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Full paper

Forecasting potential sensor applications of triboelectric nanogenerators through tech mining☆

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ABSTRACT

The Triboelectric Nanogenerator (TENG), invented in 2012, is an emerging energy harvesting technology that efficiently converts ambient mechanical energy into electricity. Much work has been done to develop this device and improve its performance. However, no systematic report about its applications through large-scale publication and patent data analysis is available. In this study, we use "Tech Mining," a systematic analytical method based on structured texts applied to publication and patent abstract data, to analyze potential applications of TENGs. A series of applications from product scale to industry scale are identified. The findings show that when used as sensors, TENGs are mostly applicable in automation and energy-intensive industries such as automotive, medical or surgical devices, consumer electronics and household appliances. TENGs in the form of sensors can also be integrated with future-oriented and exponentially growing technologies such as robotics, drones, nanotechnology, and bioinformatics that will create enormous value for future economies. Moreover, applications of TENGs as sensors are also in line with current global trends of science and technology development, including the "Internet of Things," big data, clean energy, and smart cities. Combined with those technologies and industries, TENGs can help in tackling challenges of global warming, environmental pollution and security systems. We suggest the TENG research community to widen interdisciplinary collaboration, pursue connections with industry, and file more patents as R & D progresses. In addition, research limitations and future development directions of TENG are pointed out.

1. Introduction

The identification of "potential innovation pathways and technology opportunities" [1] is important for formulating research strategy, conducting interdisciplinary collaboration, and devising policy for science, technology, and innovation. Prediction of potential applications and future development horizons is crucial for technologies that are still in an early stage of development [2]. The Triboelectric Nanogenerator (TENG) technology, introduced in 2012 [3], is found to have high potential to be applied in various fields [4]. TENG is a technology that can effectively harvest ambient mechanical energy from the living environment and convert it to electricity. Its potential for the creation of a fully integrated self-powered microsystem using low-cost fabrication processes makes TENG attractive [5,6]. In the past few years, publications have covered not only fundamental topics of TENG, such as materials [7–12], output efficiency [13,14], structures or modes [15–18] and the theoretical origin of nanogenerators [19], but also applications in environmental protection [20–22], hybrid energy cells [23–26], portable or wearable electronics [27–29], the generation of "blue" ocean wave energy [30–33] and other sensor related applications [34–42].

Most studies that address applications of TENGs have stemmed from experimental results rather than being based on discovery methods utilizing literature and/or patent analyses [43]. Such traditional approaches have contributed profoundly to framing and orienting TENG research but risk neglecting application information obtained from data. In this study, we present an evidence-based analysis of TENGs through "Tech Mining" [44] of publication and patent data to

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provide perspective on the scope of TENG research and development to date and to elucidate promising applications of TENGs.

Tech Mining is a systematic analytical framework that explores information about emerging technologies to support innovation management [45]. The large-scale data (both in source and quantity) used in Tech Mining facilitate decision making procedures using scientific evidence. The method is widely used in identifying emerging technologies [46,47], forecasting innovation pathways [48–50], extracting technology competitive intelligence [51,52] and monitoring market trends for business and exploring technology roadmaps [53].

In this study, the Tech Mining framework is applied to scientific publication and patent abstracts to address the following questions regarding the emerging TENG technology: 1) What are the topics covered by research papers in TENG? 2) What are especially promising application topics for TENG technology? and 3) From technical and market perspectives, what are the potential applications of TENG technology in those topical domains?

In this work, the publications relating to TENG and patents of sensors are systematically analyzed using tech mining to predict potential applications of TENG used as sensors in various fields. Compared to the application cases listed in the published papers, the ones identified using Tech Mining are more comprehensive. The limitations and future research directions are also discussed.

2. Methodology and data

"Tech Mining" is defined as “the application of text mining techniques to science and technology information, informed by understanding of technological innovation processes" [45]. One may use Tech Mining to analyze scientific discovery and technological development output codified in the form of scientific publications and patent documents available from public data sources. Patent and publication records include two types of data: structured data such as bibliometric elements like author names, publication date, and unstructured textual data such as the title, abstract, and descriptions. Abstracts of publications stored on Web of Science (WOS) Core Collection[2] and patents from Derwent Innovation Index (DII)[3] and other sources, including Relecura,[4] are used in this study. They are well-suited for Tech Mining as they contain a large amount of technical information. The analysis of such data provides information on R & D themes, individuals, organizations, geographic distribution, funding sources and document types, amongst others. Therefore, Tech Mining contributes significantly in “R & D Profiling” [54] that addresses the “When, Where, What and Who” questions by highlighting the timing, location, thematic focus and main contributors involved in R & D processes. Vantage Point,[5] a sophisticated Tech Mining tool, is used to analyze publication and patent data in this study, combined with an independent analytical method called Topic Modeling. Tech Mining also involves experts from respective research fields to add insight in interpreting and exploring analytical findings provided by Tech Mining In the study, we also hold workshops with researchers from academia and industry.

2.1. Research design

The structure of the analysis is shown in Fig. 1.

As shown in Fig. 1, the study is conducted through the following steps:

STEP 1: Identifying research topics of TENG studies by mining TENG publication abstracts.

The initial sources used for identification of potential applications for TENG technology are scientific publication and patent abstracts. However, we study the research topics using publication data since there are very few patents on TENG.[6] These research topics are then analyzed to identify applications that have been studied. Since the goal of this study is to systematically analyze potential applications of TENG, studied applications are seen as of interest for TENG experts and indications of scientifically sound application directions. In this step, VantagePoint is used to analyze the basic characteristics of TENG research activities from 2012 to 2015, while topic modeling is used to reveal the research topics of TENG studies.

To extract relevant publications from WOS, a keyword-based search query is formulated by TENG experts from the Georgia Institute of Technology.[7] The abstract records of scientific papers are investigated by applying text mining and machine learning techniques to identify underlying research topics in TENG related publications. Machine learning approaches have been applied to analyze patent data of various technologies [55–57]. The most popular machine learning algorithm used for topic analysis is the Latent Dirichlet Allocation (LDA) [58]. The assumption behind LDA topic models is that the documents are a mixture of topics and the algorithm seeks to detect these underlying latent topics in a document collection. The topics are perceived as a distribution over a vocabulary of words [58]. LDA is a generative probabilistic model that includes probabilistic models both at document and word level. Such two-level analysis results in LDA being superior to other topic models such as Latent Semantic Indexing (LSI) [59] or probabilistic latent semantic indexing (PLSI) [60]. Therefore, this study utilizes LDA for detecting underlying latent topics within TENG publications. Prior to processing using LDA, the text data are manipulated by removing the punctuation, numbers and stop words. The remaining raw text is tokenized, which means sentences are reduced to single words. A customized stop word list is prepared to filter out domain-specific phrases like “this research,” “this study,” “their report presents,” and other words that do not convey any specific message such as “use,” “analyze,” “explore.” In the last preprocessing step, a dictionary of the filtered words is saved as a bag of words and is used as the input for the topic modeling algorithm.

