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BROWSE THE TOTAL TECHNOLOGY SPACE MAP TO CONCEIVE NEW APPLICATIONS OF A TECHNOLOGY FOR DESIGN OPPORTUNITIES

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Abstract: Designers often explore novel applications of their technologies for innovation. However, such searches relied on experiences, expertise or gut feeling. Here we propose the use of a technology space map to enhance the creativity of such a human ideation process for new design opportunities of a given technology. We present an example map in which the domains are approximated as international patent classes and their proximities are quantified using patent data. Designers can browse the map to navigate various technology domains organized by their knowledge proximities throughout the technology space to conceive design opportunities that relate the current technology to other domains for new applications. The map is aimed to facilitate ideation across distant domains. We present one case study of using the map to conceive novel design application opportunities for artificial neural networks. On this basis, a computer system (i.e., InnoGPS) to aid in interactive digital map browsing and design information retrieval is developed.

Keywords: *design opportunity conception, creativity, ideation, and technology space map*

1. Introduction

Design engineers or companies often explore new design applications of the technologies that they have designed or mastered. However, which application remains a lasting question. Related searches and decisions are normally based on expertise, experience or intuition of the designers. Structured methods and tools for the search of new design application opportunities of specific technologies are still under-developed. User-centred methods may be useful (Chen et al. 2012), but the identified opportunities may not require the given technology but others. In this paper, I propose a methodology to identify new technology application design opportunities according to the relationships between the focal technology and other unexplored technologies in the total technology space. My eventual objective is to develop a systematic and structured method and tool to aid designers in conceiving new design opportunities related to their current technologies.

Our methodology is based on the understanding that engineering design is the synthesis of existing knowledge or concepts into new ones (Weisberg, 2006; Hatchel and Weil, 2009). Thus, design opportunity conception often involves a process of search and navigation of other technologies than the designer's own in the technology space (Shai and Reich, 2004; Hatchel and Weil, 2009; Reich and Shai, 2012). However, a designer's cognitive capacity to conceive the relevance of his/her own technology with others is conditioned by the knowledge distance between these technologies in the

total technology space (Alstott et al., 2017a). Conceptually, two technologies are proximate in the technology space if highly related or similar knowledge is required to design them, or are distant if designing them requires unrelated or distinct knowledge. Such knowledge distance may limit the ability of a designer to conceive, relate and synthesize different technologies for new designs.
To empower the search for design synthesis of distant technologies, we propose the use of a network map of various technologies in the total technology space to a visual aid. In the network map, nodes are patent classes that represent different technologies or domains and their links are weighted according to the knowledge proximities between the domains, measured using patent data. A designer can browse the map and navigate the domains in the space to obtain the inspiration for potential applications of the focal technology in other domains. The designer's use of the technology space map for finding design directions is analogous to our use of the geographical space map to find travel directions in the physical space.

