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OVERLAY PATENT NETWORK FOR ANALYZING DESIGN SPACE EVOLUTION: THE CASE OF HYBRID ELECTRICAL VEHICLES

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1. Introduction

Technology domains, such as robotics and hybrid electric vehicles, are made of various technologies that address interconnected engineering problems and perform closely related functions bounded together by the relatedness of their knowledge bases [Dosi 1982], [Arthur 2009]. This interrelatedness among technologies and the evolving nature of engineering problems and technical solutions make it difficult to predict the directions of evolution of technology domains and to systematically explore next innovation opportunities in the respective domains. It can be particularly difficult for embedded and specialized designers to foresee the direction of future technical developments because innovative efforts and self-reinforcing mechanisms often push them to specialize in narrowly-defined technologies. This exposes designers to the risk of overlooking wider changes happening around a given technology field.

The set of existing technologies and related knowledge used to solve the specific problems in a technology domain is defined as the “design space” of the domain. One can also refer to it as “design knowledge space”. A tangible understanding of the structure and evolution of the design space of a technology domain fosters creative thinking and illuminates the direction of the search for engineering design opportunities. Therefore, we develop a network-based methodology to visualize, analyze and predict the structure and evolution of the design space of a given technology domain. Specifically, the methodology is to overlay the design space of a specific technology domain and its expansion paths on the "total technology space", mapped as the network of patent technology classes connected according to their knowledge relatedness. With the overlay map, one can identify and locate the design space of a given technology domain as a subgraph of the total technology network and also analyze its evolution trajectories.

We present this technology network mapping methodology and apply it to analyzing the evolution of the design space of a rapidly evolving technology domain, hybrid electric vehicles (HEVs). HEV synthesizes an internal combustion engine (ICE) with an electric powertrain to combine the benefits of both ICEs and electric powertrains and achieve better fuel economy. In an HEV, battery-powered electric motor can provide the drive at low speeds where internal combustion engine is inefficient. The battery is often charged with electricity recovered from the excess energy of the engine when its load is low, or from some kinetic energy of braking. The design space of HEVs has rapidly evolved in the past three decades. Varieties of HEV system configurations were developed, and varieties of technologies were used in HEVs. The diversity of technologies in the design space of HEV makes forecasting the next HEV-related technologies particularly difficult, thus requiring a systematic analysis of the HEV

design space. In addition, to show the utility of our technology network map for forecasting purposes, we also provide statistical evidence on the strong conditioning effect of inter-technology knowledge relatedness on the domain's design space expansion into new technologies.
In the following, we introduce the building blocks of our theoretical and methodological framework and highlight our contributions to the existing relevant literature.

