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UNDERSTANDING EFFECTS OF ANALOGICAL DISTANCE ON PERFORMANCE OF IDEATION: KEY OBSERVATIONS AND FINDINGS

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ABSTRACT

The effect of analogical distance between design stimuli and design problem on novelty and quality of generated concepts is investigated in this research. Data from a design project involving 105 student designers, divided into 21 teams and individually generating 226 concepts of spherical rolling robots, is collected. From this data, 138 concepts generated with patents as stimuli and the patents used as stimuli are analyzed. Analogical distance of a patent is measured in terms of the knowledge distance of the technology classes constituting this patent from the technology classes constituting the design problem domain of spherical rolling robots. The key findings are: (a) technology classes in closer than farther distance from the design problem are used more frequently to generate concepts, (b) as analogical distance increases the novelty of concepts increases, and (c) as analogical distance decreases the quality of concepts increases. These observations have implications on choosing stimuli to generate concepts of desired novelty and quality.

1 INTRODUCTION

Stimuli and analogies in designing are beneficial to identify, interpret and reformulate problems; generate, evaluate, and explain solutions, etc. [1–3]. Consequently, several forms of support to foster the use of stimuli and analogies, under the ambit of 'analogical design or design-by-analogy,' have been proposed and found to be effective at improving quantity, novelty and creativity of solutions [4,5]. Broadly, analogizing involves the transfer of information or similarity features from objects in the source domain to objects in the target domain, to solve problems in the target domain [2,3]. So, the ease of analogizing depends on the distance between the source and the target domains; the longer the distance, the more difficult it may be to transfer or map an analogy [6]. Many researchers investigated the effects of stimulation from various analogical distances on the performance of ideation. But their findings have not been consistent for various reasons.

Databases of patents have been used for various purposes in engineering design, such as to forecast future technologies, generate variants of novel solutions, etc. [7–9]. Patents contain descriptions of novel and functional products and processes, and so, potentially, can stimulate designers to develop novel and functional products and processes. Consequently, patents have been used as stimuli in engineering design and found to benefit ideation [7,9]. However, descriptions in patents – owing to the domain knowledge and jargon – present difficulties in reading and understanding the described products and processes. Moreover, patent databases are huge and contain several million patents. Therefore, browsing through several patents to comprehend the description, before selecting the most relevant ones as stimuli for concept generation remains a challenge.

Broadly, this research aims: (a) to validate the efficacy of using patents as stimuli for design ideation, and (b) through this validation, determine directions to develop methods and tools to search and identify relevant patents from patent databases for effective ideation. Within these broad objectives, the research in this paper investigates the effects of using patents – located at various distances from the design problem – as stimuli on the performance of ideation.

2 LITERATURE REVIEW & RESEARCH QUESTION

Relevant sources of literature are reviewed in this section.

2.1 DESIGN-BY-ANALOGY

Analogical design has been extensively researched. However, to fit the scope of this research, only those research that use patents for stimulation in ideation or analyze the effect of analogical distance on the performance of ideation are reviewed here.

Fu et al. [8] developed a methodology to assist designers to systematically search and identify functional analogies identified from patent databases, and subsequently, to use these to develop innovative concepts. They empirically tested the effectiveness of the methodology in terms of novelty and quantity of solutions it can help develop. The experiment comprised a control group and three experimental groups of varying levels of support for functions in the design problem. No significant difference between the control and experimental groups was seen in the quantity of solutions, but the experimental group with all the functions supported generated solutions of higher novelty than the control group.

Murphy et al. [9] developed a methodology to systematically search and identify functional analogies from the patent databases. The following steps constitute the methodology: (a) process patents to identify a vocabulary of functions, (b) define a set of functions in patents comprising primary, secondary and correspondent functions, (c) index patents using the functional set to create a vector representation of the patent database, (d) develop methods for query and estimate relevance of patents to a query, and (e) retrieve and display patents relevant to the query. The methodology was tested by applying it to two cases to determine whether it can help identify functionally similar analogies.

Chan et al. [11] studied the consequences of analogical distance (near vs far), analogical commonness (more- vs less-common) and modality of stimuli representation (text vs image) on the extent of transfer of features from stimuli, breadth of search, quantity, quality and novelty of outcomes, using some patents as stimuli from patent databases. They observed that far-field analogies help develop concepts of higher novelty, higher variability in quality, greater solution transfer but fewer concepts than near-field analogies.

Fu et al. [12] developed a computational technique to quantify the similarities of functional and surface features in patents, with the objective of automatically identifying patents at different analogical distances, which could be used as stimuli for ideation in engineering design. Using the computational technique, they generated Bayesian networks of patents based on functional and surface similarities (function and surface features correspond to verbs and nouns, respectively). Further, based on similarity of functional and surface contents, several sub-clusters were manually created within the Bayesian networks.

