunction	Import
Analogy Group 2	Subfunction pair	Import, convert
Analogy Group 3	All subfunction	Import, convert/transform, transport, move/rotate/oscillate, produce, collect, export/supply

During Phase 2 of the experiment, the analogy groups were presented the four patents corresponding to their respective group and given 10 min 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 (Linsey et al. 2011). An example of an analogous patent as presented to the analogy group participants is shown in Fig. 5.

3.4 Metrics for evaluation

Goals of concept generation include generating as many unique ideas as possible and discovering novel concepts within the theoretical space of ideas. Increasing the breadth of potential solutions to span as much of the design space as possible increases the potential for successfully determining preferred and innovative solutions per a given set of selection criteria (Otto and Wood 2001; Ullman 2003; Ulrich and 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. Shah et al. (2000); Linsey et al. (2011) and Oman et al. (2012) have established rules or heuristics for defining what constitutes an independent idea. Building on this knowledge base, the definition of an independent idea utilized in this study is a physical embodiment that solves one of the subfunctions listed previously. Furthermore, the solution must consist of a *how* and *what* couple, which satisfies the functional requirement of the corresponding subfunction, as well as defines the solution *flow* domain per the functional basis framework (Hirtz et al. 2002). The *how* specifies the

Table 3 Analogous patents determined using patent-based functional analogy search

Group	Functionality level of analogies	Patent title	Patent number
Analogy Group 1	Single subfunction	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	Subfunction pair	Photovoltaic cell-powered magnetic coil for the 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 subfunctions	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

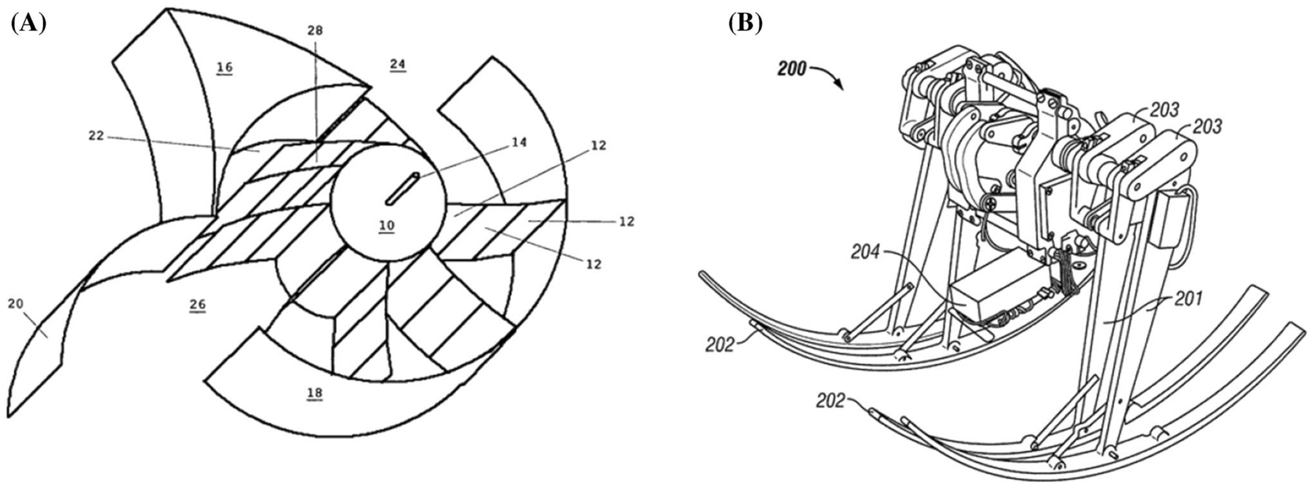

Fig. 5 Example of analogous patent presented to analogy group participants: **a** near-field analogy of power generator, **b** far-field analogy of mechanism to import human energy

Table 4 Example of novelty scoring evaluation

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

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 subfunctions for each participant.

The *novelty of ideas* metric was established as a measure of the rarity of a particular solution within each subfunction'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 subfunction solution using a formula utilized by Shah et al. (2003) and Chan et al. (2011):

$$N_i = \frac{T_i - C_i}{T_i} \tag{1}$$

where T_i is the total number of unique solutions generated for subfunction 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 Table 4 for clarification.