2. Related work

To analyze the design space of a technology domain, trace its evolution direction and identify future innovation opportunities for the domain, we first create a mathematical and visual representation of the total technology space and locate the domain within the space. The total technology space contains all known technologies with different proximities to each other in the space. We represent the total technology space in the form of a network (i.e., technology space map), in which nodes stand for different technologies and links represent the knowledge relatedness between them.
The literature on technical changes has extensively analyzed knowledge relatedness across technologies. For instance, prior work has investigated the theoretical relationship between technology relatedness and diversification at the firm and country level and knowledge spillovers across related technologies [Jaffe 1986], [Teece et al. 1994], [Verspagen 1997], [Breschi et al. 2003], [Hidalgo et al. 2007], [Bottazzi and Pirino 2010]. Such studies have shown that firms preferentially diversify in technological fields related to those in which they have already developed knowledge and capabilities. In engineering design, the functional distance between technologies has been analyzed to aid in design-by-analogy. Fu et al. [2013a,b], constructed Bayesian networks of patents (representing different technologies) based on functional similarities and analyzed how the distance of patents to a design problem in such a network may affect the effectiveness of their use as design stimuli. Specifically, they found that patents “near” the design problem in the network are more effective than those “far” ones in generating new solutions. Indeed, studies in various academic fields, including engineering design, economics, and cognitive and network sciences, have shown evidence that it is easier to understand and successfully use knowledge that is at a moderate cognitive distance from what an agent already knows [Wuyts et al. 2005], [Uzzi et al. 2013], [Fu et al. 2013a,b]. However, this does not deny the potential of combining very distant pieces of knowledge for more novel designs, whereas such potential is difficult to transform into successful outcomes. Clearly, a domain is not a cognitive agent. However, its evolution depends on decisions and actions taken by designers and firms and conditioned by the properties of the underlying technologies. In any case, having a big picture of the technology domain is useful for navigating through the wider space of technologies surrounding the domain to search for next innovation opportunities. For this reason, we hypothesize that the direction of future developments of a technology domain can be predicted by the knowledge proximity between itself and unexplored technologies, which current design activities in the domain have relied on, to different degrees.
In engineering design research, a patent database has been used for design information retrieval, knowledge discovery and design aid [Szykman et al. 2000], [Mukherjea 2005], [Fu et al. 2013a]. For example, Charkarabarti et al. [1993] used patent citations to measure the interrelatedness between different technologies. Fu et al. [2015] analyzed the text of patent documents to measure the analogical distance between different patent technologies. Engineers can use the knowledge distance information to search for inspiration from patented technologies outside their current technology domain to solve design problems in their home domain. In addition, many computational tools have been developed to aid in the search of patents in terms of contradictions to support the use of TRIZ [Altshuller and Shapiro 1956], [Cascini and Russo 2007]. Other work has been done to identify unexplored areas for possible technology development by mining and analyzing patent data [Lee et al. 2009], [Son et al. 2012], [Yan and Luo 2016a,b].
However, in general, previous patent analyses in the engineering design field often focused on a small sample of patent records and studied single technologies rather than generic types of technologies and domains of technologies. Different from other contributions to the literature, we analyze the entire US Patent and Trademark Office (USPTO) database to model and approximate the total technology space and focus our analysis at the technology domain level, which includes many different, but related, technologies. Very recently, a data visualization technique, overlay maps, has been developed and

applied to mapping technology relatedness using patent data [Kay et al. 2014], [Leydesdorff et al. 2014], [Yan and Luo 2016a]. This technique involves constructing a map in which nodes are technology classes, as defined by some official patent classification system (United States Patent Classification – USPC, International Patent Classification – IPC, or Cooperative Patent Classification – CPC), and links represent knowledge relatedness between classes. Then, the network can be overlaid with the patenting activities of the design agents, such as inventors or firms, as done in Kay et al. [2014], Leydesdorff et al. [2014] and Yan and Luo [2016a].

The patent technology network map can be used to overlay and, thus, highlight the design space of a technology domain (e.g., HEV) in the total technology space. Such a network overlaying method allows for a visual inspection of how spread a domain's design space (i.e., technical knowledge base) is and the changes of its design space over time. In this study, we adopt the overlay mapping technique to analyze and predict the evolution paths of the design space of a given technology domain. This is of important use for domain-specific engineers designing specific technologies and also for strategic planners exploring technology directions at the corporate and government levels.

3. Method and data

3.1 Technology space map

In this paper, we use the entire United States Patent and Trademark Office (USPTO) patent database from 1976 to 2006 to empirically create a technology network that approximates and represents the total space of the known technologies of human society to date. The data set contains 3,186,310 U.S. utility patents, and each of them is classified in one or multiple IPC (International Patent Classification) classes. In our patent technology network, different nodes represent different technologies, which are operationalized as three-digit IPC patent classes. IPC patent classes are defined at different aggregation levels, for example, three-digit and four-digit level classes. For the best resolution of the technology space and for ease of visualization and analysis, we chose three-digit classes to represent different technologies as nodes in the network. As a result, we obtain such nodes as F02, which contains patents for combustion engine technology, and B82, which contains patents for nanotechnology. The total technology network contains 121 nodes, which represent all three-digit IPC classes except several undefined ambiguous ones. The total technology network approximates the total technology space.

The 121 three-digit IPC classes, are connected to the degrees according to the knowledge relatedness between them. Similar to the Jaccard index [Jaccard 1901], [Small 1973], we measure the relatedness of a pair of technology classes by computing the "normalized co-reference" index [Yan and Luo 2016b], which is 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 is calculated as follows.

$$\text{CoReference} = \frac{|C_i \cap C_j|}{|C_i \cup C_j|} \tag{1}$$

where C_i and C_j denote the set of references of all patents in technology class i and class j, respectively; $C_i \cap C_j$ is the number of patents cited in both class i and class j; and $C_i \cup C_j$ represents the number of unique patents cited in either class i or class j. The index value is in the range [0,1] and indicates the relatedness of knowledge pieces required in designing both technologies. If the patents in two patent classes share an identical set of references, it indicates that the knowledge bases of both technologies are identical, and this knowledge relatedness measure is at its maximum value. We have also computed alternative measures of the technology relatedness [Yan and Luo 2016a]. Our findings are robust to the relatedness measures.