Srinivasan et al. [10] conducted experiments where student designers used different degrees of stimulation: (a) no stimuli, (b) only patents, (c) only other sources (such as articles, videos, etc. from the internet) and (d) both patents and other sources, to generate conceptual solutions of spherical rolling robots for various purposes and analyzed these solutions for novelty and quality. They found that the average quality of solutions generated with patents is higher than those generated without patents. They also observed that the average novelty and quality of solutions developed with stimulation (patents, other sources or their combination) are higher than those generated without any stimulation. However, differences in novelty and quality of solutions were only observed across different degrees of stimulation, but not within the individual degrees of stimulation, at least within the scope and sample size of the study.

2.2 ANALOGICAL DISTANCE

The Conceptual Leap hypothesis states that stimuli from far sources, owing to their surface dissimilarities, are the best sources for creative breakthroughs [13,14]. Some anecdotal evidence exists in support of this hypothesis. However, empirical findings related to the validation of this hypothesis have not been completely consistent. Chan et al. [11] found that stimuli from far sources were more beneficial for developing solutions of higher novelty and quality. Wilson et al. [15] observed no distinct advantages for stimuli from far sources over near sources. Fu et al. [16] observed that stimuli from near sources or “middle ground” helped generate solutions of higher “maximum novelty” than far sources; no significant differences were seen in “average novelty” between near and far sources. Fu et al. also observed that both the “mean quality” and the “maximum quality” of solutions generated using stimuli from near sources were higher than those generated using far sources. So, they argued stimuli from “middle ground” to be more beneficial for developing creative solutions. All the near distance and “middle ground” stimuli are perceived to be more relevant to the design problem than the far distance stimuli. Based on these findings, Fu et al. posited that comparisons of effects of analogical distance across different studies is hard owing to different metrics being used to measure distance in these studies. They also argued about the terms ‘near’ and ‘far’ as being relative and not being able to completely characterize these across different studies due to lack of a common metric to measure distance. Chan et al. [17] reasoned that the most creative solutions are more likely to be developed from near distance than far distance stimuli, owing to better perception and connection to the problem at hand.

2.3 METRICS TO ASSESS PERFORMANCE OF IDEATION

The performance in ideation is often assessed in terms of its outcomes. Several researchers proposed various metrics, namely quantity, quality, novelty, variety, fluency, usefulness, feasibility, similarity, etc. [18–21]. Shah et al. [18] proposed four metrics to assess effectiveness of ideation: quantity, quality, novelty and variety. These are defined as follows. Quantity is the total number of ideas generated. Quality is a measure of feasibility of an idea and how well it fulfills the design specifications identified. Variety is a measure of how well a solution space is explored. Novelty of an idea is a measure of its unexpectedness or unusualness in comparison to other ideas. McAdams & Wood [19] proposed the metric of functional similarity to assess the similarity between two functional vectors in terms of the angle subtended by these vectors, and was used to identify analogous products. Sarkar & Chakrabarti [20] proposed creativity of a design as a mathematical product of its novelty and usefulness. They defined novelty as a measure of newness and usefulness in terms of use and value of the design. Srinivasan & Chakrabarti [21] used novelty, variety, quantity and fluency as the four metrics to assess the impact of a framework developed to improve variety and novelty of solution space. They defined: novelty of a design as the measure of newness of the design with respect to existing designs that perform the same function, variety of a design as a measure of how different it is from the other alternative designs generated for the same problem, quantity as the total number of designs generated and fluency as the number of designs developed per unit time. Oman et al. [22] proposed 2 metrics to assess creativity of concepts, namely, Comparative creative assessment (CCA) and Multi-point creative assessment (MPCA). The CCA is based on uniqueness of an idea within a solution in comparison to the pool of ideas in the entire set of solutions. The MPCA is based on the rating by a group of judges using pairs of adjectives. Some of the metrics reviewed in this section, particularly variety and novelty, were also modified in [23,24].

2.4 SUMMARY

Many researchers used patents as stimuli to improve the performance of ideation and reported the benefits in comparison to no stimuli. In these studies, there is seldom any distinction made between solutions – in terms of ideation metrics – generated using stimuli. However, this is important because it will help characterize the stimuli used in generating solutions of desired metrics. The observations on the effect of stimulation from various analogical distances on metrics of ideation have not been consistent for various reasons, including using different metrics to estimate distance/relevance, different domains from which stimuli are sourced, etc. These existing studies primarily use analogical distance related to the attributes of target domain, namely function, behavior and structure. No study (to our understanding) uses knowledge relatedness between technology classes as a measure of analogical distance. The current studies use only a few stimuli which might not be representative of the entire technology class. Further, several metrics have been proposed to assess the performance of ideation in analogical design, but seldom has quality been used as a metric to assess the effects of stimuli, due to the scope of the studies.

2.5 RESEARCH QUESTION

Based on the issues identified from the review of literature, the following research question is posed in this research: *What is the effect of stimulation from various analogical distances on the novelty and quality of solutions generated using stimuli?*

3 RESEARCH APPROACH

The approach used in this research is described as follows.

