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Causality-based function network for identifying technological analogy

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ABSTRACT

This paper suggests a cause-and-effect function network (CEFN) to support technology innovation in a direct way. To support this CEFN, a cause-and-effect relationship, a function model and an ontological approach are proposed. In the CEFN, technologies from different domains can be connected because defining technologies as functions provides abstractive, representative and formal expressions of them. Using ontology guarantees linguistic disambiguation in defining or searching heterogeneous technologies. Consequently, this paper summarizes construction of a CEFN which can be used as a searching system, by which users can get results by making a query using only 'Action–Object' (verb–noun) combinations. The proposed system can be used both for problem solving and for discovering technological opportunity. In this paper, a method consisting of procedure and analyses to build the CEFN is suggested, and a case study is performed to demonstrate the suggested method and system.

1. Introduction

TRIZ, the theory of inventive problem solving, has been getting spotlight in technology innovation. TRIZ is a set of practical tools or methods to invent technologies, solve problems, and foresee technical trends, such as the 40 inventive principles, ARIZ (Algorithm of Inventive Problem Solving), the matrix of contradictions, laws of technical system evolution, and substance-field analysis (Altshuller, 1984; Mann, 2001, 2002b). The representative and basic tool of TRIZ is the 40 inventive principles which are inventive patterns extracted from about 40,000 patents that Altshuller, the inventor of TRIZ, had reviewed (Altshuller, Shulyak, & Rodman, 1997; Terninko, Zusman, & Zlotin, 1998). It has been largely admitted that these principles are precious in solving technological problems. And experts from various technical and non-technical fields have found and validated the usefulness of them with plentiful applications (Dourson, 2004; Hipple, 2005; Retseptor, 2003).

However, these principles are often criticized for being too abstract, their illogical sequencing, or being overlapped with one another (Cong & Tong, 2008; Mann, 2002a). and the most critical problem is that those principles are not easy to utilize for ordinary users except for TRIZ experts (Mann, 2002a). The following example is one of the application cases of the 40 inventive principles (Fig. 1). The problem in this example is ship overturning due to inflow water when its storm or typhoon, and the solution is drilling a hole in the deck. So even water flows into the ship, it runs to the bottom so that it helps to keep the balance of the ship. This simple and excellent solution was devised by applying the principle 22, 'convert harmful to useful'. This example has been largely introduced to inform the excellence of TRIZ.

However, the two problems can be pointed out in this example. First, ordinary users cannot easily select a principle among 40 principles. Like Columbus's egg, it may seem very easy to find solution after seeing the results. But deciding the most appropriate principle is elaborate and exhausted work. To utilize the 40 inventive principles at one's pleasure, therefore, they should be totally embedded to user's mind through many experiences and much time. Second, although users select a proper principle, they should still reflect on how to apply that principle to their problem. And even relevant examples to each principle are often few, unconvincing or obsolete (Mann, 2001, 2002a), so they cannot be a great help to utilizing principles and specifying solutions.

To circumvent these difficulties and drawbacks of the 40 inventive principles, this paper suggests a cause-and-effect function network (CEFN) to support technology innovation in a direct way. The CEFN is where functions, abstractive and representative expressions of technologies, are connected on the basis of cause-and-effect relationships of technologies.

The CEFN is constructed by applying three concepts: cause-and-effect relationship, function analysis, and ontology. The first concept is that cause-and-effect relationships comprise the basic components of a function network (directed acyclic graph) that consists of nodes (causes or effects) connected by links (causalities). In technologies, causes mean inventive principles and effects mean purposes. Once a technology is defined as a cause-and-effect relationship, each cause or effect can be an interface to which other cause-and-effect relationships can be connected, for two reasons. (1) An effect of a certain relationship can be a cause of another relationship and vice versa; thus, a network can be extended

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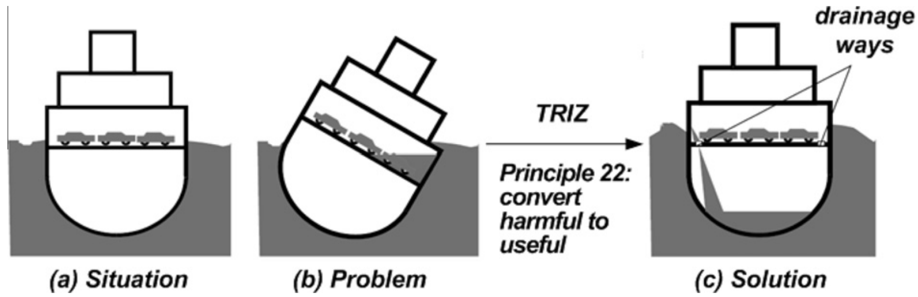

Fig. 1. The example of TRIZ employing the principle 22 (Kim, 2004).

increasingly. (2) Technologies that share a cause or an effect can be connected after their cause-and-effect relationships have been defined.

The second concept is that function is a formal expression of a technology; function offers a standard to connect technologies. To express a function, the proposed method uses 'Action–Object' (AO) forms as function models. Therefore, a defined cause and effect are expressed in AO format which is called a causal or an effect function. For example, the effect function of washing machine can be defined as 'wash clothes'. Because technologies are defined as functions, we can both understand the core of technologies and have a standard form to express technology.

The third concept is that an ontological approach can facilitate connections of cause to effect. Different technology fields use distinct terms. Therefore, even if two technologies share a cause or an effect but express them differently, the connection between them may be overlooked. For example, 'wash' in the function 'wash clothes' is almost synonymous with other verbs such as 'clean', 'launder', and 'remove'. That is, the functions 'wash clothes' and 'clean clothes' must be identified as being the same. Considering synonyms, hypernyms and hyponyms allows identification of groups of similar defined functions, and connection of these functions in a network. To do this, WordNet from Princeton and the Functional Basis from the National Institute of Standards and Technology (NIST) as domain ontology are adopted to refer to synonyms, hypernyms, hyponyms and lexical hierarchy.

To build a CEFN, this paper proposes a method that consists of procedure and analyses. The overall procedure is composed of three steps: analyzing cause-and-effect functions from technologies; building a function hierarchy; and actually building the CEFN.

This paper is organized as follows. The theoretical background is presented in Section 2. The methodology with the overall procedure and the system architecture is presented in Section 3. A case study is illustrated in Section 4. Conclusions and outlines of future work are given in Section 5.

2. Theoretical backgrounds

2.1. Cause-and-effect relationship

The basic concept of the proposed method is simple: identify and exploit cause-and-effect relationships. Almost all phenomena have a cause-and-effect relationship. Since causality is one of the most basic ways of thinking, cause-and-effect relationships facilitate understanding of phenomena. Furthermore, phenomena which are defined as cause-and-effect relationships can be connected to other phenomena if the effect (or cause) of one relationship is a cause of another relationship. For simple example, the effect of a motor can be the cause of a fan or a washing machine. Similarly, technologies that share either a cause or an effect can be collected together. A fan and a washing machine have different effects but operate on the almost same principle (i.e., rotation), so that they can be linked to a common cause. By employing the concept of cause-and-effect relationship, technologies can be connected to form a network.

Most importantly, given pre-defined and recognized cause-and-effect relationships, when we want to know either a cause or an effect of something, then we can naturally infer it based on causality. Thus, a network based on causality can be utilized either to determine a cause or identify an effect, which are the major contributions of this study. Even if a technology includes complex processes, components or composition, the technology can be easily understood if it is defined as a single cause-and-effect relationship.

As a study based on the concept of causality for technology innovation, Directed Variation describes a way of conducting problem solving and systematic innovation (Dewulf, 2006; Verhaegen, D'hondt, Vertommen, Dewulf, & Duflou, 2009). This study focuses on a properties and functions of products. A property, as an attribute of a product, is 'what a product is or has'; it is mainly expressed using adjectives. A function, as a useful action, 'is what a product does or undergoes', and is mainly expressed using verbs. This study takes 'property' and 'function' as the key concept because a property brings functions. For example, a protruded product brings the possible functions 'holding' or 'cooling', and a porous product brings the functions 'absorbing' or 'filtering'. In brief, a property acts as a cause to achieve a desired effect, and a function as an effect of a property. Therefore, given developed property-function connections as search parameters, users can learn how to achieve a function, what that function achieves. Learning to achieve is related to problem solving; what they achieve is related to product or system innovation in that finding new functions from new properties in an existing system or product can lead to identification of new markets.