The outcome of topic modeling is two matrices: document-topic and word-topic probability matrices. Since LDA is a soft partitioning clustering method, each document can be associated with several topics. Document-topic matrices can be used to illustrate the document proposition associated with each topic cluster. Words with top probabilities in each topic are calculated using the second matrix of word-topic probabilities. The top terms represent the topic and can be utilized for interpretation purposes [61]. The Gibbs sampling [62] has been used to estimate the LDA model parameters by "lda" R programming package. The model iteration is set to 5000, and the two key LDA

[2] The world’s leading citation databases provide authoritative, multidisciplinary coverage from more than 12,000 high impact research journals worldwide, including Open Access journals. Cover-to-cover indexing of content is provided by Science Citation Index Expanded (1900 - present), Social Sciences Citation Index Expanded (1900 - present), Conference Proceedings Citation Index (1990-present), Arts & Humanities Citation Index (1975 - present), Book Citation Index (2005 - present), Current Chemical Reactions (1985 - present), and Index Chemicus (1993 - present). The Web of Science Core Collection is comprised of 100 years of valuable research, fully indexed and cross searchable.

[3] Derwent Innovations Index facilitates rapid, precise patent searching and merges the value-added patent information from Derwent World Patents Index with the patent citation information from Derwent Patent Citation Index. Conduct powerful patent and citation searches of inventions in chemical, electrical, electronic, and mechanical engineering. Use additional descriptive information and coding to quickly grasp a patent’s significance and its relationship to other patents.

[4] Relecura is an IP analytics and knowledge management platform for patents and portfolios using machine learning, semantic analysis, and predictive analytics to create custom solutions. (www.relecura.com)

[5] VantagePoint is a sophisticated Tech Mining tool suite. It is software designed to be a “powerful text-mining tool for discovering knowledge in search results from patent and literature databases.”

[6] Only 6 patents are found in Derwent Innovation Index by 2016.

[7] When the research took place, Ms. Haoshu Peng was a visiting scholar at Gatech; Dr. Xudong Fang was a PhD student at GaTech; Dr. Zhen Wen and Dr. Samira Raneai were visiting PhD students at GaTech.

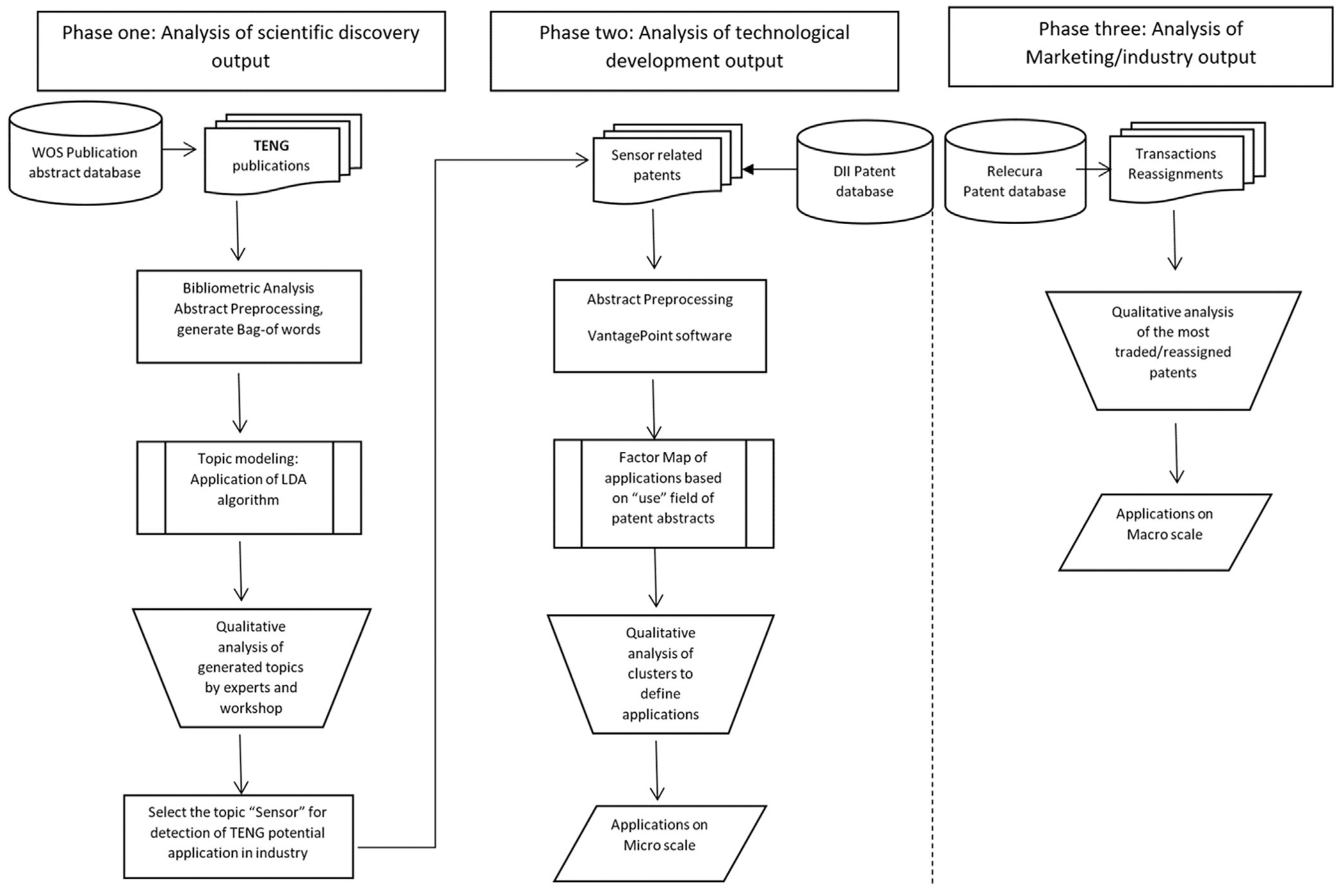

Fig. 1. Research Methodology, Data and Structure.

parameters (alpha and eta=0.01) that control for word and document probability distribution are set to their default values. The algorithm requires user input for the number of topics, based on a data-driven decision making approach. The traditional metrics for estimation of the number of topics, such as perplexity [58], are negatively correlated with the topic quality and coherence [61]. Therefore, in this study, we follow the approach suggested by Chang et al., (2009) to set the optimum number of topics based on expert evaluation and qualitative analysis of generated topics. The generated topics will be reviewed and labeled by experts based on manual screening of the top word descriptors.