2. Related literature

Prior design creativity studies have suggested that new design concepts arise from the analogy (Weisberg, 2006; Linsey et al., 2012), synthesis (Arthur, 2009), blending (Taura and Nagai, 2012), or more general forms of creative transformation of existing knowledge or concepts (Hatchel and Weil, 2009). Recently Youn et al. (2015) show empirical evidence from patent analysis that modern inventions primarily arise from the combination of existing technologies rather than the introduction of new technologies. However, it remains a question which existing knowledge or concepts to transform and how a designer may systematically search for existing technologies, knowledge or concepts for synthesis, analogy or blending to yield new ones. A recent statistical analysis of more than 2 million inventors and their patent records in the United States Patent and Trademark Office (USPTO) database shows evidence that inventors are much more likely to obtain patent grants in new but more proximate domains to their prior patenting domains, but the average value (measured by future citations) of the new patents is higher if the new patents are in a more distant new domain from his/her prior domains (Alstott et al. 2017b).
Designers are naturally limited in their abilities to conceive new design opportunities using the technologies distant from their own technologies. Prior creativity studies have already suggested that it is cognitively easy to conceive analogy or synthesis across proximate or similar domains (Fu et al, 2013a; Uzzi et al., 2013), whereas near-field analogy or synthesis is unlikely to yield novel ideas (Gentner and Markman 1997; Tseng et al. 2008). In contrast, it is relatively difficult to conceive analogy or synthesis across distant domains (Gick and Holyoak, 1980; Weisberg, 2009; Chan et al. 2015), but if succeeding, it may achieve a higher novelty and a greater chance of breakthroughs (Dahl and Moreau, 2002; Gentner and Markman 1997; Tseng, 2008; Chan et al, 2011).
Meanwhile, various methodologies were developed to facilitate design search across technical domains or disciplines. For instance, infused design facilitates the discovery and use of knowledge, methods and solutions across domains (Shai and Reich, 2004). The interdisciplinary engineering knowledge genome aids in the retrieval of knowledge and method structures in different technological domains (Reich and Shai, 2012). Design-by-analogy leverages existing technical solutions from source domains to solve design problems in target domains, and has been supported by recently developed computational methods (Linsey et al., 2012; Fu et al., 2013b).
Generally speaking, the literatures on design creativity, concept generation and analogical distance have implied the value for designers to have a macro picture of various technologies in the total technology space, as well as the information regarding their knowledge distances in the space, to aid in the search for design opportunity inspiration. For example, the Bayesian network of patents of Fu et al. (2013b) quantifies and visualizes the analogical distances between different patents and the design problem. Thus designers can potentially use the network to identify patent stimuli near or far from a specific design problem. However, the network of patents only covers a small set of patents, and addresses a specific pre-defined function design problem.
Herein, we aim to use a macro map of enormous technology domains that approximate the total technology space as a visual aid for designers to navigate and conceive high-level and open-ended design opportunities, via relating and synthesizing other technologies with the focal ones mastered by

the designers. Recent efforts of mapping patent technology classes have presented some large technology maps that are potentially useful for our interest in design ideation. These studies normally utilize the entire patent database to construct network maps of all the technologies defined in patent classification systems (Kay et al., 2014; Leydesdorff et al., 2014). In such a network, the nodes are patent classes defined in either United States Patent Classification or International Patent Classification systems to represent generic technology domains. The links between the nodes are weighted according to inter-domain knowledge proximity (Yan and Luo, 2017a). Such network maps have been used to analyse the patent portfolio diversification of inventors (Alstott et al., 2017b), firms (Yan and Luo, 2017b), regions (Boschma et al., 2015), and a system product (Song et al., 2016). In this paper we leverage such a map as a visual aid for design opportunity ideation.

3. Methodology: The Technology Space Map

We use the USPTO patent database from 1976 to 2016, instead of a small sample of specific patents, to empirically construct a technology network map to represent the total technology space. The data set contains 5,256,505 U.S. utility patents, each of which is classified in one or multiple IPC (International Patent Classification) classes. In the network map, different nodes represent different technology domains operationalized as IPC classes defined at 3/4/5/6/7-digit aggregation levels. The patent classification system provides a natural means to define almost all known technology domains, and categorize the patents belonging to different domains. Prior research has suggested 3-digit classes provide sufficient but not too much information on a map based on them, thus the best resolution for the ease of direct visual analytics (Leydesdorff et al., 2014; Yan and Luo, 2017b). Therefore, we use 3-digit IPC classes for mapping, whereas the finer-grained 4- or 7-digit classes can also be used to create and visualize maps. After removing several meaningless classes, there are 121 3-digit IPC classes, such as node "F02" for combustion engine and "B82" for nanotechnology.