2.2. Function

The core process of the suggested method of building the CEFN is to define a cause-and-effect relationship in a certain technology; this is a problem of knowledge representation. The concept of function can define and represent technologies, so is it suitable to this job. According to TRIZ, function means "the action changing a feature of any object" (Savransky, 2000). However, function has a more important meaning, in that expressing a technology as function provides an abstractive and representative expression of that technology (Chulvi & Vidal, 2009). Defining a function of a particular technology can simultaneously simplify the representation of that technology and facilitate understanding of the core of the technology.

To represent functions of technologies, one appropriate approach is the Subject–Action–Object (SAO) model which is grammatically formed into 'noun–verb–noun' combinations. In technologies, subjects and objects may refer to components of the system, and actions may refer to functions performed by and on components (Cascini, Fantechi, & Spinicci, 2004). For example, we define a SAO model of a hammer simply: the subject is the hammer itself, and the object can be a nail. The action of a hammer is 'impact' or 'drive'. As a result, the SAO model of a hammer is 'Hammer drives nail.' The SAO model has been widely used to support semantic analysis for various purposes like analyzing patents, measuring patent similarity, and evaluating patent infringement (Bergmann et al., 2008; Cascini & Russo, 2007; Cascini & Zini, 2008; Cascini et al., 2004).

However, a subject may not be necessary when defining a function; an Action–Object (AO) construction may be sufficient (Hirtz, Stone, McAdams, Szykman, & Wood, 2001) because the subject in the SAO model is the technology or product itself. Excluding the subject provides a simpler and more abstractive expression of a technology than does the SAO model, and this simplicity increases the searchability of the system to be built. Therefore, in this study an AO expression is adopted as a model to express a function; i.e., once a cause-and-effect relationship of a certain technology is understood, then a cause and an effect are expressed as AO expressions, which are called a causal function or an effect function respectively. Because both causes and effects are expressed in the same AO format, they can be connected to each other.

2.3. Ontological approach

The end goal of the proposed method is to build a CEFN that can be constructed to include a search interface. Users can use it to find common causes or previously-unrecognized effects. To offer the searching system of the CEFN, the searchability of the system must be maximized, to enable users to exploit the system with maximum effect.

If two or more technologies have the same inventive principles but different terms are used to define them as functions, then establishing the relation between them and building the CEFN become difficult. The same problem occurs when technologies have the same effects or purposes. For a simple example, if a user query includes the word 'remove', the search results should include technologies whose function models include not only 'remove' but also synonyms such as 'eliminate' and 'dispose'. To meet this requirement, the ontological approach is adopted.

An ontology is an explicit specification of a conceptualization (Gruber, 1995). In general, an ontology is used to assist in communication between humans or systems (Jasper & Uschold, 1999). In this paper, WordNet, as a lexical ontology, is adopted to establish relationships among synonyms, hypernyms, and hyponyms of words used in defining causal or effect functions. Also the function basis from NIST is employed to refer to the hierarchy of technological terms. This ontological approach complements construction of the function network in which technologies from diverse domains are linked to each other although their functions are defined using different terms.

3. Method

The CEFN is constructed in three steps (Fig. 2). The first step is cause-and-effect function analysis in which the input is a set of patents and the output is a set of cause-and-effect functions. Cause-and-effect function analysis is comprised of SAO analysis, causality analysis, and function modeling. The second step is to build function hierarchy. In this step, the terms used in defined functions are expressed into ontological representations that form a hierarchy. The final step is to build a CEFN from the results of the first two steps. Detailed explanations of each step follow.

3.1. Cause-and-effect function analysis

The goal of this study is to build a CEFN using information from patents, which are formal documents containing valuable technology information. The first step of the proposed method is to analyze cause-and-effect functions from patents that will be fundamental data of network to be built. In the cause-and-effect function analysis, we first find cause-and-effect relationships in technologies and then convert them to cause-and-effect functions.

For example, patent US5031156 is about "Method and apparatus for detecting and counting articles". In detecting and counting articles, usually the folded forward edges can be used to count articles. The physical part is directly used to count articles. This physical counter, however, has the disadvantage of wearing after prolonged use. To cover this problem, this patent suggests a method of injecting pressurized air toward surface of the passing articles. In this technology, articles, moving along a delivery path, are counted by directing a stream of pressurized air toward one major surface of the passing articles. Then sensors arranged about the air stream detect the acoustic signal from the vibration of the articles. As this technology does not rely on physical contact, so components cannot wear out. In doing so, accuracy of counting articles can be higher than before as well.

Firstly, we can define this patent's effect function, which is 'count articles'. The inventive principle of the patent is 'vibrate articles', or possibly 'inject air'. Actually, no definite rule exists which can be used to define causal function. The point is that a representative causal function should be selected that shows the novelty of the technology. An effect function should also express a representative value of the technology. In this patent, the core idea is 'vibrate articles' rather than 'inject air'. Thus, we can define the cause-and-effect function (Fig. 3) of the patent.

Analyzing cause-and-effect functions by hand is difficult, because reading and understanding patent documents is difficult and time-consuming, and because extracting and choosing a representative causality of a technology is also difficult. Therefore, to help to analyze cause-and-effect functions, the systematic process and tools are suggested (Fig. 2, upper halves of boxes). SAO analysis can be performed automatically using Natural Language Processing (NLP) technology. Knowledgist™ (www.invention-machine.com) is an NLP tool that selects subject (noun), action (verb), and object (noun) from patents documents and then constructs SAO lists. Once a document is converted to SAO lists, they help to understand the function of the patent because SAO structure includes an AO combination.

Second, causality analysis is performed to select cause and effect functions from the SAO list. Patents, as formal documents, include several components, including the title, abstract, claims, description, background, and International Patent Classification (IPC) code (WIPO, 2010). Those fields are different from features or significance in understanding patent and analyzing causality. Several useful suggestions to analyze causality according to each field are as follows.

- Title: In general, the title is the most representative expression of the technology. It usually describes value or purpose rather than cause or principle. So, the title is very useful in selecting effect function.
- Abstract: Title is useful but not enough to understand the technology sufficiently. The abstract is the second most representative information of technology. Furthermore, the abstract generally states both the purpose and the principle of the technology. Therefore, the abstract is useful in selecting both cause and effect function.