STEP 2: Choosing target application topic(s) for further analysis.

TENG is at the emerging phase of its technological life cycle and few patents are available from the chosen data sources [63]. The lack of TENG historical patent data, which is a proxy for technological development [64], hinders us in drawing any conclusion on its technology applications directly. The study takes advantage of the generated thematic research topic results from step 1 for Tech Mining and TENG experts as references to suggest the target application topic(s) for further analysis.

STEP 3: Patent analysis of the target application topic(s) to explore potential applications of TENGs.

Compared to scientific papers, patents are more informative in indicating potential applications of inventions, especially for technologies in an early stage of development. In this study of TENG, two parallel patent analyses were conducted from different perspectives and with different data. One is to directly extract applications of the chosen research topic(s) from the "USE" field of patents in Derwent Innovation Index. The other is to search applications by looking into applications of patents that are most traded or reassigned in the market.

For the first analysis, the patent data are extracted from Derwent Innovation Index (DII) using a keyword based query formulated according to the generated topics. DII is preferred because the "Use" field, which is manually rewritten by technical specialists, explicitly suggests applications or utilities of a target patent. This study analyses the "Use" section to focus on the applications of a given technology on a product level. Features of VantagePoint are used here. The textual information of this patent "Use" section is imported to VantagePoint which allows one to subject it to Natural Language Processing (NLP). As a result, NLP phrases that describe the patent applications are extracted. The resulting collection of phrases is "noisy" and may contain a large number of irrelevant words or phrases that prevent easy identification of words relevant to this study. Therefore, "Term Clumping" [65] is applied to reduce the irrelevant words through dimension reduction. Finally, a factor map technique based on Principal Components Analysis (PCA) is applied to cluster the phrase collection based on their content (and their tendency to co-occur in abstract records) to show the top applications extracted from the "USE" information of patents.

For industry level analysis, patent transaction data in Relecura are examined to show the market demands for the chosen application topic(s) and, potentially, TENG technology. Relecura collects the transaction data of 7 patent authorities (Australia, Brazil, China, Germany, EPO, New Zealand and the United States). Although not exhaustive, the data cover transactions in the main markets. Patent transactions and reassignment activities in a technology area of interest suggest leads for commercialization. However, transactions can happen in various forms such as licensing, cross-licensing, purchase and sales of similar intellectual property. This study considers the transactions between independent legal entities as authentic transactions.

Individual inventor assignments,[8] security agreement assignments,[9] assignee name change,[10] mergers or acquisitions,[11] assignments between subsidiaries and parent companies and patents used as mortgage are not included in our data.[12] In addition, Relecura provides an assignment auto-filter algorithm that improves the accuracy of the analysis by cleaning the false positives that arrive in the assignment results-set. The algorithm automatically removes assignments pertaining to self-assignments, security assignments and inventor assignments. The patent clusters with highest number of transactions, along with their assignees and assignors are identified based on the corresponding International Patent Classification (IPC) codes that categorize patent documents into technological sub-classes. The IPC technological levels can then be associated with relevant industries. The generated clusters or assignees show the industry distribution of relative patent transactions within the chosen technologies. In this study, the transaction assignee is defined as a buyer who obtains the ownership of the patent. The transaction assignor, on the other hand, is defined as the seller who is handing over the ownership of the patent in a transaction. Analysis of the transaction assignees, assignors and their industries sheds light on the top active industries in which TENG technology can be potentially applied.

3. Results

The analysis of 492 TENG papers records published between 2012 and 2015 shows fast growth of publications from 54 in 2012 to 233 in 2015. Over 1200 authors around the world are engaged in the field where each paper has been cited 9.5 times on average, a remarkable average given this relatively short time span. The average number of co-authors (around 5 per paper) indicates that this is a highly cooperative research area.

These TENG papers span the WOS categories over Materials Sciences, Nanoscience & Nanotechnology, Chemistry, Engineering, Physics, Energy & Fuels, Pharmacology & Pharmacy, Integrative & Complementary Medicine, Biochemistry & Molecular Biology, Instruments & Instrumentation, and Optics, which suggests that TENG research is highly multidisciplinary with contributions from various fields.

Besides, the leadership and geographic proximity of the top authors appear to be important in shaping TENG community growth. TENG has attracted research engagement around the world with centers of activity in China and the US under the leadership of key authors. In recent years, contributions from European and Eastern Asian countries have gradually increased.

Finally, the data of “funding acknowledgements” indexed by Web of Science suggests that both government and industry funding contribute to the development of TENG research. Governmental funding in China and the US dominates the funding sources for TENG studies. Industry-based funding comes from companies such as LG, 3M, Pfizer, Samsung, Soluxra, Bayer and Merck. The support from industry for an emerging technology suggests a promising commercialization potential.

3.1. Research topics of TENG publications

TENG publications are clustered into sub-categories using topic modeling based on their topic similarities. Table 1 shows the most frequent keywords of the resulting topics. Topic 1 is about the characteristics and measurements of TENG as a power source and energy harvesting technology. Topic 2 describes the application of TENG as sensors. This topic is most related to applications. As reported in the literature, more than any other application forms, researchers have provided dozens of cases of TENGs used as pressure sensors, vibration sensors and applied them into actual scenarios. Thus, it is likely that TENGs will first be commercialized as sensors. Topics 3 and 4 are related to biology and medicine. There are few papers describing applications in healthcare devices such as pace makers, etc. The development of medical and biological devices usually takes a long time, particularly the ones used for human beings. So, the possibility of TENG used in biological and medical industry in the near future is lower. Topic 5 is more related to materials and properties of TENG. As a result, Topic 2 is the most promising application topic addressed using the Topic Modeling method.