3.1 DESIGN EXPERIMENT

Data from a design ideation exercise in the 30.007 Engineering Design and Project Engineering course at the Engineering Product Development (EPD) Pillar of the Singapore University of Technology & Design (https://epd.sutd.edu.sg/) is used. This course is attended by the second-year students of the EPD pillar. A design project runs throughout the course and an ideation phase exercise is a part of this project. The objective in the project for each team is to conceive, design, fabricate and demonstrate a working prototype of a spherical rolling robot for system requirements of their choices, through a stage-gate process, including generating multiple, alternative concepts. A concept is an overall solution, which comprises multiple sub-functions and sub-systems. This objective is deliberately kept open-ended to provide the teams the flexibility to identify an innovative application of their choice. 105 participant designers are divided into 21 teams comprising 4-6 members in each team. These designers have undertaken several design courses and structured design projects prior to this project. These students have undergone various fundamental courses such as Mechanics (Statics and Dynamics), Strength of Materials, Mechanics of Solids, Thermodynamics, Fluid Mechanics, Fundamentals in Electricals and Electronics Engineering, etc. and have also undertaken various design projects involving requirements identification, ideation, prototyping and testing. They have also obtained significant domain knowledge in EPD.

The overall design approach used by the participants is (T: Teamwork; I: Individual task): Define problem (0.5 weeks, T), Identify requirements (0.5 weeks, T), Generate concepts (1 week, I), Evaluate concepts (1 week, T), Modify concepts (0.5 week, T), Select a concept (0.5 weeks, T), Develop a functional prototype (2 weeks, T) and Demonstrate the prototype (1 week, T). While the process is described linearly, the teams and individuals execute iteration in and between phases of the process. All the tasks, except concept generation, are team-based activities.

Data from the 'Generate concepts' phase is used for this research, which requires designers to work individually and the resulting data is collected and analyzed.

To explore the effects of patents as stimuli, the research team prepared two sets of patents for participant teams to search and identify relevant stimuli. The most cited US patent from each of the 121 3-digit patent categories, defined by the International Patent Classification (IPC) system, is provided. The forward citation count of a patent is highly correlated to its realized value or importance [25,26]. These 121 patents comprise the Most Cited category. In addition, a randomly identified patent is also provided from each of the 121 patent categories. These 121 random patents constitute the Random category. These patents from the Most Cited and Random categories provide the basic coverage of possible patents from all fields of technologies in the total technology space. Within the various fields of technologies, the patents from these two categories are located at different distances from the field of spherical rolling robots. The total number of patents provided to the designers is also tractable for the duration and resources available for ideation.

Figure 1 is a network representation of the technology space [27]. This network comprises 121 nodes, each of which represents a patent technology class in the IPC system. More than 4 million US patents issued between 1976-2010 are located within the different nodes of this network. The size of each node is proportional to the number of patents belonging to that node. Each node is positioned based on its knowledge proximity to other nodes. Knowledge proximity between different technology classes (operationalized by patent classes here) can be calculated using various metrics with the information of patent citations or classifications such as the Jaccard index, cosine similarity, co-occurrence, etc. [26,27]. For the network in Figure 1, knowledge proximity is calculated using the Jaccard index, which is recommended by Yan and Luo [28] as a superior choice of metric. The Jaccard index is the ratio of the shared references of patents in a pair of classes over the total number of unique references of patents in both these classes. The index is higher when patents in both classes share more references, indicating higher knowledge proximity between the technology fields they represent.