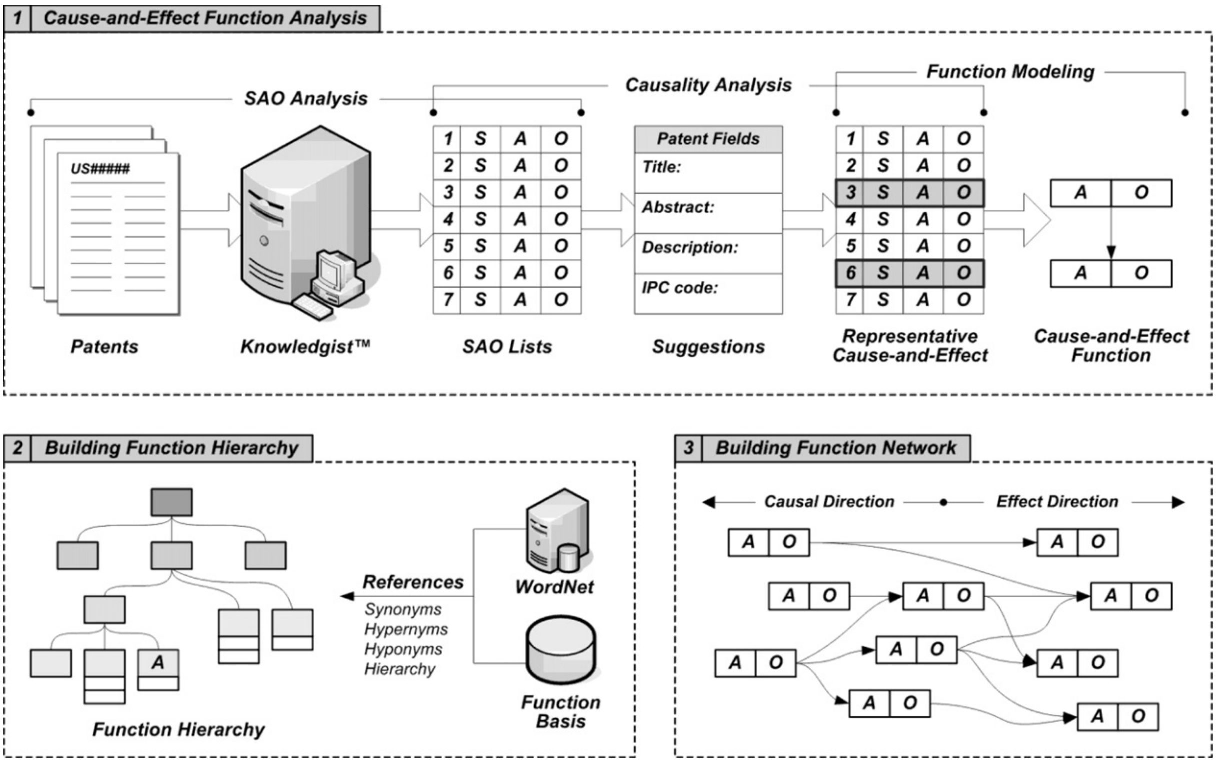

Fig. 2. The overall procedure of the proposed system.

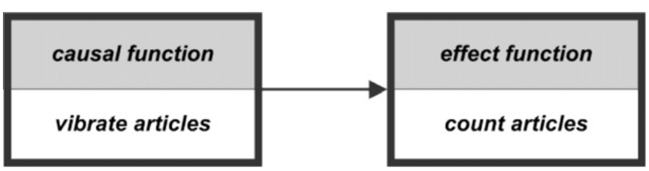

Fig. 3. The cause-and-effect function of the patent US5031156.

- Description: The description is detailed explanation of the technology, and also contains much subsidiary information. When the technology has multiple complex causalities, the description provides all the detailed information required to understand them. However, distinguishing representative functions from redundant function can be difficult.
- IPC Code: This is an internationally uniform classification of patent documents that represents the technology domain. The IPC that is truly valuable when analyzing causality. The IPC code includes two components. The first component represents the purpose or effect of the technology. The second component represents the cause or principle of the technology. For example, IPC code B08B means "Cleaning in general; Prevention of fouling in general" which are purposes. IPC code B08B-1/00 means "Cleaning by methods involving the use of tools, brushes, or analogous members", B08B-3/00 means "Cleaning by methods involving the use or presence of liquid or steam", and, B08B-5/00 means "Cleaning by methods involving the use of air flow or gas flow". Consequently, the IPC code encodes information that is valuable in analyzing causality because the code contains both cause and effect information and is a representative and implicative expression at the same time.

After identifying representative causality, it is represented as an AO function model. Once one of the SAOs is selected as a representative function, then next task is to express it as a function. By following all of these procedures, causal and effect functions are extracted from patents.

3.2. Building function hierarchy

The next step is to build a hierarchy of defined cause-and-effect functions. Even if representative functions have been defined, they are still so specific that users can have difficulty in searching for functions in the CEFN. The function hierarchy includes both horizontal relationships that join synonyms, and vertical relationships that connect hyponyms. For example, the word 'article' in the effect function 'count article' can refer to (i.e., is a hypernym of) specific items (hyponyms) such as 'sheet' or 'paper'. Similarly, the word 'count' is synonymous with such words as 'number' and 'enumerate'. Search results should include all technologies whose functions are defined using one of those words. As a result, synonyms must be included in the function hierarchy. Furthermore, even if users search the system for a term such as 'clean particles', the system should output results related to not only 'clean particles' but also to 'clean liquids' and to 'clean clothes'. Consequently, the function hierarchy must include sets hyponyms in which all relevant subordinate words are collected and categorized.

To build a function hierarchy (Fig. 4), two major references can be exploited: WordNet and the Functional Basis. WordNet is a large lexical database of English developed by Cognitive Science Laboratory of Princeton University (Miller, Beckwith, Fellbaum, Gross, & Miller, 1990). It is a domain ontology that defines and describes the general senses of English nouns, verbs, adjectives, and adverbs. More importantly, WordNet organizes words into sets linked by semantic relations such as synonymy, antonymy, and hyponymy. Therefore, the major advantage for the method described in this study is that WordNet can help to gather synonyms and hyponyms of the words in defined functions while building the function hierarchy. Furthermore, NIST has developed taxonomies (called the Functional Basis) containing over 130 functions and

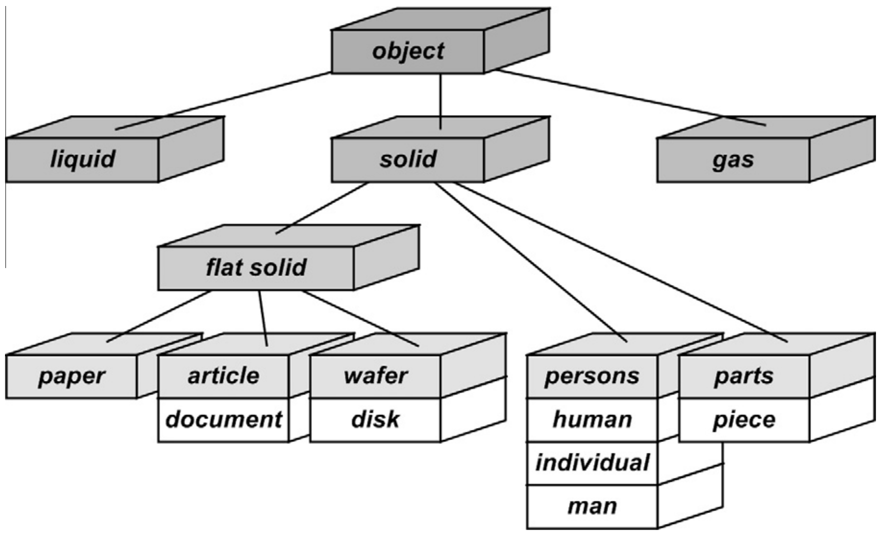

Fig. 4. Example of function hierarchy (nouns).

100 flows within the context of engineering (Hirtz et al., 2001). The Functional Basis has a hierarchy into which all the functions and flows are categorized. The Functional Basis is appropriate to build a function hierarchy in that the functions and flows of the functional bases are directly matched with actions and objects of cause-and-effect functions. WordNet search results (Fig. 5) can be used to assemble the Functional Basis which consists of lists of flows and functions having the hierarchical relationship between levels of specification (Figs. 6 and 7).

Although WordNet and the Functional Basis can be employed to help build a function hierarchy, this process is not necessarily automatic, and the hierarchy may not be complete. Firstly, from technological view point WordNet is somewhat too general and too comprehensive to define functions of patents. Therefore, synonyms and hyponyms used by WordNet should be properly selected and sometimes modified instead of being accepted unconditionally. Compared to WordNet, the Functional Basis is more engineering-oriented, but it should also be adopted carefully because its terminologies are not thorough enough to define functions of all given technologies. If needed, additional new concepts or categories can be introduced, such as 'flat solid' to organize words such as 'paper', 'article', and 'wafer' (Fig. 4).

The function hierarchy contributes to searchability in two reasons. (1) Even if the query uses specific words, the system can output all the relevant results due to the presence of synonyms in the function hierarchy. (2) The system can find not only homogeneous technologies but also heterogeneous technologies due to the presence of hyponyms. These two reasons will be demonstrated in a case study.