For all conditions including the control, 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 subfunction novelty scores.

It is important to note that although quality of the concepts produced by participants was not explicitly evaluated, quality has been shown to correlate with quantity and novelty in many published studies similar to the work presented here. In fact, a previous study with the same experimental problem and participant pool type demonstrated a correlation of sufficient quality, or, in certain cases, improved quality, when there existed an increase in novelty (Chan et al. 2011).

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-based functional analogy search methodology. Figure 6 illustrates a typical result from an ideation phase.

The quality of the sketches and descriptors was fairly consistent across all participants, with few exceptions of

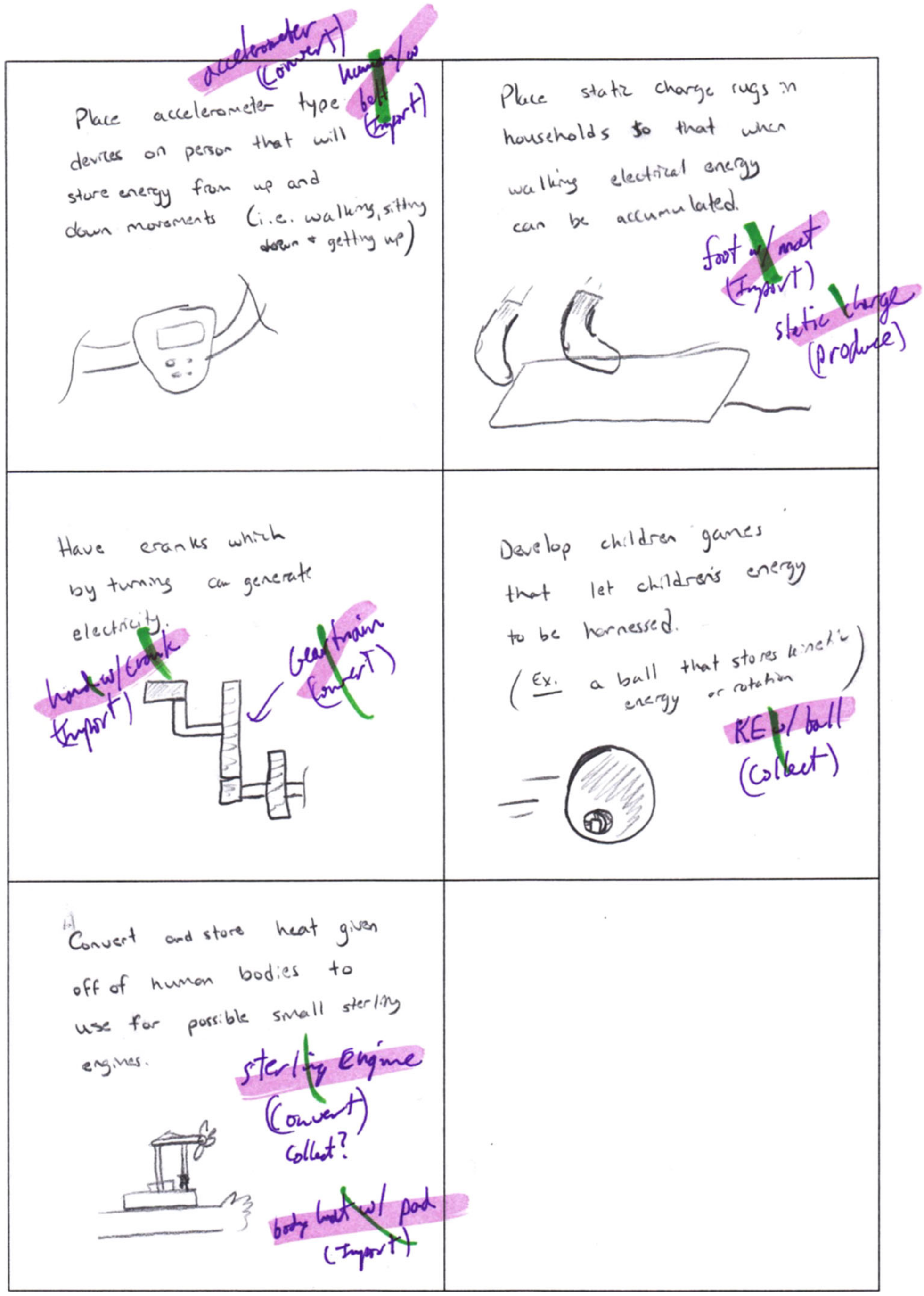

Fig. 6 Example of ideation sheet with marked up ideas

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 three treatment groups and control group per the metric discussed in the previous section. The results for each ideation phase and the total *quantity of ideas* are given in Fig. 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 falloff in the *quantity of ideas* generated from ideation Phases 1 and 3. This result is in line with previous experimental data on ideation over time (Linsey et al. 2008; Linsey 2007). The total *quantity of*

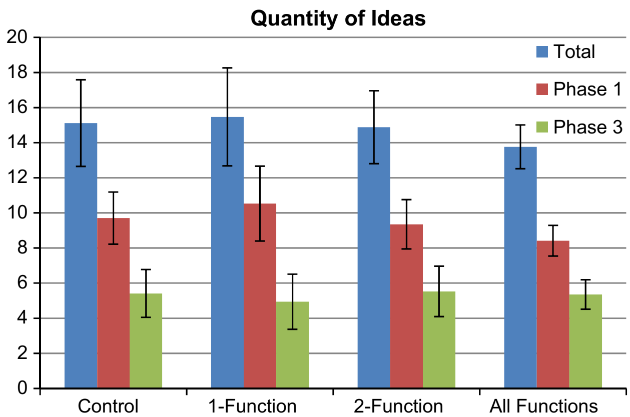

Fig. 7 Average quantity of ideas generated for each group error bars show 95 % confidence interval

Table 5 Quantity of ideas Student's *t* test results for each analogy group compared to control group

	Average	SD	*N*	*t*	*P*
Control	15.12	5.19	17		
1-Function	15.46	5.86	17	0.186	0.427
2-Function	14.88	4.37	17	−0.143	0.444
All Functions	13.76	2.63	17	−0.958	0.174

ideas was also remarkably consistent. The Student's *t* test for difference in means between the control group and the analogy groups in Table 5 shows that there is no statistically significant difference between the groups.

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