The original technology network built on the three-digit IPC classes and co-reference link weight measure is extremely dense. Out of the total 7,260 (=121×120/2) possible links among all pairs of technologies, only 65 of them are disconnected (i.e., relatedness=0). A visualization of that network will not be informative. Therefore, we apply the network filtering technique introduced by Yan and Luo [2016b] to filter the original dense network. This filtered network (visualized in Figure 1) contains only the strongest 1,083 links, accounting for only 15% of the total original links, but maintains 92% of the power of the original full network map on predicting the diversification of the innovating agents across all links and pairs of fields.

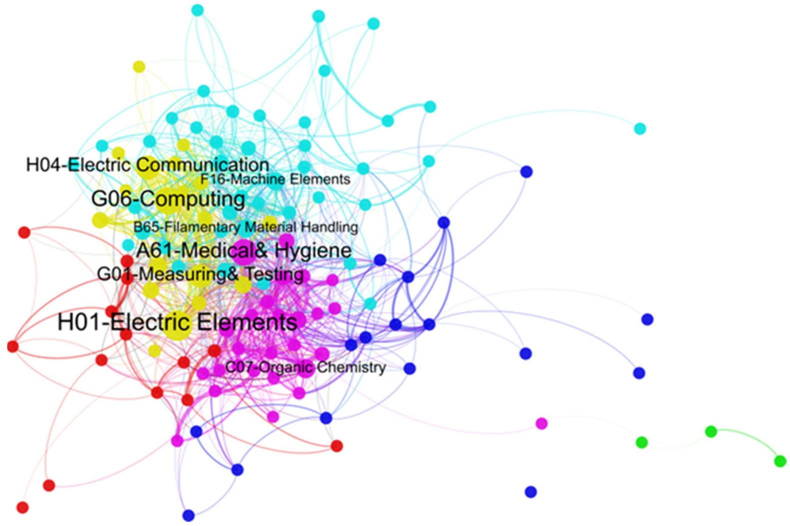

Figure 1. The filtered technology network. Clusters of technologies were identified using the Louvain community detection method [Blondel et al. 2008] and colored accordingly

3.2 Using technology network to analyze the design space of a specific technology domain

We aim to apply the technology network map to analyze the evolution of a specific technology domain. Hybrid electric vehicles (HEVs) are an emerging technology domain, which has been developed primarily in the past three decades and is still rapidly growing. Because of its advantages in fuel economy compared with traditional vehicles, HEVs have attracted extensive attention and investment from automotive companies and R&D organizations around the world. Having a better knowledge of the design space of this domain and its evolution trajectories may potentially provide guidance for future design and decision making for innovation related to HEVs.

We were able to identify the U.S. patents for technologies related to HEVs in the special category "903--Hybrid Electric Vehicles" created by the United States Patent and Trade Mark Office. This category contains 1,692 patents assigned to 40 three-digit IPC classes. This collection of patents can be used to approximate the design space of the HEV domain. Figure 2 shows the cumulated number of HEV-related patents over time and the patents of the top five patenting companies in the HEV domain, namely, Toyota, Honda, Nissan, Ford and General Motor (GM). The curves show that the development of HEV-related technologies experienced a long infancy period and started to accelerate from 1995. The figure also shows that three Japanese companies occupy the top three positions all the time. In addition, most HEV-related patents have been granted in the IPC classes "vehicles in general (B60)", "electric power (H02)" and "machine elements (F16)", "combustion engines (F02)", "computing (G06)", etc., which represent a combination of mechanical, electrical and computing technologies.

In the results section, we will show a procedure of overlaying the total technology network map (Figure 1) with the design space of HEV and the HEV-related design space of the leading firm, Toyota. Before that, we first statistically analyze the expansion of the HEV design space and show that it is significantly conditioned or driven by the knowledge relatedness between corresponding technologies. That is, the design space of HEVs has expanded to include those new technologies with higher relatedness to the technologies previously used in HEVs, than other unexplored technologies. This evidence provides the foundation for the use of a network map of related technologies for analyzing the evolution or expansion of the design space of a specific technology domain in the total technology space.