3.3. Building function network

Until now, we have explained how to define a cause-and-effect function that only focuses on a single technology. But a

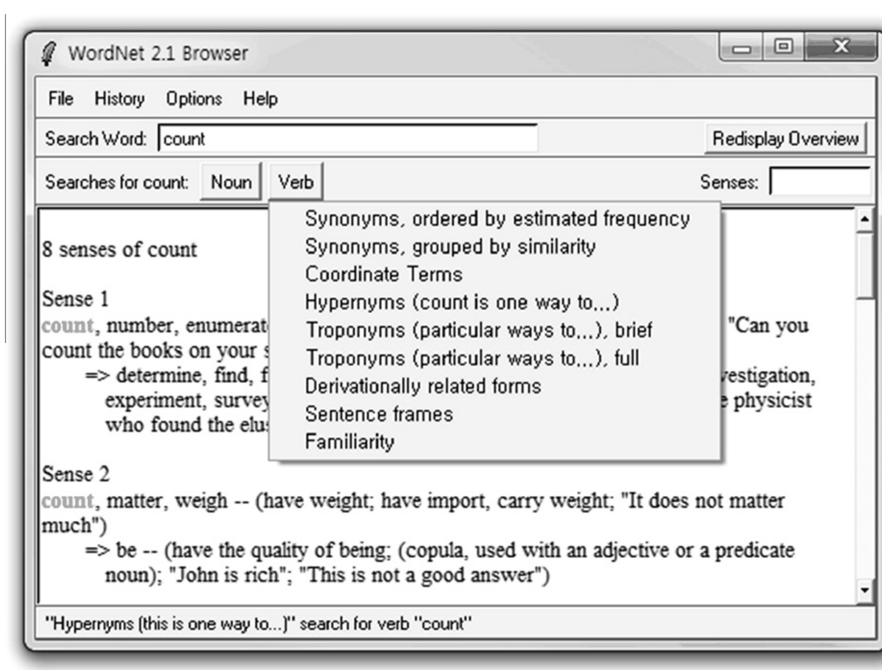

Fig. 5. Example searching result of WordNet.

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Material	Human		Hand, foot, head
	Gas		Homogeneous
	Liquid		Incompressible, compressible, homogeneous,
	Solid	Object	Rigid-body, elastic-body, widget
		Particulate	
		Composite	
	Plasma		
	Mixture	Gas-gas	
		Liquid-liquid	
		Solid-solid	Aggregate
		Solid-Liquid	
		Liquid-Gas	
		Solid-Gas	
		Solid-Liquid-Gas	
		Colloidal	Aerosol
Signal	Status	Auditory	Tone, word
		Olfactory	
		Tactile	Temperature, pressure, roughness
		Taste	
		Visual	Position, displacement
	Control	Analog	Oscillatory
		Discrete	Binary
Energy	Human		
	Acoustic		
	Biological		
	Chemical		
	Electrical		
	Electromagnetic	Optical	
		Solar	
	Hydraulic		
	Magnetic		
	Mechanical	Rotational	
		Translational	
	Pneumatic		
	Radioactive/Nuclear		
	Thermal		
Overall increasing degree of specification →			

Fig. 6. Functional basis reconciled flow set (object).

cause-and-effect relationship in a certain technology can be related to that of another technology, because some causes can have multiple effects (Fig. 8a), and some effects can have multiple causes (Fig. 8b). Therefore, when system users define a large number of cause-and-effect functions and feed them to the system, functions that share either cause or effect spontaneously meet and form networks. In this process, the function hierarchy is very valuable because it merges different expressions that have the same semantics (Fig. 8c).

Moreover, the cause-and-effect relationship in a certain technology can be expanded to that of another technology. This means that some causal functions can be effect functions in another technology. The CEFN can be expanded in this way. Consequently, a CEFN can be built that includes a large number of cause-and-effect functions: the CEFN can be a function pool which has a logical relationship structure.

To demonstrate how different technologies can be linked, patent US5339842 was analyzed and studied. Patent US5339842 is about "Cleaning methods and apparatus for removing particulate materials from the surfaces of objects". The application of thin coating less than about 10 μm has become an increasingly important step in the manufacturing of various products such as, for example, flat panel displays, high definition television, lenses, or silicon wafers and so on. As the thickness of such coatings decreases, however, it is very important and difficult to clean the particles whose size is of less than about 1 μm from flat or curved planar surfaces. Therefore, this patent suggests a method of using sound waves to remove submicron-sized particles from surfaces. Sound wave is given to a container and then it makes the particles vibrate and removed from the surface. So the cause-and-effect function of this patent has the cause 'vibrate particles' and the effect 'remove particles'.

The function hierarchy can be used to detect a relationship between the patent US5339842 and patent US5031156 (Section 3.1). The causal function of the first patent is 'vibrate particles' and the second patent is 'vibrate articles'; these two functions can be abstracted into the same function, 'vibrate solid'. Therefore the relationship of those patents can be represented as a network (Fig. 9). On the contrary, of course, some effect can be related to multiple causes.

The complete CEFN can be utilized to find inventive principles (Fig. 9, upper arrow), or to discover new effects (Fig. 9, lower arrow). To discover inventive principles, the CEFN can identify the inventive principle of a certain technology. For example, assume that a user wants to know how to 'count paper'; i.e., that 'count paper' is the effect function, and that the user wants to find a causal function of that effect function. So the user searches for 'count paper' as an effect function in the CEFN, and then finds that 'vibrate

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock
Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack
Control Magnitude	Actuate		Enable, initiate, start, turn-on
	Regulate		Control, equalize, limit, maintain
		Increase	*Allow*, open
		Decrease	Close, delay, interrupt
	Change		Adjust, modulate, *clear*, demodulate, invert, normalize, rectify, reset, scale, vary, modify
		Increment	Amplify, enhance, magnify, multiply
		Decrement	Attenuate, dampen, reduce
		Shape	Compact, compress, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop		End, halt, pause, interrupt, restrain
		Prevent	Disable, turn-off
		Inhibit	Shield, insulate, protect, resist
Convert	Convert		Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, *process*, solidify, transform
Provision	Store		Accumulate
		Contain	*Capture*, enclose
		Collect	Absorb, consume, fill, reserve
	Supply		Provide, replenish, retrieve
Signal	Sense		Feel, determine
		Detect	Discern, perceive, recognize
		Measure	Identify, *locate*
	Indicate		Announce, show, denote, record, register
		Track	Mark, time
		Display	*Emit*, expose, select
	Process		Compare, calculate, check
Support	Stabilize		Steady
	Secure		*Constrain*, hold, place, fix
	Position		Align, *locate*, orient
		Overall increasing degree of specification →	

Fig. 7. Functional basis reconciled function set (verb).

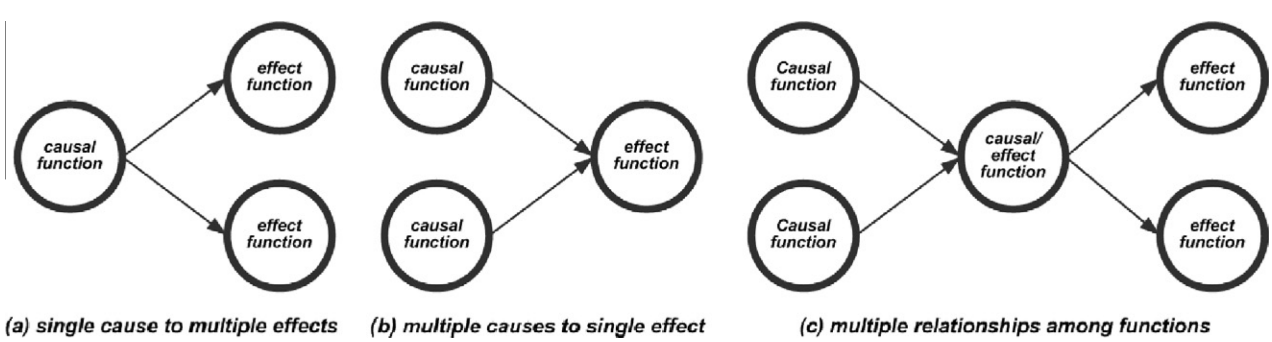

Fig. 8. Types of network formation.

paper' is a causal function of 'count paper'. From this fact, user can learn that vibrating the paper is exploited to count the paper, so that these two technologies are analogous. Therefore, the CEFN can be regarded as a kind of technological analogy network. By exploiting analogy, cause-and-effect relationships, users can get insights to solve problems.