In Fig. 8, three solutions are shown which are derived from analogies extracted from the patents given in Phase 2. In Fig. 8a, a novel solution for importing kinetic energy from humans is derived from a patent for importing wave motion. The floating bridge utilizes functional similarity to extract the energy from humans crossing the river. In Fig. 8b, a novel solution for converting energy is shown derived from the analogy of the wireless antenna. Wireless power transmission and conversion eliminates the need for local generation and storage, although many other feasibility issues such as signal attenuation limit the practicality of this solution. Finally, in Fig. 8c, the patent solution is mapped between similar domains as a near-field analogy. The ocean wave power-harnessing solution is adapted to extract energy from the lower-amplitude waves generated in river systems. These examples are typical of the novel solutions generated as a result of the introduction of analogous patent.

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 Sect. 3.4. The mean *novelty of ideas* and standard errors for each treatment group are derived as shown in Fig. 9.

Upon initial inspection, the "All Functions" treatment 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 6, indicating a significant shift in novelty.

The "All Functions" treatment 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 that 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 treatment groups to the All Functions group as shown in Table 7.

The All Functions treatment group has a statistically significant higher average *novelty of ideas* than the 2-Functions treatment group at the 94 % confidence level, and a statistically significant higher average *novelty of ideas* than the 1-Function treatment group at the 98 % confidence level.

5 Discussion

As stated previously, there was no significant negative or positive effect of level of functionality across all conditions on *quantity of ideas,* which may indicate that the additional cognitive load required to process the analogical stimuli, abstract, and transfer the analogical content, could be canceling out any positive effects of the stimuli itself on fluency of ideas. It is interesting to consider how to reduce the cognitive load required to process the analogical stimuli in order to see greater net benefits of the tool/method. For example, as Linsey et al. (2008) have shown, seeing a functional model of the patent chosen for analogical stimuli, or seeing multiple representations, such as a