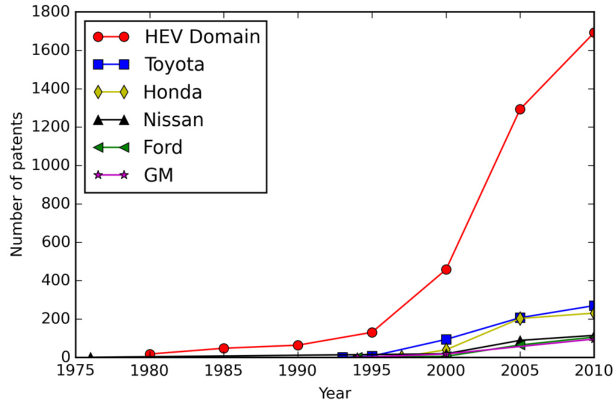

Figure 2. Cumulative number of HEV-related patents over the years

4. Results and discussion

4.1 Knowledge relatedness and design space expansion

Figure 3 shows that, as the design space of HEVs expands to cover an increasing number of technologies (Figure 3A), the "coherence" among these HEV-related technologies in its design space is constantly declining (Figure 3B). Here, coherence is calculated as *the average relatedness between the classes that had HEV-related patents at a given point in time.* We follow the literature (e.g., [Leten et al. 2007] and [Teece et al. 1994]) to label this measure as the "coherence" among different technologies, and a high coherence of the design space of a domain indicates that the designs in the domain are based on a set of technologies with high knowledge relatedness to each other. Therefore, the trends in Figure 3 might imply that the HEV design space first expanded and utilized the most related technologies, and thus, the later-engaged technologies would be naturally less related and less coherent with the earlier ones. Note that, despite its continual decline, the coherence of the HEV design space is always greater than the average coherence between all 121 technologies in the total technology space (the dashed line in Figure 3B).

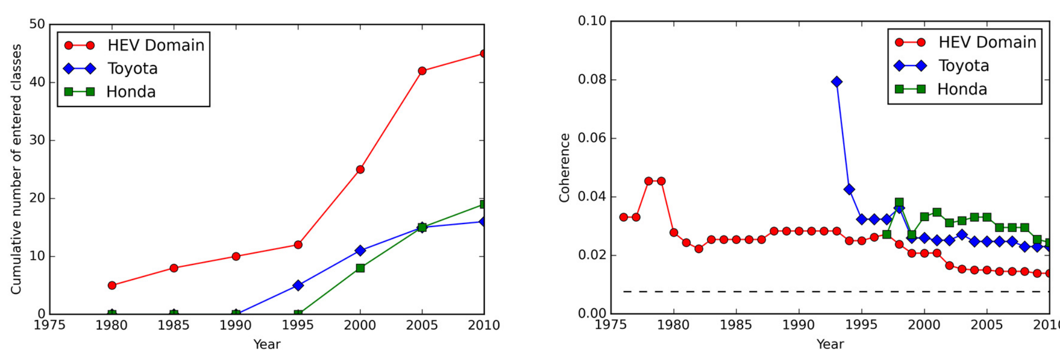

Figure 3. Expansion of the design space of HEVs and the decline in knowledge coherence

We also measured how frequently the HEV design space had expanded to technologies that had higher relatedness to the prior technologies already included in the HEV design space than other unexplored technologies in the space. A technology's relatedness percentile is expressed as a percentile rank of its relatedness to the prior technologies in the design space of interest, which is relative to all of the other technologies not previously in this specific design space. Figure 4 reports the cumulative probability distribution of the relatedness percentiles of technologies newly included into the design space of the HEV domain in general and HEV-of-Toyota and HEV-of-Nissan. The dashed line stands for the distribution consistent with the null hypothesis, in which new technologies are explored randomly regardless of the domain's relatedness to those technologies. The curves in Figure 4 clearly show that the HEV design space is more likely to expand to cover technologies with which the prior design space of HEVs has a higher relatedness than a lower one. The top 10% technologies, by their high relatedness to the current design space, explain approximately 90% of all technologies newly included into the design space of HEVs. The result for the HEV design space is statistically significant and also holds true for the two leading HEV manufacturers, Toyota and Honda.