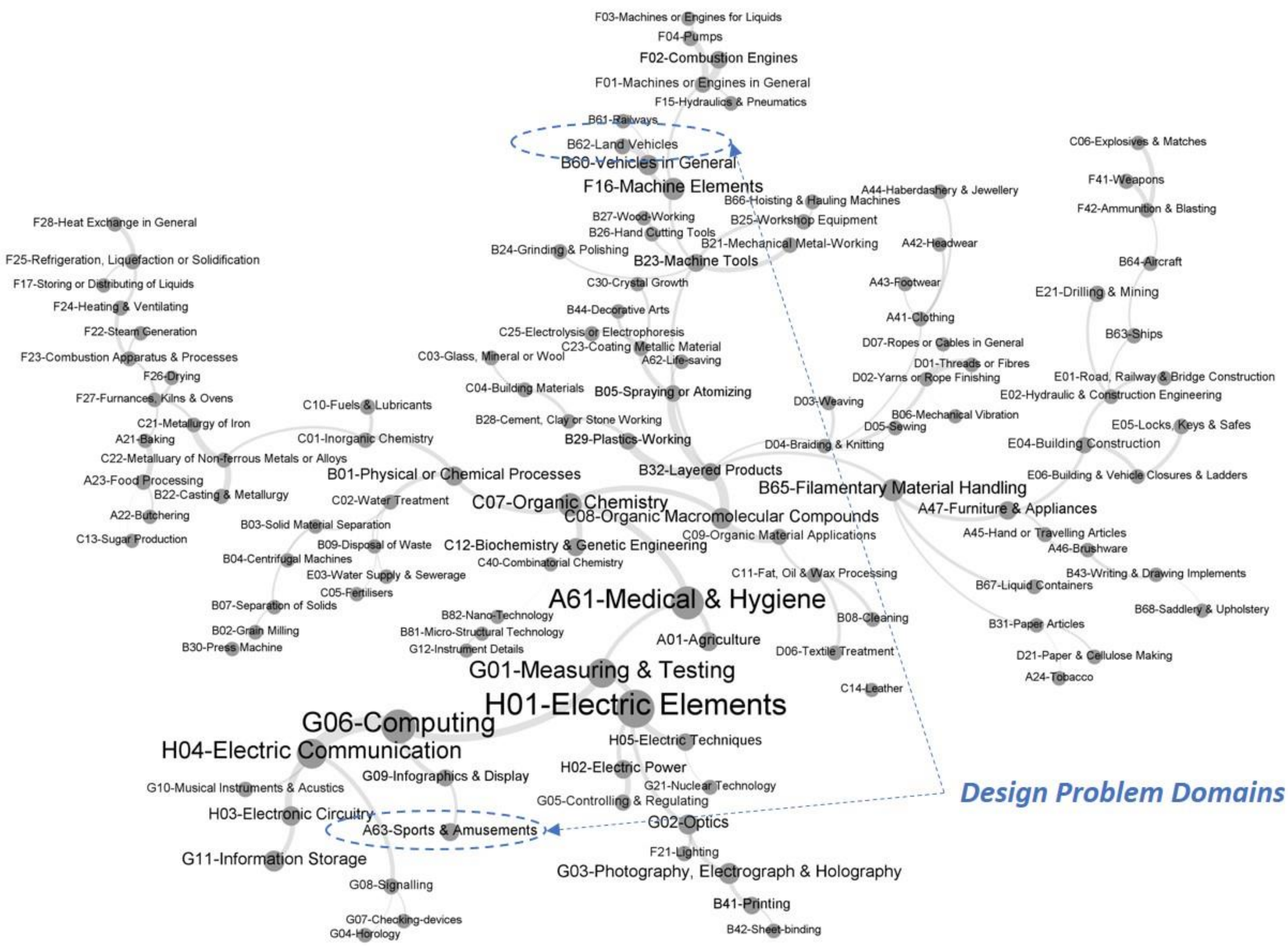

Figure 1: Technology Map showing the various Technology Fields and domains of Design Problem

If design processes in two fields requires distant or distinct scientific and design knowledge, i.e., low knowledge proximity, designers in one field may find it difficult to understand or design using knowledge and technologies from the other field [29]. Prior patent data analysis has statistically shown that inventors are more likely to succeed in filing patents in proximate fields in the space [26]. The thickness of links connecting a pair of technology classes, i.e., nodes, is proportional to the knowledge proximity between them. Though almost all the nodes are connected in the technology space network, only the 120 strongest links that connect all the 121 nodes are shown, i.e., a maximal spanning tree [28]. Figure 1 also highlights the two technology fields (i.e., patent classes) in which most patents related to spherical rolling robots are identified: A63 (Sports and amusements) and B62 (Land vehicles). These are considered the design problem domains for spherical rolling robots. Note that the patents in the Most Cited and Random categories identified in the 121 technology classes have different knowledge proximity (or distance) to the design problem domains of spherical rolling robots.

In each design team comprising 4-6 members: (a) 1-2 participants are provided no stimuli (control condition), (b) 1-2 participants are provided with the 121 patents from the Most Cited category, and (c) the remaining participants are provided with 121 patents from the Random category. The participants in the experimental groups ((b) and (c)) are provided with the title, abstract and images of the 242 patent documents. If the participants find these contents relevant and inspirational to their design problem, they are expected to read the sections on technical description of the patents in more detail for specific design concept stimulation. In addition to the given 242 patents, all the participants can use other resources (such as the internet, books, databases, etc.). The participants are instructed to generate functional and novel concepts, but not maximize the number of concepts generated. The participants are asked to sketch concepts with annotations and briefly explain how they work. In addition, the participants must document the following: patents used, other resources accessed, and how stimuli are transformed into concepts. The participants are given a week to generate concepts. A consent form for approval is collected from all the participants. A pre- and a post-ideation survey is conducted to collect information relating to demography and experience, such as age, gender, academic background, nationality, and other demographic data of the participants, to understand their experience of using patents *a priori* and *posteriori* to this exercise, the effects of their usage, and other related factors.

3.2 DATA ANALYSIS

A patent can belong to multiple technology classes in the IPC system. In this study, all the technology classes used to classify a patent are considered. For example, the patent “US3009235A” on “Separable Fastening Device” belongs to the technology classes A44 (Haberdashery & Jewellery), B65 (Filamentary Material Handling) and D03 (Weaving). The proximity of a technology class to the problem domains, A63 and B62 is taken as the average of the proximities of this technology class to each of the problem domains. For example, the proximity of A44 to the problem domains is the average of the proximities of A44 to: (a) A63 and (b) B62.

Various metrics to assess the performance of ideation have been proposed. In this research, novelty and quality are used because: (a) stimuli are primarily used to explore new solution spaces (related to novelty) and (b) while exploring these spaces it is critical to ensure that all the important system requirements of a problem are fulfilled (related to quality).

From the documentation of sketches and annotations of concepts, the patents used as stimuli are identified and, novelty and quality of the generated concepts are assessed as follows.