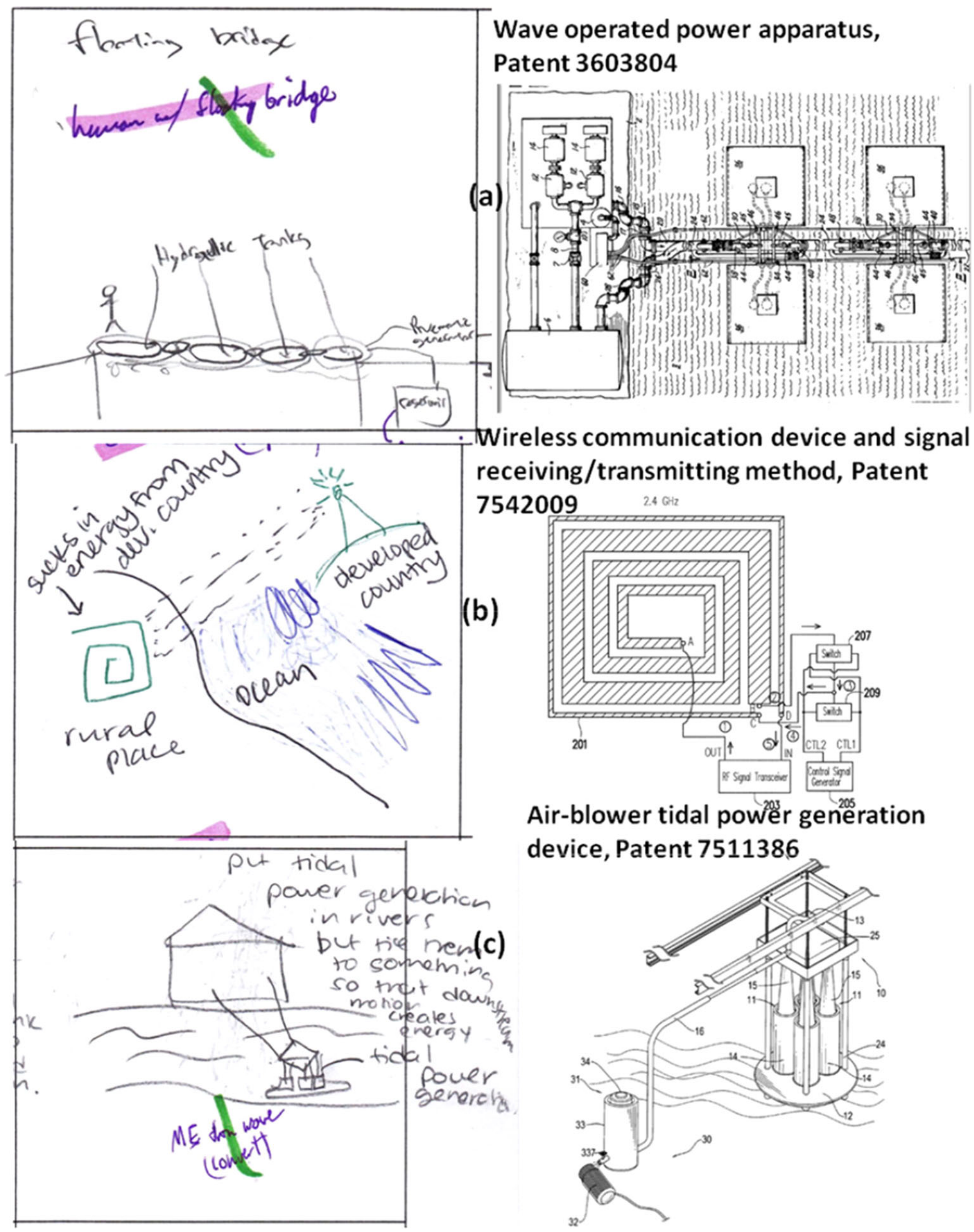

Fig. 8 Sample solutions from each of the three analogy groups showing novel solutions derived from a patent: **a** all functions group—floating bridge, **b** single function group—energy-harvesting antenna, **c** function pair group—river power extraction device