A workshop is held involving both Tech Mining and TENG experts to evaluate the findings. TENG experts acknowledge that sensor applications are the most debated and promising application direction in the TENG research community. Tech Mining experts suggest to further examine sub-topics of sensor-related publications so that a clearer picture of studied applications can be drawn. That will also provide evidence for the experts to address potential applications of TENGs.

3.2. Sub-topic analysis of sensor related publications

In this section, the focus is on identification of sub-topics from the publications clustered under the “sensor" topic (Topic 2) in Table 1. 128 publications with a focus on TENG in sensor applications are found through Tech Mining methods described in the first step of Section 2.1.

TENG experts then categorize the sensor-related publications based on the sensors’ physical characteristics and sensor classification standards.[13] Table 2 shows the sensor types, their functions and applications that have been studied in the 128 TENG publications:

As shown in Table 2, TENG-based sensors can be roughly categorized into 12 different types with the three broad application areas (energy harvesting, monitoring, and power sources). Furthermore, TENGs are expected to function as electronic components utilized in industries such as logistics, remote sensing, healthcare, and so on. However, the limited applications found in the papers cover only part of the applications of sensors. Therefore, figuring out more comprehensive applications of the 12 types of sensors is the next step of this study.

3.3. Analysis of sensor patents

Patent data are a prime source to identify applications [66] via Tech Mining. They provide abundant information on the technology properties and utilities. As sensors are the most promising application of TENG, analysis of sensor patents will compensate the inadequacy of TENG patents. As a result, two parallel patent analyses are carried out for different purposes: one to analyze extended applications of the 12 types of sensors identified in TENG publications; the other to analyze the transactions/reassignments of sensor patents to reveal potential market opportunities for TENG-based sensors.

[8] Individual inventors assign patents to their employers as per their contracts.

[9] These transactions occur when patent holders assign patents to banks/funding agencies to secure a loan. Hence, these patents would be transferred back to the patent holders on the repayment of loans, and might not be helpful in our analysis.

[10] Apple changed its name from Apple Computers Inc. to Apple Inc. in the year 2007. This change of company name was recorded with the USPTO and shows up as re-assignment record for many of their patents.

[11] When a company merges with or acquires another company, the patents are assigned to the newly created entity (merger) or to the acquiring company.

[12] The analysis is restricted to assignment records for Australia, Brazil, China, Germany, EPO, New Zealand and United States where assignment transfer records are available in Relecura. However, different data sources have different data availability.

[13] An international standard provided by Jiangmen Leader Electronic Co., Ltd.

Table 1
Themes clustered from TENG research publications using Topic Modeling.

Topic 1	**Topic 2**	Topic 3	Topic 4	Topic 5
Energy	**Selfpowered**	Cells	Scaber	Electrooptic
Triboelectric	**Sensor**	Cell	Chinese	Surface
Power	**Triboelectric**	Mice	treatment	Water
Harvesting	**Flexible**	Activity	Patients	Films
Nanogenerator	**Nanogenerator**	Angiogenesis	Species	Charge
Mechanical	**Device**	Cancer	Taiwan	Corrosion
Selfpowered	**Piezoelectric**	Autophagy	Activities	Thermal
Generator	**Sensors**	Pulmonary	Antioxidant	Optical
Voltage	**PDMS**[a]	Liver	Pioglitazone	Thin
Current	**Voltage**	Activation	Vitro	Temperature
Teng	**Pressure**	Apoptosis	Herbal	Field
Applications	**Wearable**	Trek	Elephantopus	TiO
Density	**Detection**	Induced	Groups	Electric
Contact	**ZnO**	Bone	China	Polymer
Source	**Electrode**	Inhibition	Medicine	Contact
Nanogenerators	**Human**	Physiol	Traditional	Polymers
Maximum	**Active**	Triptolide	Hypertension	Nonlinear
Hybrid	**Devices**	Patients	Safety	Oxidation
Technology	**Transparent**	Binding	Diseases	Silicon
Vibration	**Film**	Endothelial	Studies	Nanoparticles

[a] PDMS (polydimethylsiloxane).

Table 2
TENG modes and their studied sensor applications.

Sensor Types	**Functions**	**Application**
Vibration impact Acceleration sensor	Power source	Machines operation monitoring Environment/healthcare monitoring
Displacement sensor		Personal healthcare geography research
Speed rotation sensor		Implantable biomedical microsystem
Flow rate sensor		Touchpad/ wearable devices Portable electronics
Gas humidity sensor	Monitoring	Process control
Temperature sensor		Chemical engineering
Solution component sensor		Security surveillance
Magnetic current sensor		Artificial skin
Optical sensor		Human-electronic interfacing
Acoustic sensor	Energy harvesting	Tracking system
Pressure sensor		Blockage detection
Orientation sensor		Flow control
Others		Logistics monitoring Acoustic source locator Environmental noise reduction

3.3.1. Extended applications for TENGs in the form of sensors

21,767 patents of the 12 types of sensors, identified as TENG-relevant (Table 2), and filed between 2006 and 2015 are downloaded from DII. After the process of Term Clumping, a factor map is generated that shows the top 20 applications mapped by VantagePoint. The number of applications is reset by Tech Mining and TENG experts together to make the map more readable and measurable. Each application is shown as a node. The resulting map, shown in Fig. 2, reveals application topics and connections (based on co-occurrence of terms in the patents analyzed).

The links between the nodes indicate the strengths of the connections: the closer the connection, the stronger the link. More so, a thicker line indicates stronger association between two nodes (reflecting a path erasing algorithm). The names of the nodes are automatically selected from the first terms in the information boxes[14] (Fig. 3) clustering to constitute the nodes. Nodes that are labeled with identical cluster names by the system are manually renamed by experts based on the contents in the information boxes. The renamed nodes represent a more general concept of the related concepts listed in the corresponding information boxes.

Fig. 2 shows 7 key application clusters in different colors: 1) Power source and storage, 2) Internet of Things and display, 3) Chip/tape carrier or film, 4) Optical devices, 5) Medical diagnostics, 6) Bar code, and 7) Information kiosk.

If we zoom in to the applications with information boxes, more details are revealed as shown in Fig. 3. Here, applications that have also been studied in TENG publications include: cardiac pacemakers, portable machines or hand-held devices, power storage systems, medical instruments, motion sensing devices, nano-devices, nano-biotechnology devices, home security systems, chemical sensing, acoustic touch apparatuses, and others. This means applications mined here are overlapping with but not limited to the ones that have been studied by TENG researchers.