The fifth author of this paper, with expertise in spherical robots, rated novelty of concepts on a 4-point scale (0-3), corresponding to no, low, medium and high novelty. This expert has extensive knowledge of prior art in spherical rolling robots.

Quality of a solution, as mentioned earlier, is a measure of the fulfillment of requirements. In the assessment of quality, three abstraction levels, namely functional-, physical principle- and structural-levels are considered. Quality of concepts is assessed using the formula:

$$Q = 0.5 \times f + 0.3 \times w + 0.2 \times s \qquad \text{(Eq. 1)}$$

where Q is the overall quality of a concept, *f* is a measure of the degree of fulfillment of the identified requirements by the functions in the concept, *w* is the degree of fulfillment of the identified functions by the working principles in the concept and *s* is the degree of fulfillment of the physical principles by the components and their relations in the concept. A weighting scale of 0.5, 0.3 and 0.2 is used corresponding to the function-, working principle- and structure-levels, respectively, because higher abstraction levels are the basis for building the lower abstraction levels. *f*, *w* and *s* are rated by the first author using a 3-point scale (0-2), corresponding to no, partial and complete fulfillment. Therefore, the overall quality of a concept, calculated using Eq. 1, will also vary between 0 and 2. Before rating all the concepts, an inter-rater reliability test is conducted using two additional raters (second and third authors) for 20 concepts. After two rounds of iterations involving analyzing, settling and reconciling differences (reaching Cohen’s Kappa ratio of 0.86), the learning from these iterations is used to rate the quality of the remaining concepts. The overall quality is calculated using the *f*, *p* and *s* scores for each concept using Eq. 1. The frequency distribution of the generated concepts over their quality scores has three distinct zones: $Q \leq 1.2$, $1.2 < Q < 1.7$ and $Q \geq 1.7$. These zones are categorized as low-, medium- and high-quality grades.

In this study, the technology classes constituting the patents used to generate concepts are analyzed. The distributions of the technology classes in patents, located at various proximities to the design problem domains, to generate concepts of various grades of novelty and quality are studied. This approach will enable an investigation into the effect of analogical distance on the novelty and quality of concepts.

4 FINDINGS

In this study, 226 distinct system-level concepts are generated by the 105 participant designers. Each system-level concept constitutes multiple sub-functions and sub-systems. Out of these 226 concepts, 138 (~61%) are generated with patents as stimuli and 88 (~39%) without patents. Owing to the designers being given the flexibility to access other resources (such as books, internet, etc.) for concept generation, the designers also identify patents on their own (constitute Own category), in addition to the given patents (Most Cited and Random categories). Among the 138 concepts generated with patents, 87 concepts (~63%) are generated using patents from the Own category, 27 concepts (~20%) using patents from the Most Cited category and 24 concepts (~17%) using patents from the Random category. Further, in addition to patents in the Own category, the designers also used other kinds of stimuli (such as the text, images, videos of products and processes obtained through internet search) described in patents. So, the following various degrees of stimulation are observed: (a) without any stimuli (10 concepts, 4%), (b) with other resources only (78 concepts, 35%), (c) with patents only (23 concepts, 10%) and (d) using both patents and other resources (115 concepts, 51%). These are explained in detail in [10].

In this study, the patents used to generate the 138 concepts and the constituting technology classes in these patents are analyzed. This group includes all categories of patents, inclusive of those generated without and with other resources. Figure 2 shows the number of patents used (sum of all patent categories) to generate concepts of various grades of novelty and quality. The number of patents used in these various groups is unequal because this is not a variable that is controlled. The number of patents used to generate concepts of medium novelty and medium quality is observed to be the highest.

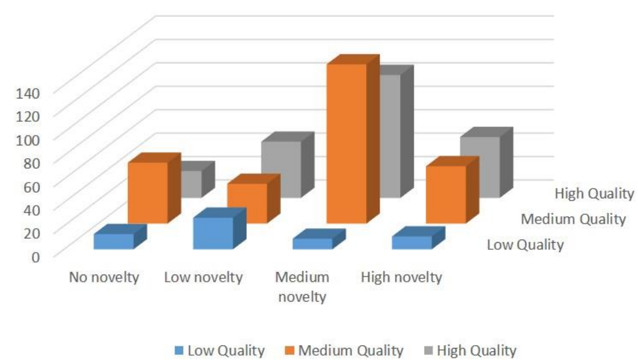

Figure 2: Frequency of patents used to generate concepts of various grades of novelty and quality

As stated earlier, a patent, according to the IPC system, can belong to one or more of the 121 technology classes shown in Figure 1. For example, patent "US 5529138 A" on Vehicle collision avoidance system is classified into G05 (Controlling & Regulating), B62 (Land Vehicles), B60 (Vehicles in General), F16 (Machine Elements) and G01 (Measuring & Testing). Figure 3 shows the frequency distribution of patents used to generate concepts of all grades of novelty and quality in the 121 technology classes, which correspond to the 121 nodes in Figure 1. In this figure, the technology classes in the abscissa are arranged in decreasing proximity to the problem domains, A63 and B62, from left to right. Note that proximity of a technology class represents its closeness in terms of distance to the problem domains; so, the higher the proximity closer the distance. It is observed in Figure 3 that the technology classes in closer proximity to the problem domains appear more frequently than those in farther proximity.