The 121 nodes are connected in the network and positioned on the map according to their knowledge proximity. A qualified measure of knowledge proximity must capture the intuition that the knowledge required to design technologies in one class can also be easily used for designing technologies in the other. In the literature, various measures using the information of citations, classifications, inventors and so on in patent documents have been proposed (Yan and Luo, 2017a). Such measures are based on the structure of patent data and can be calculated using millions of patent document records to obtain statistical significance. In particular, a recent comparative study shows Jaccard index is a most representative choice among all because the network resulting from it are the most correlated with the networks base on other measures. Jaccard Index is calculated as the number of shared references of the patents in a pair of patent classes normalized by the number of unique references of patents in either class. The index value is in the range [0,1] and indicates the proximity of knowledge required in designing both technologies and the opposite of cognitive distance to conceive these technologies. More than 5 million US patent records and their citation information are used to calculate the proximity between any pair of the 121 patent classes. The use of the richest possible historical data ensure the best empirical approximation of the "total technology space".

The original network is highly dense, suggesting the technology space is high-dimensional. Thus mapping the technology space is equivalent to a projection from a high-dimensional space to a two-dimensional plane. Such a projection may result in different network map layouts, some of which are more informative than others. Force-directed algorithms are widely used to generate aesthetically pleasing network layouts via minimizing graph energy (Kobourov, 2012). Force-directed algorithms often produce locally optimal layouts for high-dimensional systems, but can easily reach a globally optimal layout for low-dimensional systems. Therefore, we first filter the original network to a maximum spanning tree (MST) that only includes the strongest 120 links that connect the 121 technology domains into a tree structure, i.e., the backbones of the technology space, significantly reducing the dimensionality of the technology space. On this basis, we ran the force-directed algorithm on the MST to reach a stable layout without link crossing. Figure 1 shows the resulting network map visualization. The relative positioning of technologies is generally satisfactory, e.g., "Electric Communication" and "Computing" are proximate while "Machine Elements" and "Infographics and Display" are distant.

Now it comes to the use process of the map as a visual aid for conceiving new applications of a focal technology in other domains for new design opportunities. For example, “Sphero” is a spherical rolling robot toy designed and commercialized by the company Sphero Inc. Sphero is propelled by a self-contained cart. It has an on-board micro controller unit, and users may manipulate its motion remotely via a smartphone or tablet. Assume the designers of Sphero need to explore new product lines, by applying the spherical rolling robot technologies that they have mastered to new applications in other technical domains than toys. The node on the map for toy designs is “Sports and Amusement”, where one can find most of the toy-related patents including those of Sphero in the corresponding IPC class.