Additional applications can be found in Fig. 3 by relating the applications identified through the patent analysis to the ones identified in TENG publications. These include (by cluster in different colors):

1) grid-tied electrical system, solid state light, fiber optic communication, bar code reader, dehumidifier, electric fan, water heater, electric toy, motors;
2) wireless device, mobile TV receiver, computers, electronic blackboard, Bluetooth devices, credit card, smart card, computer server, carbon dioxide sensor, electroencephalography, carbon monoxide sensor;
3) semiconductor element, optical waveguide, microreactor, immunoanalytical chip, color filter, rib material, tape carrier package & plastic leaded chip carrier, ball grid array;
4) projection lens, gradient index lens, micro lens, diode laser, photonic integrated circuit, array radar, chemical sensing;
5) molecular diagnostics, biological sample analysis, food analysis, chemical sample analysis;
6) information kiosk, order entry system, and
7) optical character recognition, and bar code symbol.

The applications are related to an amazing range of industries, including finance (e.g., credit card, smart card), automobile (e.g., battery, drive source), medical/health (e.g., diagnostics), ICT (e.g.,

[14] The information boxes are the ones labeled with “Abstract USE (NLP) Phrases”

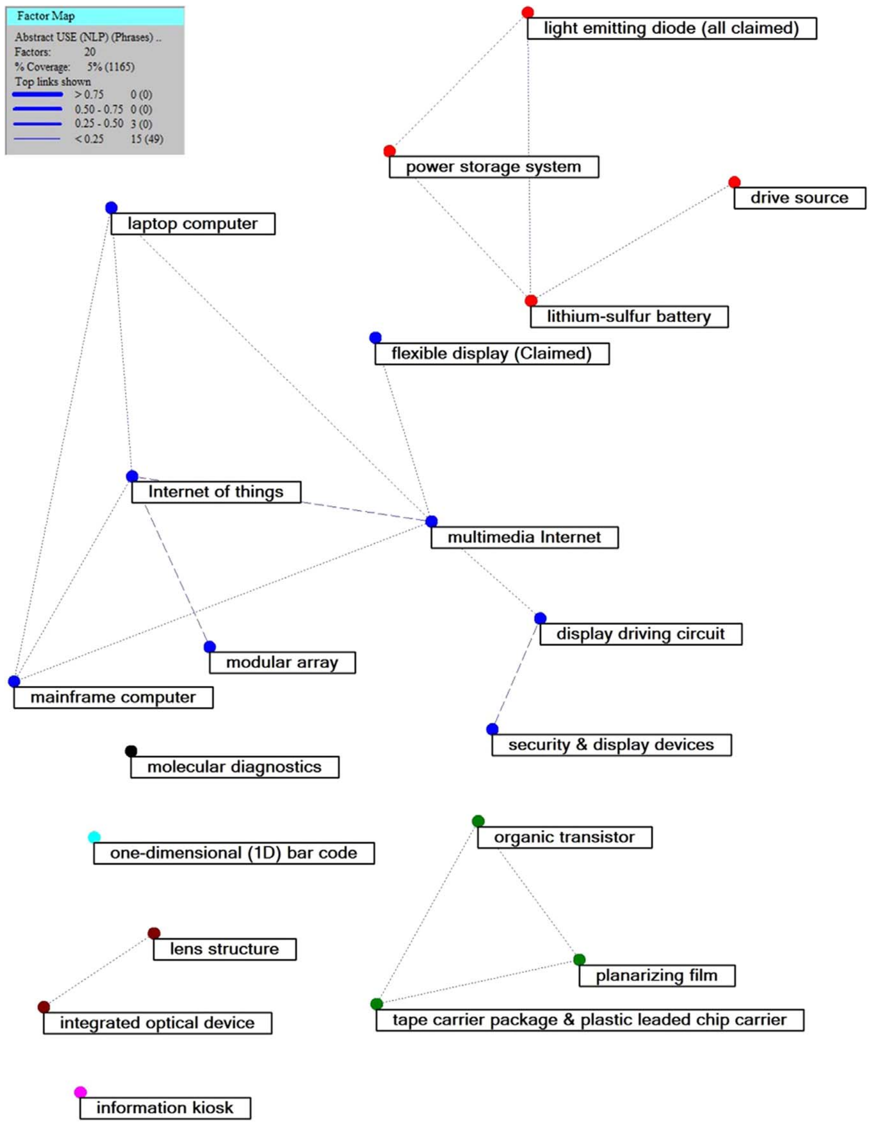

Fig. 2. Application Factor Map of Sensor Patents.

portable machine, displays, computer server, multimedia, semiconductor), security & protection, wholesale & retail (e.g., super market bar code system, order entry system), environment (e.g., chemical analysis, dehumidifier, food analysis), and transportation (e.g., information kiosk). It should be pointed out that since only the top 20 application areas have been analyzed, the results presented here are not exhaustive.

3.3.2. *Sensor patent transactions in the market*

The objective of the second patent analysis is to explore potential market segments for TENGs used as sensors. Transactions or reassignments of sensor patents are analyzed to show the most traded/reassigned technologies. The search didn't limit sensor technologies to the 12 types – in order to compensate for the disadvantage of limited transaction data.[15] This also helps to reveal more applications with fewer conditions. Here, the applications are described on a relatively macro level corresponding to the "Technology" and "Sub-technology" terms, while the findings in the former patent analysis are specific applications on the individual patent level. "Technology" and "Sub-technology" terms are identified based on a methodology developed by Relecura using factors in various patent parameters including keywords and classification codes. In Relecura, "Technology" terms are correspondent to IPC class level and "Sub-technology" terms are correspondent to IPC sub-class level.

We analyzed sensor patents starting from the 1980s when the transaction data became available. Table 3 shows the list of Top10 most traded/reassigned technologies. These 10 technologies account for approximately 60% of the whole 562,819 patent transactions through the years. Each technology was then divided into 5 sub-technologies. The Top5 active assignees and assignors of each most-traded/reassigned-technology are also listed (Table 3).

According to the analysis, sensor patents that relate to testing materials, digital data processing, diagnosis & surgery identification, pictorial communication, and semiconductor devices have been most reassigned since the 1980s.