Next, the distributions of patents used to generate concepts of various grades of novelty and quality in the 121 technology classes are analyzed (see Annex section). In other words, each block in Figure 2 is expounded to study its distribution in the 121 technology classes. Figures A.1-A.12 in the Annex section show the distribution of patents used to generate concepts of various combinations of: (a) no-, (b) low-, (c) medium-, and (d) high-novelty and (a) low, (b) medium- and (c) high- quality, in the 121 technology classes. The 121 technology classes in the abscissa of these images are also arranged based on decreasing proximity to the problem domains.

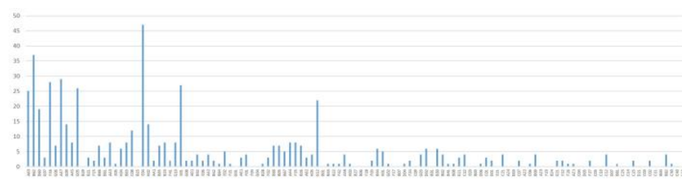

Figure 3: Distribution of patents used to generate concepts of all grades of novelty and quality in 121 technology classes

Other metrics reviewed by Yan and Luo [28] to measure the knowledge proximity between technology classes are also explored in this study, and lead to similar findings. However, only the distributions based on the Jaccard Index as a proximity metric are shown in this paper.

The variation in average proximity of stimuli domains (technology classes) to problem domains across the frequency distributions in Figures A.1-A.12 is used as a representative measure to assess the effect of the analogical distance on the novelty and quality of concepts generated. Figure 4 shows the variation in average proximity with novelty for various grades of quality. It is observed that the concepts of higher novelty (for Low and High Quality concepts) are generated using technology classes of lower average proximity. For concepts with Medium Quality, the average proximity of the stimulating technology classes first increases and then decreases. The differences in average proximity are significant for Low Quality concepts (One-way ANOVA: $f=5.662$, $p=0.002$, $df=3$).

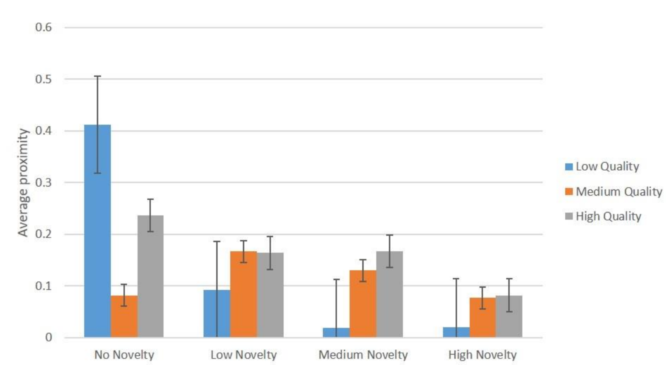

Figure 4: Average proximity of frequency distributions over novelty for various grades of quality

Figure 5 shows the variation of average proximity with quality for various grades of novelty. It is seen that the concepts of higher quality (for Medium and High Novelty) are generated with technology classes of lower average proximity. For the concepts of No Novelty, the average proximity decreases and then increases as the quality of concepts increases. However, for the concepts of Low Novelty the average proximity increases and then decreases as the quality increases. The differences in average proximity are statistically significant for No Novelty (One-way ANOVA: f=6.086, p=0.003, df=2).

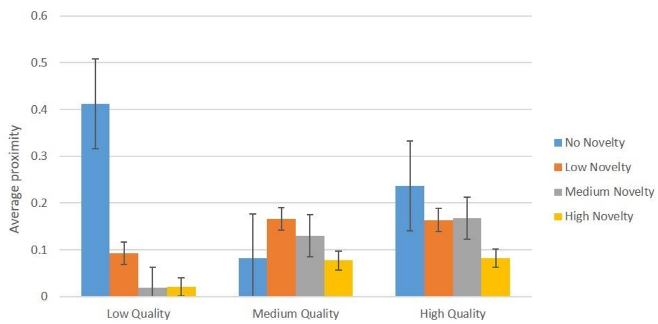

Figure 5: Average proximity of frequency distributions over quality for various grades of novelty

5 DISCUSSION

In this research, the primary objective is to examine the effect of analogical distance on the performance of ideation, viz. the novelty and quality of concepts generated in the ideation. It is observed that with the increase in the analogical distance of the technology classes in the patents used, the novelty of generated concepts increases, for Low and High Quality concepts (see Figure 4**Error! Reference source not found.**). Therefore, stimuli from domains that are farther than nearer in distance from a problem will likely help generate solutions of higher novelty. It is also observed that with the decrease in analogical distance of the technology classes, the quality of generated concepts increases, for Medium and High Novelty concepts (see Figure 5). So, it can be reasoned that stimuli from domains that are nearer than farther to a problem will likely help generate solutions of higher quality.