The second way of utilizing the CEFN is to discover new effect functions (Fig. 9, lower arrow). A single cause can have multiple

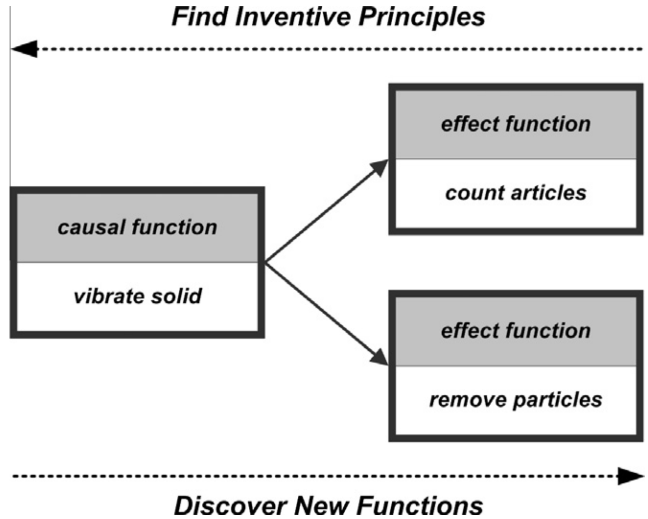

Fig. 9. Multiple relationships between the functions.

effects; this means that new opportunities can be discovered that were not identified by utilizing a recognized cause. For example, assume that someone has developed an efficient technology of vibration such as oscillators or ultrasonic generators, and wonders how this technology can be utilized in diverse ways. So this user searches the system using 'vibrate object' as a causal function, and the system outputs two effect functions: 'count papers' and 'remove particles'. As a result, users can discover new effect functions while searching a causal function. For more realistic demonstration, this paper presents a case study using 50 granted patents.

4. Case study

4.1. System architecture

Users can employ the complete CEFN as a searching system. The system architecture (Fig. 10) of the CEFN can be explained from two perspectives. From the user's perspective, a user makes a query as an AO function model, and inputs it to the CEFN. The input action and object (verb and noun) are searched in the function hierarchy database to collect related synonyms and hypernyms. Next, in the cause-and-effect function database, functions that match the collected words are extracted and visualized as a network. Finally the result is sent to the user's interface. From the administrative perspective, an administrator (e.g., a technical expert or patent analyzer) retrieves patent documents from a patent repository such as USTPO. The retrieved patents are transformed into SAO lists using Knowledgist™. After analyzing cause-and-effect functions, resultant functions are stored in cause-and-effect function database. By referring to WordNet and the Functional Basis, synonyms and hypernyms used in defining functions are also stored in the function hierarchy database.

4.2. Patent analysis and function models

To demonstrate the proposed method, this paper provides a case study using 50 US patents (Table 1, Appendix A), which have a variety of IPC codes (Appendix B). These patents were all granted, which means that their technological principles and purposes have been verified.

The first step of the case study is patent analysis to make cause-and-effect function models from the patents. Although this paper focuses on defining cause-and-effect functions of technology, the number of causal or effect functions need not be one. To make technology understandable, more than one causal or effect function can be defined in function models. If the function models include distinctive functions that adequately describe the patents' cause-and-effect relationships, then function models that share a cause or effect can be joined to form a network. Patents US4217491 and US4009389 have almost the same causality, but US4217491 has one more function 'Measure Angles'. In the CEFN, those two patents can be connected in that they have the same causal and effect functions. In brief, even if function models are different depending on the user's judgment, the CEFN can be both built and searched.

Meanwhile, it is recommended to select representative functions in defined function models (Table 1, Appendix A, bold); representativeness is not mandatory when building the CEFN, but contributes to system usability and visibility, because representativeness helps users to understand implications or insights of technologies.

4.3. Two-way utilization of function network

4.3.1. Finding inventive principles

As discussed, the complete CEFN is utilized in two ways. The first way (Fig. 11) is to find inventive principles of a particular function desired to be achieved. In the network system, if users

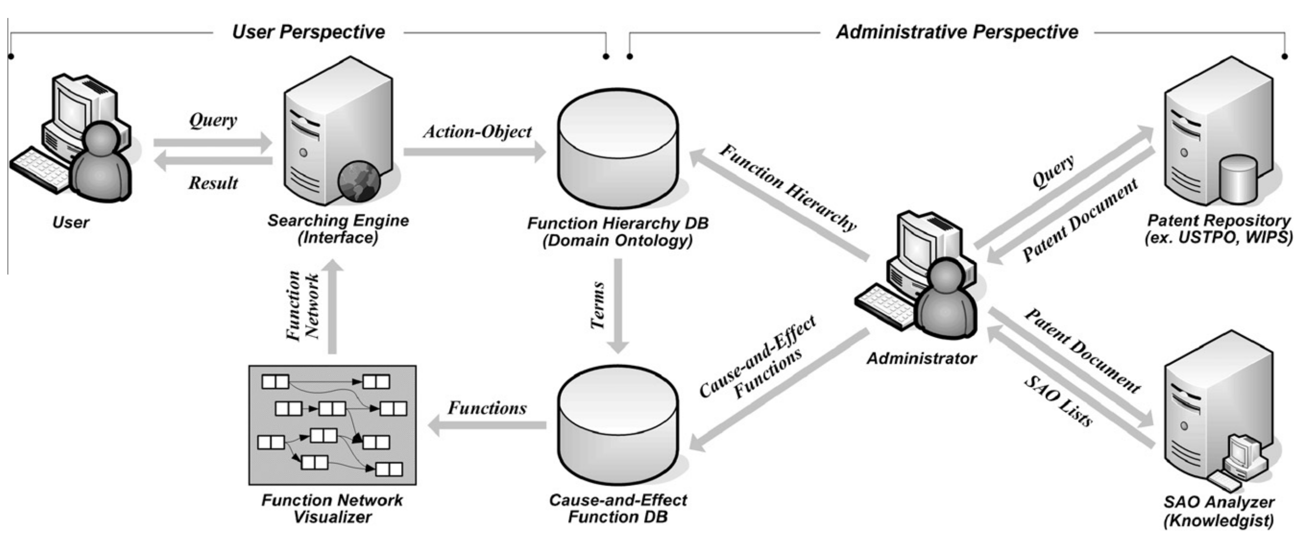

Fig. 10. The system architecture of the function network.

Table 1
Cause-and-effect function models of selected patents.

Pat. #	Title	Cause-and-effect function models
4217491	Counting system for articles conveyed in a stream	**Project Light** → Measure Angles → **Count Articles**
4300546	Hand-held atomizer especially for dispensing inhalation-administered ...	**Apply Ultrasonic** → **Atomize The Liquid Medicament** → Dispense Medicament
4009389	Apparatus for the automatic counting of passengers	**Project Light beam** → **Count Passages**
5339842	Methods and apparatus for cleaning objects	**Provide Ultrasonic** → **Vibrate Particles** → **Remove Particles**
5402781	Method and apparatus for determining bone density and diagnosing ...	**Generate Vibration** → **Vibrate hard Tissue** → Measure Induced Vibration → **Measure Bone Density**
5803099	Ultrasonic cleaning machine	**Produce Ultrasonic Vibration** → **Vibrate Cleaning Vessel** → **Clean Object**
5927308	Megasonic cleaning system	**Apply Megasonic Energy** → **Vibrate Substrate** → **Remove Particles**
7178897	Method for removing liquid in the gap of a printhead	**Vibrate Drop Generator** → Dissolve Residue → **Make Liquid Pressure Differentials** → **Clear Residue**
7810743	Ultrasonic liquid delivery device	**Provide Ultrasonic Energy** → Energize Liquid → **Atomize Liquid** → Deliver Atomized Liquid

have a desired function, they can make a simple query comprised of action-object combination such as ‘count persons’ as effect function, which means semantically ‘how to count persons?’

After receiving the query, the system starts building a function hierarchy of the query based on domain ontology. The complete function hierarchy contains the words ‘enumerate’ and ‘number’ as the synonyms of the word ‘count’ (Fig. 11, right); it also includes several synonyms and hypernyms of the word ‘persons.’ The function ‘count object’ is connected by arrows to the inventive principles (Fig. 11, left). The hierarchy identifies six representative causal functions and their intermediary functions. Consequently, users are provided with several implications that can help to solve the problem ‘how to count persons?’ Methods to count objects include ‘employ optical sensor’, ‘emit acoustic energy’, ‘provide pressurized air’, ‘vibrate object’, ‘provide ultrasonic’, ‘project light’, which are all causal functions that cause objects to be counted in various technology domains. The results can be implications, for two reasons: (1) users can consider technologies in various technology domains; and (2) users can consider principles of not only ‘count person’, but also ‘number article’.