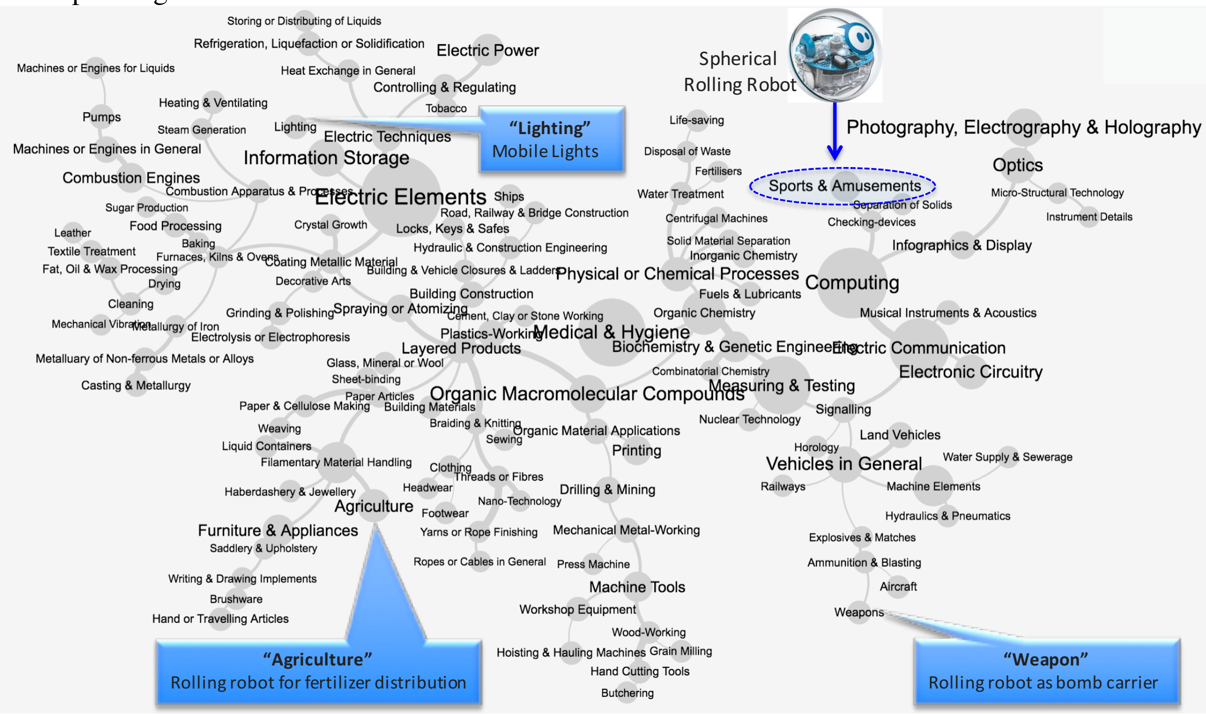

Figure 1. The technology space network map, overlaid with 3 design opportunities of applying spherical rolling robots to applications in other domains. Node sizes correspond to the total patent counts in respective IPCs.

The designers may browse the map to navigate the technologies across the technology space, which are distant or proximate to “Sports and Amusement” to different extents, to conceive out-of-the-box design opportunities of applying spherical rolling robots in those domains. For instance, observing “Lighting” on the map may inspire the designer about potential applications of spherical robots to providing mobile lights at home or in public spaces. Seeing “Agriculture” on the map may inspire the designer about agriculture uses of spherical rolling robots, such as soil loosening and fertilizer distribution on farmlands. “Weapon” may stimulate the idea to use spherical robots as bomb carriers. These simple ideas are annotated on the map in Figure 1. In these ideas, spherical rolling robots with basic functions, such as locomotion and remote control, can be viewed as a platform for design variants according to the specific design requirements defined by applications in the new domains. Note that, the ideas conceived via such a process are abstract on high-level design opportunities and directions, because the inspiration is provided at the level of domains, i.e. 3-digit IPCs.

4. Case Study: Explore Design Applications of “Neural Network”

Now we report a real exercise in which the technology space map was used to enhance the ideation for design application opportunities of “artificial neural network”. In July 2017, a group of undergraduate students at Singapore University of Technology & Design were entering an international innovation contest on designing novel and useful applications of “neural network”. This group of students brainstormed for two days, but only generated one idea that is to “*extract the emotional implications of text messages and modifying an image of a face to resemble the same emotion*.” This idea could be

classified in the neighbourhood around "Computing" on the technology space map. For broader search of more novel design applications of artificial neural network, we ran a 30-minute individual ideation session with the students browsing the technology space map. We provided each of the students with the map in Figure 1 printed on an A3 paper, and a brief introduction about how the map was constructed before the exercise. The students were asked to individually browse the map, and relate artificial neural networks to the technologies on the map for design opportunities, and annotate the conceived opportunities on the map with arrows to the nodes that stimulated respective ideas.
By analysing the 7 maps annotated by 7 students in 30 minutes, we found that 54 ideas of new design applications of artificial neural networks were conceived, with reported inspiration from 29 different technology domains that have varied distances to "Computing" in the technology space. Some of the ideas include suggesting fonts based on the semantics of a paragraph inspired by the node "Writing and Drawing Implements", neural network arts inspired by the node "Decorative Art", protein creation inspired by "Biochemistry & Genetic Engineering", and so on. In particular, as reported in Figure 2, many ideas were generated regarding the applications of artificial neural networks in rather distant domains from the main domain of artificial neural networks – "Computing". For example, 5 ideas were about applications of neural networks in food processing, and another 5 ideas were about applications in the domain of writing and drawing, which are distant from computing in the technology space. These results suggest that the map enable out-of-the-box thinking, and enlarge the knowledge distance between the perceived application domains and the designer's technology.

Figure 2. The map nodes that inspired the largest numbers of new ideas about the applications of the neural network technology. Numbers of ideas generated regarding a domain are reported in parentheses.