It is also shown that technology classes nearer than farther to problem domains are used more frequently to generate concepts (see Figure 3). Owing to higher knowledge relatedness of stimuli in closer proximity, these can be better related to the design problem, and therefore, used more frequently.

5.1 SIGNIFICANCE OF FINDINGS

The overall objectives of this research are: to validate the efficacy of using patents as stimuli to support ideation and through this validation, to determine vistas for developing methods and tools to search and identify relevant patents to be used as stimuli for improved ideation. The research pursued in this paper is a step towards these broad objectives, where participant designers generated alternative concepts of spherical rolling robots without and with patents. In an earlier research, Srinivasan et al. [10] studied the effects on concept generation: (a) without and with patents, as well as (b) using various degrees of stimulation: (i) no patents, (ii) patents only, (iii) other resources only, and (iv) combination of patents and other resources. They observed that concepts generated with patents have higher quality than concepts generated without patents. Further, concepts generated with: (a) patents only and (b) combination of patents and other resources have higher quality and novelty than concepts generated without any stimuli. Based on these observations, several guidelines were proposed for developing new methods and tools for identifying and searching patents. In this research, the effect of stimulation from different analogical distances on novelty and quality of concepts generated using stimuli are investigated. The findings in this study reveal that, based on the novelty and quality requirements of designers, assistive methods and tools can suggest multiple patents located at appropriate distances from design problems, for designers to identify and select the relevant stimuli.

Using stimuli that are located at different distances from the problem domain can help generate solutions that vary over a spectrum of novelty and quality. Ideally, designers would like solutions to have a blend of novelty that is high enough to allow market penetration and quality that is suitable to fulfill the needs of customers. This spectrum of solutions can help designers to combine the features from solutions of desired novelty with the features from solutions of required quality into blended solutions.

Many researchers (e.g., [10]), reported the benefits of using stimuli in enhancing performance of ideation, in comparison to no stimuli. However, only few researchers (for instance, [17]), make distinctions within solutions that use stimuli using metrics. Further, research on effects of using stimuli seldom studies the effect on quality of solutions generated using stimuli. The findings in this paper help fill this gap. In other words, solutions generated using stimuli from domains at closer distance from the problem domain help generate solutions of higher quality but lower novelty, and solutions generated using stimuli from domains in farther distance from the problem domain help generate solutions of higher novelty but lower quality.

Several studies have been conducted to study the effect of analogical distance on the performance of ideation and the findings have not been consistent for various reasons. The study described in this paper is different from the existing studies in the following aspects. The existing studies assess analogical distance in terms of functional, behavioral and structural attributes, but in this study the knowledge relatedness between technology classes is taken as a measure of analogical distance. It must be noted that the analogical distance in this study is between the technology classes which are used to classify patents, but not patents themselves. In addition, existing studies use smaller samples of stimuli to study their effects. However, in this study, 121 patents, one each from the 121 technology classes of the IPC system, that encompass the technology space are provided to the student designers. In addition, the designers are also allowed to choose patents on their own and use them as stimuli.

Data of 138 concepts generated by multiple designers, ideating individually for different problems and requirements, with patents as stimuli in uncontrolled conditions is used in this research. This data spans a wide spectrum of variables. The designers in this study needed more domain knowledge to accomplish the tasks than other laboratory-based controlled ideation experiments. From the alternative set of concepts generated by individuals within a team, one concept is chosen and modified, if necessary, then prototyped and demonstrated by each team. Arguably, the performance of a prototype depends on the set of alternative concepts generated earlier. The participants are graded based on their performance at the end of each phase of the development process. Moreover, some of these projects are further pursued towards entrepreneurial and co-curricular activities. Therefore, the participants had adequate vested incentives to pursue this ideation exercise seriously. The validity of the findings in this study must be considered in the context of this wide span of variables and the seriousness with which this exercise is pursued.

This study represents a unique intersection between research and education, as the opportunity of exploring spherical rolling robots and the related design brief of the course, originated from an ongoing multimillion dollar research project at the university. The data from this ideation exercise and the ensuing research results will be used in this project.

5.2 LIMITATIONS

The significant results reported in this paper must be considered within the following limitations of this study. Firstly, the number of patents used for generating concepts of various grades of novelty and quality is unequal (see Figure 2). These numbers must be identical to allow fair, unbiased comparisons, though this was not a control variable in this study. Secondly, the concepts analyzed in this study are generated using: (a) patents only and (b) combination of patents and other resources. For concepts generated with patents and other resources, only the proximity of patents is assessed. Though other resources as a source of stimuli has a significant influence on novelty and quality of solutions [10], their proximity to problem domains is ignored and thereby, their influence on novelty and quality of solutions masked. Thirdly, the metric used to assess proximity of technology classes in patents is based on knowledge relatedness between these classes, but does not necessarily consider the relevance of a stimulus to a design problem. Further, this metric measures proximity between domains, but not between a stimulus and a design problem. So, using this proximity metric, two different stimuli from the same technology class but different degrees of relevance to a design problem will have the same proximity to the design problem. Potentially, these stimuli with the same proximity to the problem owing to the difference in their relevance to the problem can help generate concepts of different novelty, quality or both. Fourthly, in this experiment, the designers are given abstracts, images, and technical descriptions of 121 patents from the Most Cited and Random categories. These descriptions are often long and tedious. So, browsing through the 121 patents to identify relevant stimuli and use related information for generating concepts, all within a week, may have been cumbersome for these designers, and consequently, may have affected the concepts generated using these patents. Fifthly, the proximity of technology classes to problem domains is assessed with A63 and B62 as the problem domains. These technology classes are identified as problem domains because they contain more patents of spherical rolling robots than other classes. However, other technology classes also contain patents of spherical rolling robots, and by considering these, the proximity values and hence, the resulting distributions for various grades of novelty and quality of concepts will change. Finally, there are general limitations in the characterization of analogical distance. There is lack of clarity about: how far must the analogical distance be for a stimulus domain to be called a “far domain” and how near should the analogical distance be for a stimulus domain to be called a “near domain”. It is also not clear from this study and other existing studies on how far or how near should designers traverse in terms of analogical distance to generate concepts with significant differences in novelty and quality.