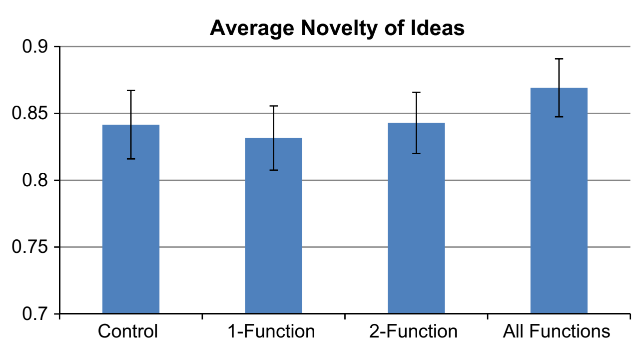

Fig. 9 Average novelty of ideas generated for each group across Phases 1 and 3, *error bars* show 95 % confidence interval

Table 6 Novelty of ideas Student's *t* test results for each analogy group compared to control group

	Average	SD	*N*	*t*	*P*
Control	0.8416	0.0538	17		
1-Function	0.8316	0.0505	17	−0.556	0.291
2-Function	0.8429	0.0481	17	0.075	0.470
All Functions	0.8892	0.0455	17	1.613	0.048

physical manifestation, sketch, and semantic description of the artifact described in the patent, can lead to greater success in analogical transfer. Perhaps, there are other

Table 7 Novelty of ideas Student's *t* test results within the analogy groups compared with all functions group

	Average	SD	*N*	*T*	*P*
1-Function	0.8316	0.0505	17	−2.276	0.014
2-Function	0.8429	0.0481	17	−1.634	0.056
All Functions	0.8892	0.0455	17		

methods yet to be explored for understanding the functionality of the patent technology without having to read highly technical patent content/figures that may lead to lower cognitive load in processing analogies. This question could be addressed in future studies.

The strong significant effect on *novelty of ideas* due to the functionality level of the analogies was not expected. To reiterate, the results indicate the All Functions condition achieved statistically significant higher levels of *novelty of ideas* than the other functionality levels (1-Function and 2-Functions) and the control condition. We explore some possible theories to explain this effect, which remain open questions and could be tested with further experimentation.

Threshold of "open goals": One possibility for the lower levels of *novelty of ideas* in the control and 1-Function and 2-Functions conditions employs the concept of open goals, or unsolved problems that people keep in mind once they have been exposed to a design problem until it is solved (Moss et al. 2007; Tseng et al. 2008). Perhaps, the exposure to analogical stimuli creates a set of open goals in a designer's mind that align with or correspond to the functionality and subfunctionalities of that stimuli. As she processes and attempts to solve a design problem after being exposed to this analogical stimuli, she can keep a certain number of ideas or open goals in her short-term memory; perhaps, the effect we are seeing is that we have not yet reached the maximum threshold for number of functionalities and subsequent open goals able to be kept in mind during ideation. Thus, more functions are better, up to the point that has been tested in this experiment, which are 7 subfunctions.

Narrowed scope of design space: It could be that the narrow focus of the 1-Function and 2-Functions analogies causes design fixation, constricting the design space through the implied scope of the stimuli, which is limited to just those 1 or 2 subfunctions. This phenomenon has been observed previously in work with good and poor example solutions, in which the good example solution did not address a subfunction of the design problem, and all participants did not include that subfunction in any of their solutions, while those in the poor example condition and control condition did include the subfunction (Fu et al. 2010). Fixation can occur not only with respect to specific feature transfer, but also with the exclusion of specific functionality through fixation on the implied scope of the design problem in external analogical stimuli. The design fixation theory is contradicted by the *quantity of ideas* result, which showed the overall number of unique ideas to be the same across all groups—though this could be confounded by other factors like cognitive load, etc.

Full functionality points to (holistic) system level of design, limited functionality points to limited scope of problem: Similar to the previous theory, it could be that the All Functions analogical stimuli allow for designers to frame and approach the design problem from a more holistic or system-level standpoint, which may or may not allow lead to more novel designs. Again, the limited functionality of the 1-Function and 2-Functions stimuli might have limited the participants to design more at the subfunction or subsystem level, potentially keeping them from seeing the big picture or addressing all functions in novel ways.

Difficulty in mapping narrow functionality: Similar to the concept of the constricted design space, another theory is that the participants have greater difficulty mapping the analogies at the narrowly focused functional level. It could be that analogical transfer is easier or more apparent at the higher functional level.