Although the two analyses use different data sources and data types, the applications shown in Fig. 3 and Table 3 overlap. For example, ICT and medical or healthcare industries have taken the largest portion of applications. Sensor patents used in computers, display devices, semiconductor devices, medical devices, digital components and optical devices are not only intensively reassigned, but also the most addressed applications in our earlier analysis. Such findings also indicate consistency of sensor applications mined through different

[15] Relecura provides patent transaction data of 7 countries including: Australia, Brazil, China, Germany, EPO, New Zealand and United States

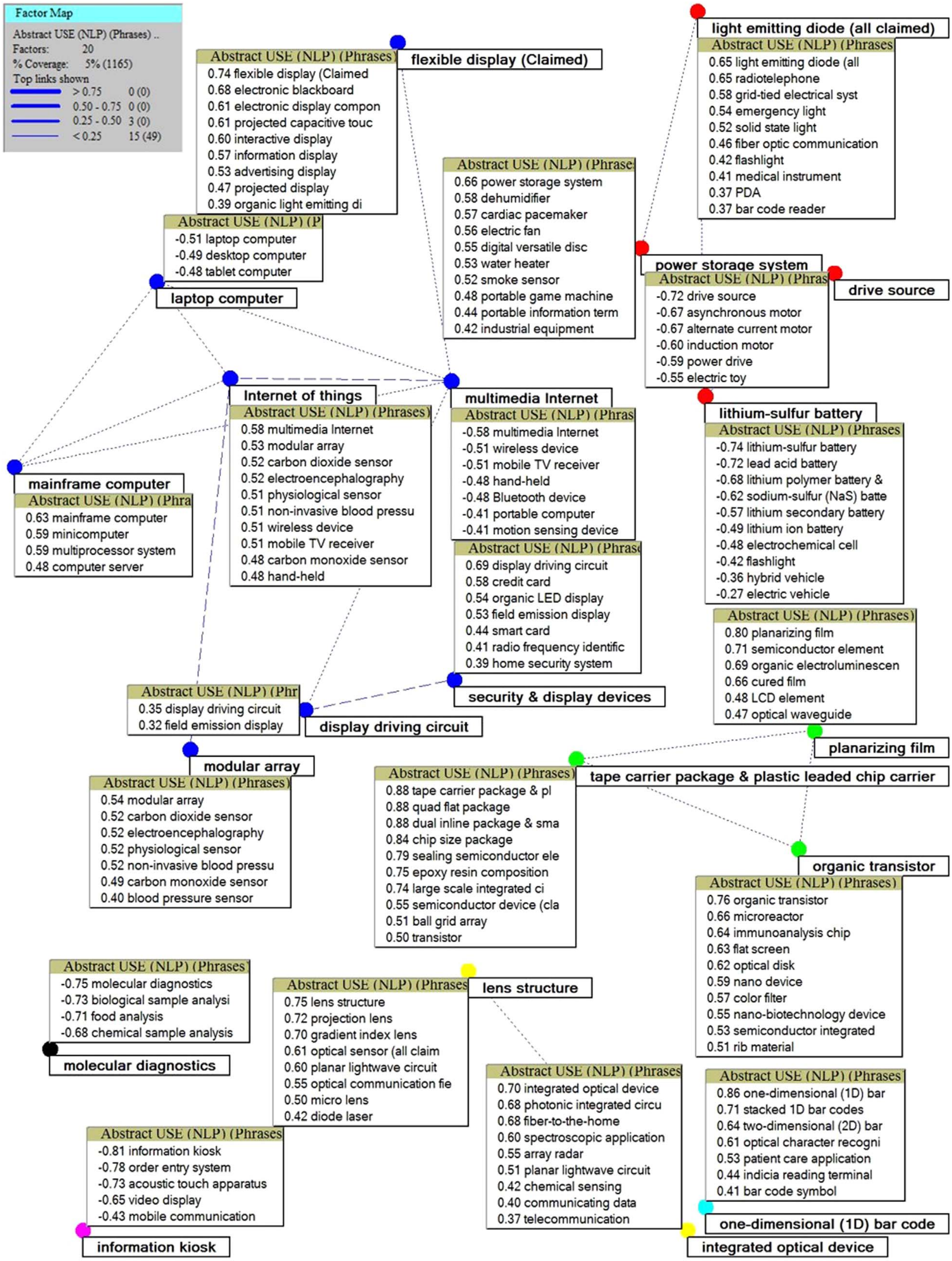

Fig. 3. Application Details of Sensor Patents.

methods.

Some other applications of the most reassigned sensor patents include detecting through ultrasonic, sonic or infrasonic, use as heater or cooler, probes, or drug delivery devices like pumping and suction devices, and gas treatment devices. Data processing and presentation technologies have also been heavily reassigned with obvious reasons in

Table 3
Top10 Sensor Technologies in Patent Transactions.