First, the results are comprised of not only homogeneous technologies but also heterogeneous in terms of technology domain. The most important advantage of defining and representing technology as function is to have an abstractive and practical representation of technological knowledge. This means that even if two technologies are from different domains, they can be defined as the same single function, or they can be at least linked if they share a causal or effect function. This fact is proved by the observation that the patents of causal functions have a variety of IPC codes. As classification of patent, in brief, IPC represents technology fields

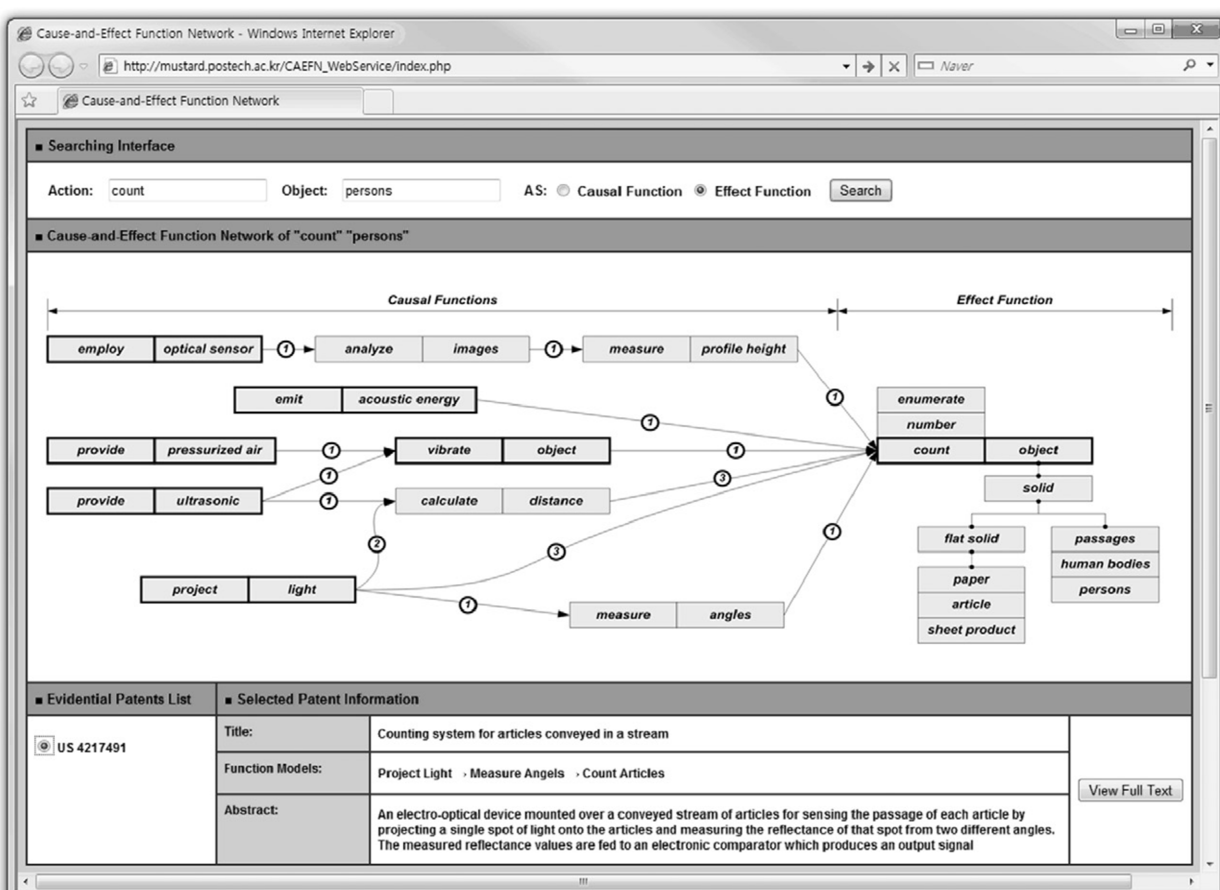

Fig. 11. The way of finding inventive principles.

or domain of patents. The IPC codes belonging to six representative causal functions are as follows: B07, B61, G07, G06, G01, H01, which are very different fields. As a result, the system provides various inventive principles to achieve a certain effect from diverse technology fields.

Second, because the ontological approach is used, the system can collect as many patents as the number of relevant words in the function hierarchy. Therefore, even if users ask the system to find methods to 'count persons', the system also returns the inventive principles of technology used to 'number articles'. Considering the principle of 'number articles' does not necessarily guarantee that the user will find a key solution, but they may gain valuable insights from similar technologies.

Arrows that join the inventive principles are labeled (Fig. 11, circles) with the number of evidential patents from which the linked functions and their relationships are extracted. The user can ascertain the detailed information on any causal function by clicking on these circles; this action causes the system to list the relevant patents (Fig. 11, bottom left). Clicking on one of these patents causes the system to show detailed information about it (Fig. 11, bottom center).

4.3.2. Discovering new functions

The other way of utilizing the CEFN is to discover new functions. As a corollary to the first way, if the system is given a causal function, it can provide various effect functions.

For example, if users input the causal function 'provide ultrasonic', the system can output numerous effect functions (Fig. 12) that mean the potential purposes or effects of the causal function 'provide ultrasonic', including 'sort parts', 'determine bone mass', 'count object', 'enhance shaving', 'clean object', 'atomize liquid'. From these effect functions, users can have a chance to expand the utilization of existing technologies. Some of these effect functions might have already been known to users, but unexpected effect functions give users new ways of utilizing their own technology that might lead to new business opportunities or supply chain expansion.

Assume that some manufacturer produces an ultrasonic generator which is supplied to a company that makes cleaning products. After searching 'provide ultrasonic' in the CEFN, the user might find new effect functions that have not been recognized. If the user is interested in one of the effects, 'atomize liquid', she can identify the evidential patents by clicking the numbered circle in the middle of that relationship. The number in the circle indicates the number of patents have the same cause-and-effect relationship, i.e., 'provide ultrasonic' and 'atomize liquid'. When a user then clicks on one of those patents, the system shows its detailed information (Fig. 12, bottom center) to help the user to study the technology. The network also reveals other causes that have the effect 'atomize liquid', because three arrows point toward that effect. For example, the effect function of Patent US7810743 is same as that of US5449502 (Appendix A, number 47), but has one more intermediary function 'energize liquid'. Consequently, users can find various ways to achieve the desired function; this variety can help to direct the development of new technology.

Furthermore, as the CEFN evolves, results from the system will improve in both quantity and diversity of technology domain. In fact, the patents relevant to the effect functions shown in Fig. 12