This case study aims to illustrate the utility of the total technology space map as a visual ideation aid. After the exercise, we sought for feedback from the students regarding their experiences of using the technology space map as a rapid ideation aid. All of them agreed that the visual technology map stimulated them to realize the relevance of some technologies or domains that they would not be able to perceive without browsing the map, due to the knowledge distance and their specialization and limited cognitive capacity to cross the distance. That is, the total technology space map enables out-of-the-box thinking for ideation beyond the designer's specialization and familiarity.

5. Discussion

The knowledge distances between different technologies in the technology space may condition the ability of the designer to relate his/her initial technology (e.g., spherical rolling robot, artificial neural network) and other technology domains (e.g., agriculture, vehicle, weapon) in the space. The case study above suggests that the total technology space map provides a macro picture of possibilities and might empower the designers to cross a greater cognitive distance to conceive design synthesis or analogy of different technologies and domains with a greater knowledge distance. Meanwhile the conceived ideas using the abstract map are about abstract design opportunities or directions. The designers also need to be aware of the conditioning effects of the knowledge distance on their ability to actually pursue the design and implementation of these design opportunities.

After a high-level design opportunity is conceived relating to a new domain, the designer may need to further exploit and learn detailed knowledge of the technologies in the domain, in order to generate more nuanced concepts that can be embodied and prototyped. For instance, the toy designers of Sphero can develop corresponding knowledge by working with the experts in a new domain of interest, e.g., agriculture, to actually pursue the perceived design opportunity. Another strategy for rapid learning is to read patents classified in the new domain. The designer may begin with the most recent or most cited patents that represent the most valuable and most foundational technologies of that domain. Alternatively, the designer may search for patents containing design information of particular functions, properties or artifacts.

In fact, we have integrated the map and such map-based functions as technology positioning (e.g., position "neural network"), new domain recommendation, and domain-specific patent retrieval (e.g., click a node to view patents and other information in the corresponding domain) in a computer aid system, i.e., InnoGPS, to enable interactive digital map browsing for design opportunity conception as well as rapid learning of design knowledge across domains. Figure 3 is a screenshot of InnoGPS. The screen shows the result of a search for "neural network" technologies in the total technology space. One can visually learn that most of neural network technologies are in the Computing domain, but also spread out in many other domains. Colour intensity indicates the number of neural network-related patents in respective domains. Particularly, the grey domains host no neural network-related patent and thus present novel design opportunities for designers to apply neural network technologies there. One can also find neural network and general patents in respective domains for rapid learning.