Technologies	Sub-technologies	Normalized Assignees	Normalized Assignors
Testing Materials (55,466/9.86%)	Analyzing Materials by Miscellaneous Methods	Panasonic (1831)	Panasonic (1404)
	Analyzing Materials using Electric, Electro-Chemical, or Magnetic Means	Roche (1724)	Roche (1162)
	Analyzing Materials using Optical Means	Siemens (1066)	Bayer (690)
	Measuring or Testing Processes involving Enzymes, Nucleic Acids	US National Institutes of Health (NIH) (1025)	University Of California (676)
	Analyzing Materials, Visualizing Interior of Solid Objects using Sonic Waves	US Energy (852)	Siemens (668)
Digital Data Processing (55,320/ 9.83%)	Medical Diagnostics	Covidien(2814)	Siemens(1345)
	Surgical Instruments, Devices or Methods	Philips(1880)	Olympus(1156)
	Diagnosis using Ultrasonic, Sonic or Infrasonic Waves	Siemens(1610)	Nellcor Puritan Bennett (887)
	Surgery by Heating or Cooling the Tissue	Olympus(1280)	Panasonic(798)
	Sensors, Probes Used for Surgery	US National Institutes Of Health (NIH)(1085)	Roche(638)
Diagnosis & Surgery Identification (54,765/9.73%)	Digital Interface Arrangements	Microsoft(3526)	Microsoft(2970)
	Other Data Processing Equipment	Google(1643)	Hewlett Packard (HP)(1487)
	Application Specific Digital Computer	Avago(1287)	Silverbrook Research(1250)
	Function Specific Digital Computer	Hewlett Packard (HP)(1116)	Avago(789)
	Circuits for Display Devices	Samsung(1028)	IBM(759)
Pictorial Communication (44,862/ 8%)	Hardware or Software Aspects of TV Signals	Fujifilm(1407)	Kodak(1460)
	Generation, Transmission, Storage, Reproduction of Documents or Pictures, Storage or Transmission Aspects of Cameras	Intellectual Ventures(1320)	Silverbrook Research(1401)
	Color TV Details	Panasonic(1305)	Avago(1252)
	TV Systems	Google(1280)	Fujifilm(1235)
	Multiple Semiconductor or Solid State Devices Components Formed on A Common Substrate	Avago(1255)	Olympus(1141)
Electric Elements - Semiconductor Devices (37,761/6.7%)	Multiple Semiconductor or Solid State Devices Components Formed on a Common Substrate	Avago(1223)	Avago(1057)
	Manufacturing or Treatment of ICS and Semiconductor Devices	Freescale(1064)	Micron(950)
	Semiconductor Devices Sensitive to Infra-Red, Light, Electromagnetic or Corpuscular Radiation, Converting Radiation into Electrical Energy	Globalfoundries(894)	Citi (934)
	Connecting/Disconnecting Semiconductor Bodies	Aptina Imaging (851)	Magnachip Semiconductor (715)
	Hardware or Software Aspects of TV Signals	On Semiconductor (740)	IBM (627)
Miscellaneous Technologies (34,528/ 6.13%)	Metal Working	Schaeffler (680)	IBM (486)
	Analytical and Immunological Testing	Panasonic (422)	Schaeffler(426)
	Analyzing Materials by Miscellaneous Methods	Roche (417)	Roche (320)
	Stock Material or Miscellaneous Articles	HGST (388)	Bayer (308)
	Machine Element or Mechanism	Siemens(355)	Siemens(298)
Data Presentation (24,470/4.34%)	Reading or Recognizing Printed or Written Characters	Google(872)	Silverbrook Research(964)
	Sensing Digital Cards	Microsoft(778)	Microsoft(665)
	Record Carriers along with Marking Devices	Hewlett Packard (HP)(501)	Hewlett Packard (HP)(475)
	Digital Interface Arrangements	Avago(457)	Avago(324)
	Generation, Transmission, Storage, Reproduction of Documents or Pictures, Storage or Transmission Aspects of Cameras	Apple(442)	Kodak(285)
Drug Delivery Devices (21,786/3.87%)	General Characteristics of Drug Delivery Apparatus	Baxter(710)	Baxter(417)
	Introducing Medicine by a Subcutaneous, Intra-Vascular or Intramuscular Way	Covidien(574)	Gambro(354)
	Medical Suction or Pumping Devices	Roche(563)	Dragerwerk(314)
	Medical Diagnostics	Gambro(550)	Searete(274)
	Influencing Patients' Respiratory System by Gas Treatment	Medtronic(401)	Mallinckrodt(257)
Greentech – Others (21,192/ 3.77%)	Surgery	Siemens(364)	Siemens(283)
	Medical Diagnostics	Google(262)	Silverbrook Research(231)
	Analyzing Materials by Miscellaneous Methods	Panasonic(231)	Panasonic(199)
	Molecular Biology and Microbiology	Therasense(193)	Hewlett Packard (HP)(175)
	Nanotechnology	Philips(178)	Goldfinger Technologies LLC (148)
Measurement-Electric & Magnetic Variables (19,227/3.42%)	Arrangements for Testing Electric Properties, Locating Electric Faults	Western Digital (465)	HGST (424)
	Measuring Magnetic Variables	Freescale (316)	IBM (337)
	Measuring Resistance, Reactance and Impedance	Philips (269)	CITI (296)
	Currents or Voltages or for Indicating Presence	State Electric Net Corp. (248)	JP Morgan Chase (159)
	Measuring Electric Variables using Miscellaneous Methods	HGST (233)	Philips (125)

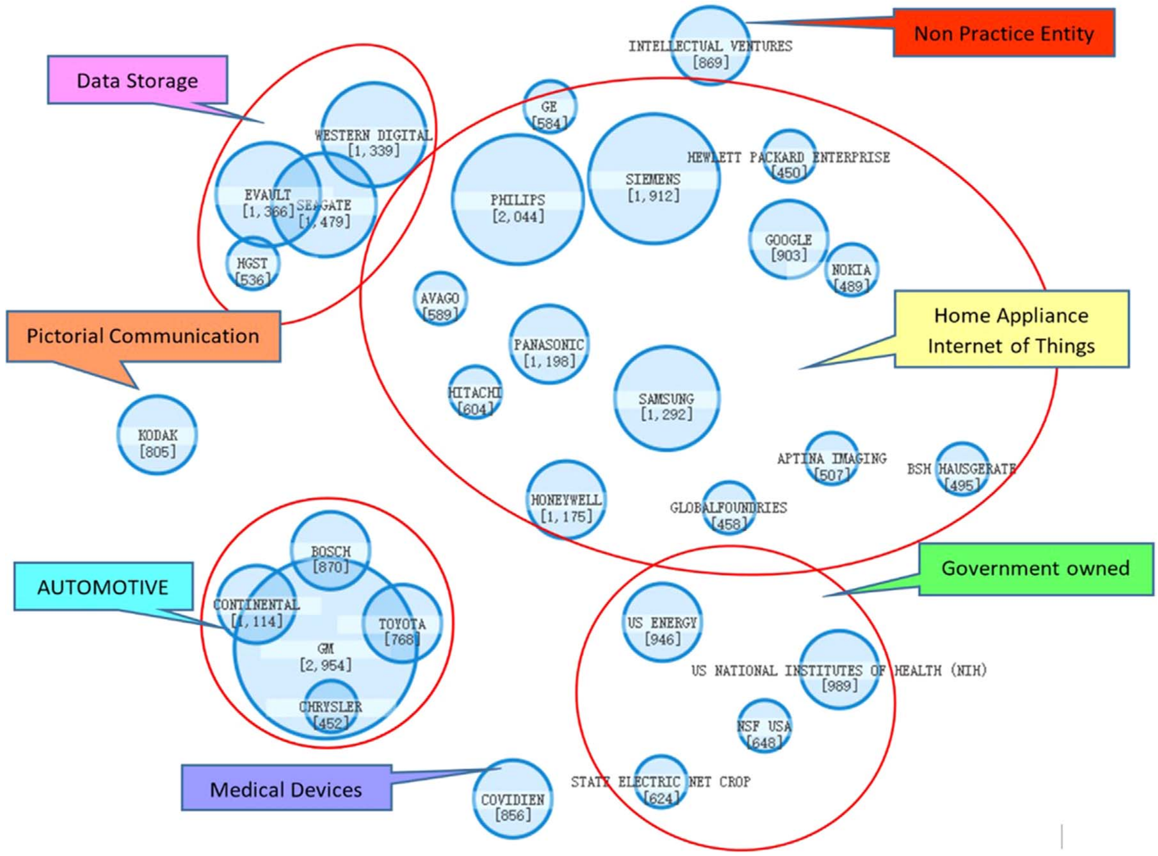

Fig. 4. Top30 Assignees of Sensor Patents in Transaction.