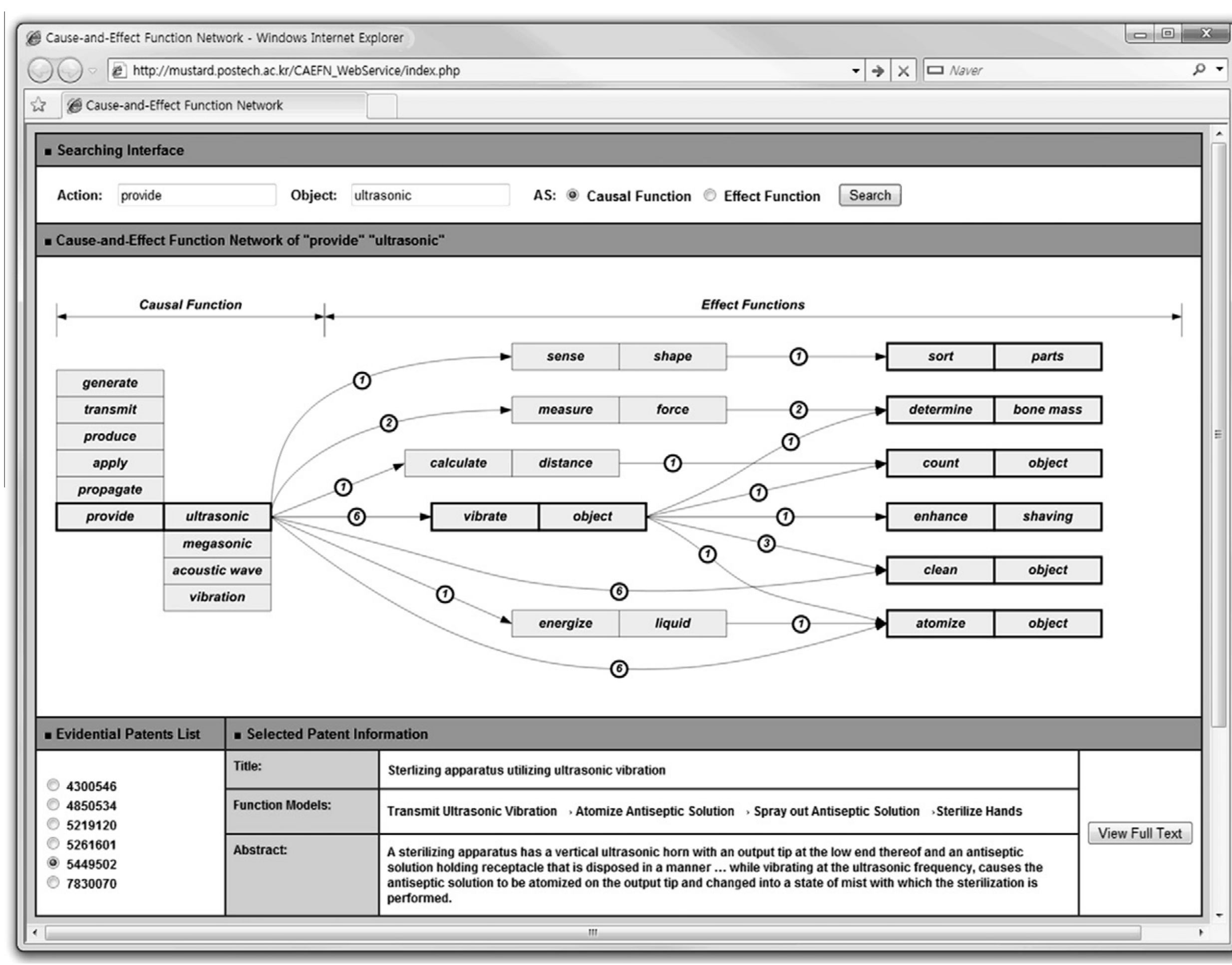

Fig. 12. The way of discovering new functions.

have various IPC codes; this means that a single causal function can be utilized in various technology fields. As a result, if technologists develop new technology or new material, and know its values or effects, the CEFN can show how their invention can be utilized in diverse domains.

5. Conclusion

This study presents a new method of identifying connections among technological innovations and a system that utilizes that method. The proposed method defines specific technologies in generalized forms and connects them to form a network that is based on causality. The proposed method employs cause-and-effect relationships, function analysis and ontology. The objective of the method is to build a CEFN that can be used in a searching system. In this system, users can get results immediately, because they have only to make a query as a 'verb' + 'noun' combination. The CEFN and system contributes both to providing inventive principles or technological causes for problem solving, and to discovering technology opportunities or technological effects for new business opportunities. As the system accumulates more cause-and-effect functions, it provides an increasing number of technology innovation implications or insights.

The fundamental contribution of this study is to find connections among heterogeneous technologies. The proposed method can link technologies from different fields because defining technologies as functions provides abstractive, representative and formal expressions of them. Moreover, using ontology guarantees linguistic disambiguation when defining or searching heterogeneous technologies. A specialist in one field can gain great benefits by becoming aware of implications or insights from other fields. Consequently, this study has possibility of developing into a method for technological convergence.

For future work, we will seek ways to automate the process of defining causality of technologies. The current software allows SAO analysis to be performed semi-automatically, but humans must still intervene in the process of analyzing causality. A rule-based approach may be a method of achieving full automation. In further study, the several suggestions presented to extract cause-and-effect should be transformed into rule bases that are machine readable. By doing this, users can be automatically given a list of causality alternatives ranked in order; such a list would help to define causality more efficiently. Such automation would allow efficient processing of massive patent databases.

Acknowledgement

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Appendix A. Analyzed cause-and-effect function models from patents used in the case study

#	Pat. #	Patent title	Cause-and-effect function models
1	3997866	Acoustic bus passenger counter	**Emit Acoustic Energy** → **Count Passages**
2	4009389	Apparatus for the automatic counting of passengers	**Project Light beam** → **Count Passages**
3	4127766	Automatic and accurate passenger counter with storage and retrieval	**Provide Light** → **Count Object**
4	4217491	Counting system for articles conveyed in a stream	**Project Light** → Measure Angles → **Count Articles**
5	4278878	Passing person counting apparatus	**Provide Light** → **Count Person**
6	4300546	Hand-held atomizer especially for dispensing inhalation-administered medicaments	**Apply Ultrasonic** → **Atomize The Liquid Medicament** → Dispense Medicament
7	4356387	Apparatus for counting the number of objects passing a given point	**Emit Radiant Energy** → Form Intersection → **Count Object**
8	4450352	Method and device for counting sheet material	**Direct Laser Beam** → Reflect Laser Beam → Measure Signals → Compositing Signals → **Eliminate Disturbance**
9	4528679	Automatic counting system for passages	**Provide Ultrasonic** → **Count Passages**
10	4540887	High contrast ratio paper sensor	**Emit Light** → Sense Light → Subtract Reflective Outputs → Provide High Contrast Ratio → **Recognize Paper**
11	4576286	Parts sorting systems	**Transmit Acoustic Energy** → Sense The Shape → **Sort The Part**
12	4799622	Ultrasonic atomizing apparatus	**Provide Ultrasonic** → Generate Vibration → **Atomize Liquid Material**
13	4807263	Counter of objects being transported	**Employ Optical Sensor** → Analyze Images → Measure Profile Height → **Count Newspaper**
14	4850534	Ultrasonic wave nebulizer	**Provide Vibration** → **Nebulize Water**
15	5005192	Method of and apparatus for counting flat objects in a stream of partially overlapping objects	**Generate Ultrasonic Wave** → Receive Ultrasonic Wave → Calculate Distance → **Count Sheets**
16	5031156	Method and apparatus for detecting and counting articles	**Provide Ultrasonic** → Vibrate Paper → **Count Paper**
17	5172024	Device for the removal of the ice formed on the surface of a wall, notably an optical or radio-electrical window	**Generate Acoustic Wave** → **Eliminate Ice**
18	5219120	Apparatus and method for applying a stream of atomized fluid	**Apply Ultrasonic** → Atomize Fluid → Deliver Fine Spray → **Coat Surface**
19	5255301	Apparatus for counting the number of passing persons by stature	**Radiate Light** → Receive Light → **Calculate Height** → Compare Threshold → **Count Passing Persons**

(*continued on next page*)

Appendix A (*continued*)