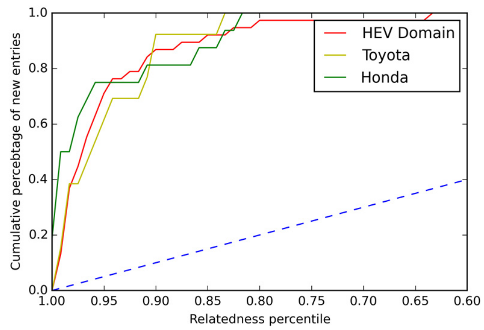

Figure 4. Distribution of the new entries' relatedness percentile

To further test the hypothesis that the HEV design space tends to first use more related than less related technologies at any given point of time, we calculated and compared the geometric means of the values of the relatedness of newly used technologies versus unexplored technologies to currently used technologies. We found that newly used technologies are statistically better related (with a higher relatedness value) to the current design space than technologies that remain unexplored for the innovation of HEVs. We also computed the ratio using alternative measures of technology relatedness [Yan and Luo 2016a] and found that results are robust to the measures used. These results suggest that the design space of the HEV domain tends to expand to new technologies that are more related to the technologies previously in the HEV design space than those less related technologies.

Therefore, the trajectory of the expansion of HEV design space follows the network paths indicated by the relatedness to technologies included in the current HEV design space. The design space expansion mechanism is largely driven by the relatedness between unexplored potential new technologies and previously used technologies in the current design space. The above statistically significant results suggest that the technology network provides information (i.e., the relatedness between various technologies) on what new technologies a domain will evolve into in the future given its design space's prior positions on the total technology space map.

In the following section, we further show how the total technology space map can be used as a tool for inventors and R&D managers at firms and governments to visualize and analyze the design space structure and evolution of their domain, and explore where they should focus their inventive efforts for future expansion in the continual search for innovation.

4.2 Visualize the HEV design space and its expansion paths within the total technology space

In Figure 5, the network map of total technology space (Figure 1), as the base map, is overlaid with the technologies that the design space of HEV incrementally included over time (i.e., the patent classes where the HEV patents are assigned) and the most likely longitudinal expansion paths among them. The technologies in the HEV design space are highlighted in blue and labeled with their IPC class titles and the earliest year when a HEV-related patent was granted in the patent class representing this technology. The node color intensities denote the numbers of HEV-related patents in the corresponding classes as of 2010.

A directed arrow in purple highlights the strongest (in terms of the relatedness value) link from any of the technologies previously in the HEV design space to a technology newly engaged into the HEV design space, implying the most likely expansion path into the new technology. We have statistically established the expansion mechanism that the design space of a domain is most likely to expand to utilize new technologies via the strongest links. When identifying the strongest path to a newly utilized technology, we only consider those technologies that were previously in the HEV design space and are still active and useful for the design of HEVs to the date of expanding to the new technology. Here, "active" means that, in the most recent five years, there was at least one HEV-related patent granted in the class representing the corresponding technology. The relatedness *percentile* of the highlighted links, i.e., the percentile of all links of the starting technology that have a relatedness value equal to or lower than the highlighted most likely expansion path, are also reported on the map. The high values of the highlighted relatedness percentiles suggest strong compliance with the relatedness-driven expansion mechanism.