More functionality = more opportunity for analogical transfer: From a purely combinatoric viewpoint, it could simply be that the more functionality that is addressed in the analogical stimuli, the more opportunities there are for analogical transfer to occur from that stimuli to potential design concepts. There is likely a limit at which a designer will become overwhelmed by too many subfunctions, so this combinatoric theory has limits; however, there is potential for support of this combinatoric framework through computational assistance, such as in A-Design (Campbell et al. 1999, 2003).

Potential "sweet spot" in level of functionality: Building off the previous theory, it could be that similar to the suggestion of a "sweet spot" of distance of analogy from the design problem (Fu et al. 2013), there is "sweet spot" of level of functionality of analogy. If it is too simple, a designer might trivialize the stimuli or disregard it as not useful; if it is too complex, a designer may not be able to handle it or process it; if it is in prime place between these two ends of the spectrum, designers may perform best.

These theories of explanation for the increased *novelty of ideas* in the All Functions condition raise many interesting areas for further exploration of how designers think about, interact with, and use analogies during ideation. While we anticipate that these results are applicable across a diversity of design problems and designers, we will not know whether that is the case until we have additional experimental evidence from these alternate contexts. It is important to acknowledge that the results and conclusions drawn here have only been shown for particular subfunction pairs and sets that have been tested, for the particular design problem at hand, and for the particular analogical stimuli that were chosen. As with any experimental study, these limitations of applicability and extension of the findings are inherent to the assumptions and simplifications that are intrinsic to the laboratory-based study of design and creativity.

6 Conclusions

The experiment presented in this paper examines the efficacy of the patent-based functional analogy search methodology 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 subfunctions 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 identified by the patent-based functional analogy search methodology 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-based functional analogy search methodology is the significant 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-based functional analogy search methodology 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 methodology. This finding is in agreement with the results presented in Murphy's work (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-based functional analogy search methodology compared to alternative design-by-analogy methods, such as the WordNet procedure.

Acknowledgments The authors would like to thank Dr. Matthew Campbell, Dr. Richard Crawford, and Dr. Joseph Beaman for their discussions and insights on this work. This work was supported by the National Science Foundation, Grant Numbers CMMI-0855326, CMMI-0855510, and CMMI-0855293, and support from the SUTD-MIT International Design Centre (IDC), http://idc.sutd.edu.sg.

Appendix 1: Abstracts of patent analogical stimuli by treatment condition

Analogy Group 1: single subfunction

US Patent 5080079: Fuel injection apparatus having fuel-pressurizing pump

Abstract: A fuel injection apparatus has a piezoelectric element for generating a high-pressurized air–fuel gas mixture. The piezoelectric element is arranged at a side of a pumping chamber, and a diaphragm is arranged between the piezoelectric element and the pumping chamber. The piezoelectric element produces a pumping function in accordance with a current signal.

US Patent 7571500: Inflating/deflating device for an inflatable air mattress

Abstract: An inflating/deflating device includes a fan unit disposed inside a main housing. A release valve assembly is connected to a deflating port of the main housing for fluid communication with a first air passage of the fan unit. An inlet valve assembly is connected to an inflating port of the main housing for fluid communication with a second air passage of the fan unit. A control unit is provided to control the release and inlet valve assemblies. The control unit is operable to switch a first or a second actuating position. The control unit actuates the fan unit and the inlet valve assembly to perform an inflating mode in the first actuating position, and actuates the fan unit and the release valve assembly to perform a deflating mode in the second actuating position.

US Patent 7542009: Wireless communication device and signal receiving/transmitting method

Abstract: A wireless communication device using a single spiral inductor antenna and a signal receiving/transmitting method thereof operated on multi-band is provided. The single spiral inductor antenna is designed to have a plurality of different inductance paths. Different inductance values are inducted with signal paths switched by a plurality of switches so as to meet the requirements of multi-band operation. As the circuit structure of the single spiral inductor antenna is used, the circuit area is reduced effectively.