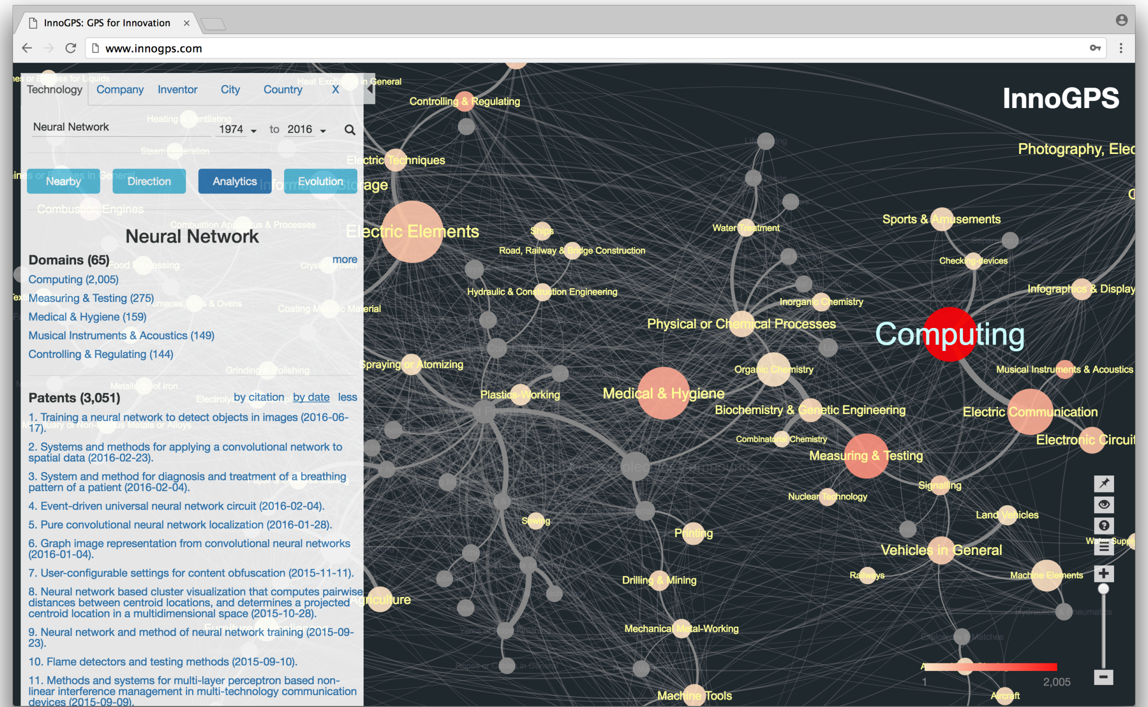

Figure 3. InnoGPS screen shot (http://www.innogps.com)

Interested readers can test use InnoGPS at http://www.innogps.com. In future research, machine learning based on designers' map browsing behaviours and artificial intelligence recommendations for designer's expressed or latent interests can be potentially added into the system to further enhance the human process of design opportunity conception. For instance, an algorithm can be developed to recommend the designers a mix of technology domains with near, moderate and far distances to the position of the initial technology of the designers. Such an artificially intelligent computer-aided ideation technology is aimed to make the previously intuitive human ideation of design opportunities more informed and supported.

6. Conclusion

In this paper, we have presented the total technology space map as a systemic visual aid to empower designers in conceiving new applications of technology for design opportunities. The designer may browse the map to navigate the technologies to conceive design opportunities that relate his/her technology to various technology domains in the technology space. The case study has suggested that the map may stimulate out-of-the-box thinking and enlarge the cognitive distance between perceived application domains and the original technology for new applications. Moving forward, such a hypothesis needs to be further tested with experimental data.

This research contributes to design creativity research and practice. The technology space map is aimed to be useful to support design opportunity conception at the very early stage of creative design processes. Traditionally, the conception of new design opportunity relies on human intuition, experiences and gut feeling. The technology space map makes the exploration of new design opportunities more guided and visually informed. Given that these benefits are only illustrated in a single case study in this paper, further research should conduct controlled experiments to compare such benefits with the ideation output without the map or with using traditional stimuli.

Meanwhile, the effectiveness of the technology space map for design opportunity conception might be affected by the design features of the map itself. First of all, the descriptions of technology fields may affect the conception. The same technology field can be described using different words, influencing human perception about the technology. In particular, the definitional resolutions of "technologies domains" also matter. The example network map in this paper is comprised of 3-digit IPC classes, which represent relatively large and general technology domains and may stimulate only high-level design opportunities or directions. In contrast, maps using 4- or 7-digit IPC classes may provide more nuanced inspiration. Also, patent categories defined differently in IPC, USPC, CPC (Cooperative Patent Classification) may provide different inspirations. Secondly, knowledge proximity between technology domains can also be measured in various ways. Different measures, in addition to Jaccard index used in this paper, may lead to different map structures, which in turn affect the navigation routes and browsing focuses, and thus cognitive conception outcomes. Different visualizations and structure layouts of the same network can also affect the effectiveness and outcomes of design opportunity conception. In addition, the browsing routes and navigation strategies over the map may also affect conception outcomes.

In general, we still have limited understanding of the influences of many factors on the effectiveness of the map in supporting design opportunity conception. In future research, human experiments on alternative map designs, navigation strategies and use contexts are most needed to explore potentially better maps that are more engaging and inspirational, as well as the contextual or process factors that condition the effective use of the map for design opportunity conception.

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