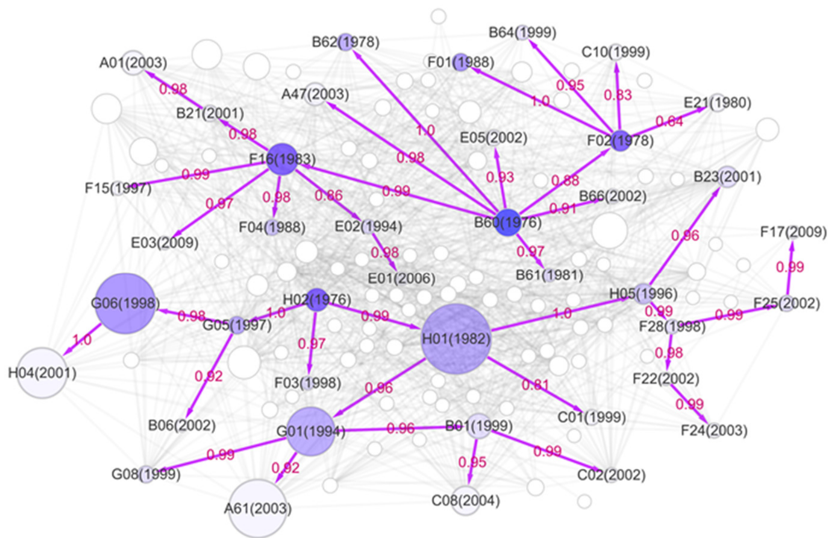

Figure 5. The total technology space map overlaid with the HEV design space and its most likely expansion paths (the titles of the highlighted technologies are provided in the appendix)

The overlaid network map clearly reveals that the HEV design space firstly emerged on the basis of two technologies, i.e., "vehicles in general" (B60, 1976) and "electric power" (H02, 1976), in 1976. Over the next few decades, these two technologies remained the most popular for HEV-related patenting. The HEV design space then expanded from these two original technologies into others, which gradually formed two separate clusters. The cluster originating from "vehicles in general" (B60, 1976) is more concerned with basic hybrid schemes and mechanical engineering, such as combustion engines (F02, 1978), machines or engines in general (F01, 1988), fuels and lubricants (C10, 1999), machine elements (F16, 1983) and mechanical metal working (B21, 2001). On the other hand, the cluster originating from electric power (H02, 1976) is more concerned with electric and electrical engineering, such as electric techniques (H05, 1996), controlling & regulating (G05, 1998), computing (G06, 1998), electric communication (H04, 2001), and signaling (G08, 1999). The overlay map clearly shows the dual-cluster structure of the design space of the HEV to date and the parallel evolutionary trajectories over time.

Such structures and trajectories clearly show that the design of HEVs is enabled by the simultaneous development of mechanical and electric/electrical technologies. Compared to traditional internal combustion engine vehicles, the HEV powertrain uses more electric technologies, such as motors, regulators, generators and batteries, which in turn require a greater number of different sensing and controlling technologies than traditional vehicles. Moreover, when running at low speeds, HEVs can be entirely driven by the electric power stored in batteries to avoid the low efficiency of engines at low speeds, so the requirements of combustion engines in HEVs are also different from those in traditional vehicles. Meanwhile, when HEVs are powered mainly by batteries, heat management is significant because of the high discharge power required for vehicles. Therefore, special engines, heat management system and the corresponding mechanical elements need to be developed specifically for HEVs.

4.3 Overlay HEV-related design space of Toyota

A technology overlay map can be further applied to visualize and analyze the HEV design space of a company and its main expansion paths. Here, we choose Toyota, which has the largest number of HEV-related patents, as an illustrative example. Figure 6 shows the same base map of the total technology space as in Figure 5, but this map is overlaid with only Toyota's HEV design space and expansion trajectories. One can observe that Toyota's HEV-related design efforts started first in "vehicles in general (B60)", "combustion engines (F02)" and "machines or engines in general (F01)", and then expanded into "electric power (H02)". These technologies served as the basis for further expansion in two respective large clusters of technologies. Over time, Toyota has developed a HEV design space that covers 16 technologies. Most of Toyota's HEV-related design activities concentrate around two foundational technologies, "vehicles in general" and "electrical power", over time.