US Patent 3567143: Paper guiding arrangement for a business machine

Abstract: A paper roll supplies a paper band through an inlet opening in the housing of a business machine to a platen which transports the paper band back toward the top of the paper roll. When the diameter of the paper roll is small, the paper band is curved and tends to reenter the inlet opening which is prevented by a closure means mounted on the carrier of the paper roll and substantially closing the inlet opening when the carrier is displaced due to the reduction in the diameter of the paper roll.

Analogy Group 2: subfunction pair

US Patent 3584636: Photovoltaic cell-powered magnetic coil for the operation of fluidic circuit flapper

Abstract: A photofluidic eye comprising a photovoltaic cell and a magnetic coil operated flapper assembly powered thereby for alternately opening and closing fluidic back pressure orifices. No external power or switching arrangement is employed to avoid the occurrence of an electric spark when an environment containing explosive materials is present.

US Patent 7588105: 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.

US Patent 7533426: Gray water interface valve systems and methods

Abstract: Embodiments of the present invention provide systems and methods for a gray water interface valve for use with a vacuum source and a collection tank. The systems and methods comprise a basin for collecting gray water, the basin having an outlet; a reservoir in fluid communication with the outlet, the reservoir adapted to house gray water; a vent line associated with the reservoir; a pressure switch associated with the reservoir, the pressure switch adapted to signal when the reservoir is full; a controller associated with the pressure switch, the controller adapted to begin a discharge cycle by checking and switching on the vacuum source if necessary; a solenoid valve activated by the controller in order to control the flow of vacuum through the system; and a drain valve adapted to open via vacuum pressure and evacuate gray water from the reservoir, wherein the drain valve is adapted to close before all of the gray water from the reservoir is emptied to reduce noise.

US Patent 7511386: Air-blower tidal power generation device

Abstract: An air-blower tidal power generation device includes a rack, an air-blower mechanism, and a power generation mechanism. The air-blower mechanism includes a pumping device, a buoy, and an air conduit. The pumping device includes a cylinder and a stationary barrel movably coupled together. The power generation mechanism includes a constant-pressure and pressure-regulation device and a power generator having an air-driven turbine. Thus, tides move the buoy up and down to drive the pumping device for cyclically drawing and pumping air, and the air is preserved in the constant-pressure and pressure-regulation device to provide a constant pressure for subsequent and stable supply of airflow to the turbine for driving the power generator to generate power.

Analogy Group 3: all subfunctions

US Patent 3603804: Wave-operated power apparatus

Abstract: An elongated U-shaped pipeline has floats pivoted on transverse axes for rocking thereon in response to wave action in water which the floats are buoyant. Rocking of the floats operates pumps arranged in pressure compounding relation, and the fluid under pressure is delivered to a shore-based storage tank. The storage tank being sealed allows buildup of a pressure head. The fluid is let out through a regulator to operate machinery. Spent fluid from the plant is spilled out into a recovery tank, directly under the motor or turbine. It is then picked up by the lower leg of the pipeline and returned to repeat its cycle again. The floats support the pipeline and can be flooded to sink below the surface to avoid damage by storm waves.

US Patent 7549412: System for recovering wasted energy from an internal combustion engine

Abstract: An internal combustion engine and its method of operation including at least one embodiment operating on a six-stroke cycle and including at least one piston and cylinder assembly. The six-stroke cycle includes two power strokes, the latter of which is the result of a water-to-steam conversion process utilizing the heat of the exhaust gas from the first power stroke. A second embodiment comprises a hybrid power generating assembly incorporating alternative, first and second power sources, respectively, comprising an internal combustion engine and a water injection engine, the latter of which operates on the water-to-steam conversion process, wherein the required heat therefore is derived from the exhaust gas of the internal combustion engine. Another preferred embodiment comprises the utilization of different normally wasted heat sources from an IC engine for the generation of sufficient work energy to drive a power takeoff, such as hybrid drive assembly.

US Patent 7549418: Method and device for capture, storage, and recirculation of heat energy

Abstract: A heat generation and storage device supplements building heating and hot water systems. A roof cap including an air passage is connected to air outlets disposed within the roof structure of a building and to air passages formed by panels mounted over the surface of a building's roof. The roof cap is connected to a vent which either exhausts air to the atmosphere and/or recirculates air to a liquid heat storage tank. Heated air and heated water from the storage tank supplement a building's heating and hot water systems.

US Patent 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.

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