#	Pat. #	Patent title	Cause-and-effect function models
20	5261601	Liquid dispensing apparatus having a vibrating perforate membrane	**Provide Vibration** → Atomize Liquid → **Dispense Liquid**
21	5316591	Cleaning by cavitation in liquefied gas	**Promote Cavitation** → **Clean Substrate**
22	5339842	Methods and apparatus for cleaning objects	**Provide Ultrasonic** → Vibrate Particles → **Remove Particles**
23	5402781	Method and apparatus for determining bone density and diagnosing osteoporosis	**Generate Vibration** → Vibrate hard Tissue → Measure Induced Vibration → **Measure Bone Density**
24	5449502	Sterilizing apparatus utilizing ultrasonic vibration	**Utilize Ultrasonic Vibration** → **Atomize Antiseptic Solution** → Spray Out Antiseptic Solution → **Sterilize objects**
25	5529635	Ultrasonic cleaning of interior surfaces	**Provide Ultrasonic** → Cause Cavitation → Maximize Agitation → Dislodge Material → **Clean Surface**
26	5574485	Ultrasonic liquid wiper for ink jet printhead maintenance	**Generate Ultrasonic** → Excite Cleaning Solution → **Remove Viscous Plugs**
27	5803099	Ultrasonic cleaning machine	**Produce Ultrasonic Vibration** → Vibrate Cleaning Vessel → **Clean Object**
28	5852647	Method and apparatus for measuring bone density	**Take Two X-ray Images** → Compute Differences of Transmissivity → **Measure Density of Bones**
29	5866887	Apparatus for detecting the number of passers	**Emit Light** → Receive Light → Calculate Distance Changes → Sense Human Bodies → **Count Human Bodies**
30	5895364	Non-invasive technique for bone mass measurement	**Generate Vibration** → Measure Force → **Determine Bone Mass**
31	5927308	Megasonic cleaning system	**Apply Megasonic Energy** → Vibrate Substrate → **Remove Particles**
32	5938117	Methods and apparatus for dispensing liquids as an atomized spray	**Vibrate Member** → Atomize Liquid → **Dispense Liquid**
33	5954885	Cleaning method	**Apply Megasonic** → **Clean Substrate**
34	6029521	Method for measuring cover thickness of reinforcing bar in concrete by using stress wave	**Apply Impact** → Generate Dilatational Wave → **Calculate Travel Time** → **Measure Cover Thickness**
35	6152383	Ultrasonic nebulizer	**Employ Ultrasonic Vibrator** → Produce Sound Wave → **Nebulize Liquid**
36	6311702	Megasonic cleaner	**Employ Megasonic Energy** → **Clean Substrate**
37	6467476	Liquid dispensing apparatus and methods	**Vibrate Shell Member** → **Nebulize Liquid** → **Deliver Drug**
38	6474349	Ultrasonic cleanout tool and method of use thereof	**Use Ultrasonics** → **Clean Tubular**
39	6546927	Methods and apparatus for controlling piezoelectric vibration	**Vibrate Plate** → Supply Liquid → **Aerosolize Liquid** → **Deliver Liquid**
40	6810807	Method and apparatus for cleaning coating materials from a substrate	**Use Ultrasonic Transducer** → **Clean Coating Materials**
41	6946036	Method and device for removing particles on semiconductor wafers	**Apply Ultrasonic Wave** → **Detach Particle**
42	7178897	Method for removing liquid in the gap of a printhead	**Vibrate Drop Generator** → Dissolve Residue → Make Liquid Pressure Differentials → **Clear Residue**
43	7458374	Method and apparatus for vaporizing a compound	**Heat Drug** → **Vaporize Drug** → Delivery Drug
44	7500313	Oscillating razors	**Apply Vibration** → **Vibrate Blade** → **Enhance Shaving**
45	7518288	System for megasonic processing of an article	**Apply Fluid** → **Clean Semiconductor Wafers**
46	7744016	Ultrasonic Washing Machine	**Transmit Ultrasonic** → **Washing Disk**
47	7810743	Ultrasonic liquid delivery device	**Provide Ultrasonic Energy** → Energize Liquid → **Atomize Liquid** → Deliver Atomized Liquid
48	7819335	Control system and method for operating an ultrasonic liquid delivery device	**Apply Ultrasonic** → Energize Liquid → **Delivery Liquid**
49	7830070	Ultrasound atomization system	**Generate Ultrasonic Vibration** → **Atomize Fluid**
50	7896539	Ultrasound apparatus and methods for mixing liquids and coating stents	**Generate Ultrasound** → Mix Different Liquids → **Coat Stent**

Aligned by patent numbers.
Bold means representative function.

Appendix B. IPC codes of patents used in the case study

IPC	Description	Relevant Patents
A61	Medical or veterinary science; hygiene	US4300546, US5261601, US5402781, US5449502, US5895364, US6467476, US6546927, US7458374
B01	Physical or chemical processes or apparatus in general	US7896539
B05	Spraying or atomizing in general;	US4799622, US4850534, US5219120, US6152383, US7744016, US7810743, US7819335
B07	Separating solids from solids; sorting	US4576286
B08	Cleaning	US5339842, US5529635, US5803099, US5927308, US5954885, US6311702, US6474349, US6946036
B26	Hand cutting tools; cutting; severing	US7500313
B41	Printing; lining machines; typewriters; stamps	US5574485, US6810807, US7178897
B61	Railways	US5866887
C02	Treatment of water, waste water, sewage, or sludge	US5316591
G01	Measuring; testing	US3997866, US4009389, US4540887, US5852647, US5938117, US6029521
G06	Computing; calculating; counting	US4217491, US4278878, US4450352, US4528679, US4807263, US5005192
G07	Checking-devices	US4127766, US4356387, US5255301
H01	Basic electric elements	US5172024, US7518288, US7830070, US5031156

References

Altshuller, G., Shulyak, L., & Rodman, S. (1997). *40 principles: TRIZ keys to innovation*. Technical Innovation Center, Inc..

Altshuller, G. S. (1984). *Creativity as an exact science: The theory of the solution of inventive problems*. CRC.

Bergmann, I., Butzke, D., Walter, L., Fuerste, J. P., Moehrle, M. G., & Erdmann, V. A. (2008). Evaluating the risk of patent infringement by means of semantic patent analysis: The case of DNA chips. *R&D Management, 38*, 550–562.

Cascini, G., Fantechi, A., & Spinicci, E. (2004). Natural language processing of patents and technical documentation. *Document Analysis Systems VI*, 89–92.

Cascini, G., & Russo, D. (2007). Computer-aided analysis of patents and search for TRIZ contradictions. *International Journal of Product Development, 4*, 52–67.

Cascini, G., & Zini, M. (2008). Measuring patent similarity by comparing inventions functional trees. *Computer-Aided Innovation (CAI)*, 31–42.

Chulvi, V., & Vidal, R. (2009). TRIZ on design-oriented knowledge-based systems. *The TRIZ Journal*, March Issues.

Cong, H., & Tong, L. H. (2008). Grouping of TRIZ inventive principles to facilitate automatic patent classification. *Expert Systems with Applications, 34*, 788–795.

Dewulf, S. (2006). Directed variation: Variation of properties for new or improved function product DNA, a base for 'connect and develop'. In *ETRIA TRIZ futures*.

Dourson, S. (2004). The 40 inventive principles of TRIZ applied to finance. *The TRIZ Journal*.

Gruber, T. R. (1995). Toward principles for the design of ontologies used for knowledge sharing. *International Journal of Human Computer Studies, 43*, 907–928.

Hipple, J. (2005). 40 inventive principles with examples for chemical engineering. *The TRIZ Journal*.

Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., & Wood, K. L. (2001). A functional basis for engineering design: Reconciling and evolving previous efforts. *Research in engineering Design, 13*, 65–82.

Jasper, R., & Uschold, M. (1999). *A framework for understanding and classifying ontology applications* (Vol. 99, pp. 16–21). Citeseer.

Kim, H. (2004). *Creativity of thinking*. Jeehye.

Mann, D. (2001). An introduction to TRIZ: The theory of inventive problem solving. *Creativity and Innovation Management, 10*, 123–125.

Mann, D. (2002a). Evolving the inventive principles. *The TRIZ Journal*.

Mann, D. (2002b). *Hands-on systematic innovation*. Belgium: CREAX Press.

Miller, G. A., Beckwith, R., Fellbaum, C., Gross, D., & Miller, K. J. (1990). Introduction to WordNet: An on-line lexical database. *International Journal of lexicography, 3*, 235.

Retseptor, G. (2003). 40 inventive principles in quality management. *The TRIZ Journal*.

Savransky, S. D. (2000). *Engineering of creativity: Introduction to TRIZ methodology of inventive problem solving*. CRC.

Terninko, J., Zusman, A., & Zlotin, B. (1998). *Systematic innovation: An introduction to TRIZ*. CRC.

Verhaegen, P. A., D'hondt, J., Vertommen, J., Dewulf, S., & Duflou, J. R. (2009). Relating properties and functions from patents to TRIZ trends. *CIRP Journal of Manufacturing Science and Technology, 1*, 126–130.

WIPO. (2010). International Patent Classification (IPC). http://www.wipo.int/classifications/ipc/en/.