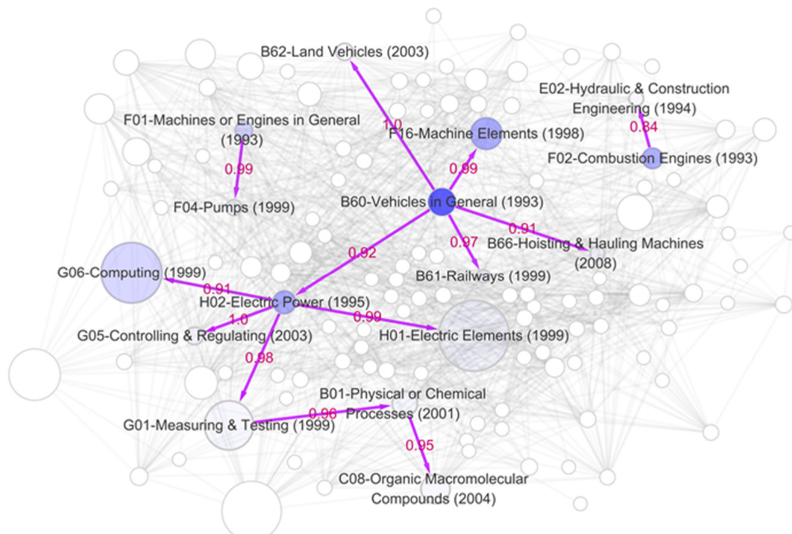

Figure 6. The total technology space map overlaid with the HEV design space of Toyota and its most likely expansion paths

5. Summary

In this paper, we have presented a new methodology that uses an overlay technology network map to visualize and analyze the structure and evolution trajectories of the design space of a technology domain in the total technology space. Specifically, we demonstrate this methodology in analyzing the design space of the HEV domain and the HEV-related design space of Toyota Motor Company. This methodology may aid engineers and technology firms in the search for innovation opportunities for their technology domains. The methodology is grounded in the relatedness-driven mechanism of the evolution of a design space, i.e., the expansion of the design space of a domain or a firm is strongly driven by or conditioned on the knowledge relatedness between the new technologies and the ones already in the design space. We show statistical evidence that the design space of a domain, i.e., HEV, or a company, e.g., Toyota, primarily expands into new technologies more related to technologies in its prior design space. That is, for designers and technology firms, viable innovation opportunities for the future are most likely to be found in the neighborhood surrounding their current design spaces in the total technology space.

Our work contributes to the growing design research and design theory literature, including the studies on infused design [Shai and Reich 2004], C-K theory [Hatchuel and Weil 2009], knowledge genome [Reich and Shai 2012], integrated innovation process [Luo 2015] and design-by-analogy [Fu et al. 2015], which have increasingly suggested the importance of managing knowledge across and within technology domains and systematically exploring the knowledge space for creativity and innovation. Our work responds to the calls from such prior design research, with a data-driven and scientifically grounded knowledge management tool to support engineers and technology firms in analyzing their own design knowledge space in relation to the unexplored technologies in the total technology space, for the interest to search for the next innovation opportunities. The core of the tool is the empirically-built total technology network map and the overlay technique, which embody and concretize the previously conceptual total technology space and the design space of a domain or an innovation agent within the total space tangible. Therefore, with this technology network map tool, the search for the next innovation opportunities can be conducted by analyzing the design space of a domain or agent overlaying the total technology space map. This present paper should not be viewed as a conclusion but an invitation for feedback and improvement on such a methodology. Future research may apply the same method and tool to analyze more technology domains and more companies.

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Appendix

Table 1. Titles of 3-Digit IPC Classes Highlighted in the Overlay Maps (Figure 5 and Figure 6)

Class ID	Class Title	Class ID	Class Title
A01	Agricalture	F01	Machine or Engines in General
A47	Furniture & Appliance	F02	Combustion Engines
A61	Medical & Hygiene	F03	Machines or Engines for Liquids
B01	Physical or Chemical Process	F04	Pumps
B06	Mechanical Vibration	F15	Hydraulic Pneumatics
B21	Mechanical Metal Working	F16	Machine Elements
B23	Machine Tools	F17	Storing or Distributing Liquids
B60	Vehicles in General	F22	Steam Generation
B61	Railways	F24	Heating & Ventilation
B62	Land Vehicles	F25	Refrigeration, Liquefaction or Solidification
B64	Aircraft	F28	Heat Exchange in General
B66	Hoisting & Hauling Machines	G01	Measuring & Testing
C01	Inorganic Chemistry	G05	Controlling & Regulating
C02	Water Treatment	G06	Computing
C08	Organic Macromolecular Compounds	G08	Signaling
C10	Fuels & Lubricants	H01	Electric Elements
E01	Road, Railway & Bridge Construction	H02	Electric Power
E02	Hydraulic & Construction Engineering	H04	Electric Communication
E03	Water Supply & Sewerage	H05	Electric Techniques

For more information about IPC classes, please visit the web page of International Patent Classification, at http://www.wipo.int/classifications/ipc/en/.

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