6 CONCLUSIONS

In this research, the effects of stimulation using patents located at various analogical distances on the novelty and quality of concepts generated using these patents are investigated. Significant findings from this research are: (a) as the analogical distance increases the novelty of generated concepts increases, (b) as the analogical distance decreases the quality of generated concepts increases, and (c) more stimuli from nearer than farther domains are used to generate concepts. In conclusion, stimuli from domains at closer distance than farther help generate solutions of higher quality and stimuli from domains in farther than closer distance help generate solutions of higher novelty. The findings and observations have important implications on ideation methods for selecting stimuli for generating solutions of desired novelty and quality, and further for industries and other organizations, especially in fast-paced, low cycle time and highly competitive design fields.

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ANNEX: PATENT DISTRIBUTION FOR VARIOUS GRADES OF NOVELTY AND QUALITY IN THE 121 TECHNOLOGY CLASSES

Figure A.1: Distribution of patents used to generate concepts of low quality and no novelty

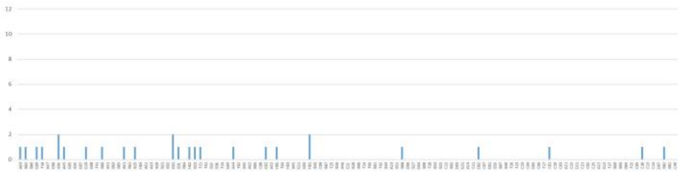

Figure A.2: Distribution of patents used to generate concepts of low quality and low novelty

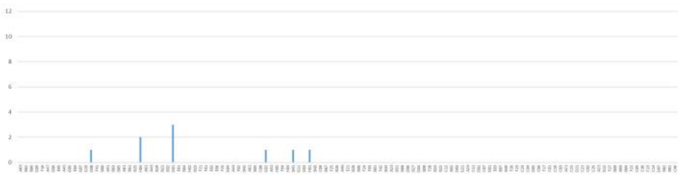

Figure A.3: Distribution of patents used to generate concepts of low quality and medium novelty

Figure A.4: Distribution of patents used to generate concepts of low quality and high novelty

Figure A.5: Distribution of patents used to generate concepts of medium quality and no novelty

Figure A.6: Distribution of patents used to generate concepts of medium quality and low novelty

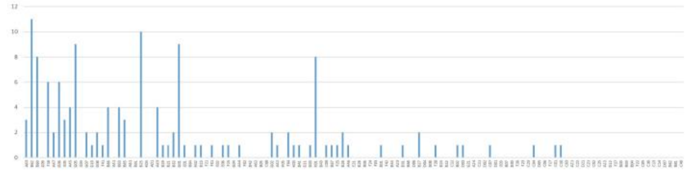

Figure A.7: Distribution of patents used to generate concepts of medium quality and medium novelty

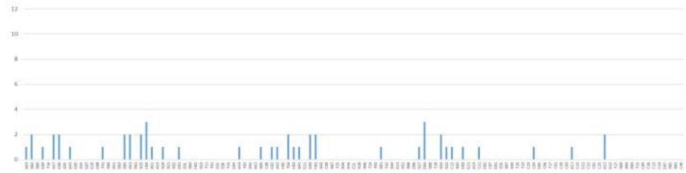

Figure A.8: Distribution of patents used to generate concepts of medium quality and high novelty

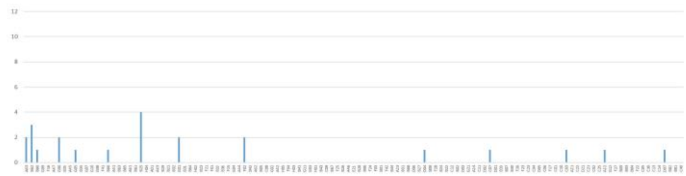

Figure A.9: Distribution of patents used to generate concepts of high quality and no novelty

Figure A.10: Distribution of patents used to generate concepts of high quality and low novelty

Figure A.11: Distribution of patents used to generate concepts of high quality and medium novelty

Figure A.12: Distribution of patents used to generate concepts of high quality and high novelty