Table 4
Potential Applications of TENGs used as Sensors.

Micro **Specific applications**	**Sub-technologies**	**Technologies**	**Macro** **Industries**
Grid-tied electrical system, Motor	Analyzing materials by different means/	Testing Materials	Automotive
Electric toy/fan, Solid state light	methods		Finance
Fiber optic communication, Dehumidifier	Heating or cooling the tissues,	Digital Data Processing	Medical
Bar code reader, Water heater	Detecting through ultrasonic, sonic or		Measuring & Controlling Devices
Wireless device, Computer server	infrasonic waves	Diagnosis & Surgery Identification	Pharmaceutical
Mobile TV receiver, Electronic blackboard	Measuring or testing processes involving		Optical devices
Bluetooth devices, Credit/smart card	enzymes nucleic acids	Miscellaneous Technologies	Household Appliance
Carbon dioxide/Monoxide sensor	Medical Diagnostics		Food Products
Electroencephalography	Probes, Computer, TV system	Electric Elements-Semiconductor	Customer Electronics
Semiconductor element, Microreactor	Digital interface arrangements	Devices	Wholesale & Retail
Optical waveguide, Immunoanalysis chip	Data processing equipment		Environment
Color filter, Rib material	Metal working	Pictorial Communication	Semiconductors & Related Devices
Tape carrier package & chip carrier	Analytical and immunological Testing		Electronic Computers
Gradient index lens, Projection lens		Data Presentation	Computer Peripheral Equipment
Micro lens, Diode laser, Array radar	Reading or recognizing printed or written		Transportation
Photonic integrated circuit	characters	Drug Delivery Devices	Chemical
Molecular diagnostics, Food analysis	Sensing digital cards		Motors & Generators
Biological sample analysis	Record carriers along with marking devices	Greentech - Others	Surgical & Medical Instruments &
Chemical sample analysis			Apparatus
Information kiosk	Testing electric properties	Measurement-Electric & Magnetic	
Order entry system, Bar code symbol	Measuring magnetic variable	Variables	
Optical character recognition			

the time of wireless communications and Internet of Things.

Finally, since the industry backgrounds of assignees and assignors in patent transactions represent industrial supplies and demands of sensor technologies, we analyze the top assignees or the buyers who initiated sensor patent transactions (Fig. 4) to understand what sensor technologies the market requests the most.

The industries clustered in Fig. 4 in circles show the dominant industries and sectors that initiated most sensor patent transactions. The sizes of the bubbles indicate the numbers of patents each assignee/buyer holds. The distances between bubbles show the similarities of the patent portfolios or technologies.

First, the automotive industry obviously contributed to a multitude of transactions of sensor technologies. The overlaps among the leading automotive companies such as GM, Toyota, Continental and Chrysler may indicate intensive cross-licensing activities in the industry and potentially a technology alliance is forming. Another cluster is formed by companies like Seagate, Western Digital, HGST, and Evault that produce hard drives or provide digital data storage services. The third cluster involves companies that produce home appliances, consumer electronics and components for the Internet of Things. These companies include Siemens, Philips, Panasonic and Samsung which have been most active in the sensor patent transactions, according to the sizes of the bubbles. The fourth cluster does not represent an industry but groups government-funded reassignments. It shows that DoE, NSF and NIH in the US and State Electric Net Crop in China owned or acquired sensor patents. What's more, Covidien leads the transactions of sensor patents in medical devices, while Kodak leads transactions of sensor patents in pictorial communications. Last, but not least, Intellectual Ventures, which is a Non-Practicing Entity, has unsurprisingly been building a sensor patent portfolio, too. It should be mentioned that several pharmaceutical and healthcare companies like Roche, Bayer, Baxter, Gambro, Medtronic and Therasense, as well as Optics Device-focused companies such as Olympus that appear in Table 3 are not seen in Fig. 4 because of different analytical goals and methods.

The results of the presented analyses are summarized in Table 4, which lists applications from the micro-level to macro-level. The applications on a micro level are refined based on applications of individual patents. They are associated with specific products or scenarios. Applications on sub-technology and technology levels were refined from the analysis of patent transactions corresponding to IPC codes on sub-class and class levels. The industry level applications are listed based on the findings of Table 3 and the analysis of the Top30 transaction assignees and their industries. As shown in Table 4, Automobile, Medical/Healthcare, Data storage and recovery, Home appliance/Customer electronics, Optics devices are the industries that most actively traded/reassigned sensor patents. Specifically, TENG expert point out that the application of TENG-based sensors used in medical devices or healthcare industries are likely to lag because of the regulations and strict evaluation process, although a lot of TENG research is happening in these areas.

Researchers may combine applications on different levels to explore new applications. However, since the findings are mainly based on the applications of sensor patents, TENG researchers may need to evaluate how to use the findings to guide their research in exploration of TENG applications. Although the list in Table 4 is not exhaustive, it is our hope that the areas listed encourage researchers and developers to explore new applications of TENGs.

4. Discussion and conclusions

This study aims to forecast applications of the TENG technology through Tech Mining methods. Using 2012–2015 publication data of TENG from Web of Science, the study first analyzes the development trends of TNEG research community. The results show that researchers from China and the US are spearheading the R & D. The TENG research community has experienced a fast growth in terms of publications, research initiatives, and R & D funding on an international level. Analysis also shows that sensors were the most studied applications of TENGs. Moreover, TENG has attracted attention from industry in its early stage of development, indicating the potential to be commercialized.

Justified by TENG researchers, sensor patent data is used to forecast potential applications of TENG (instead of TENG patent data due to the limited number of patents) in two ways, to: 1) revealing extended applications of TENGs used as sensors that complement the ones previously reported in TENG publications, and 2) exploring the market demands for sensor technologies by investigating patent transactions. The findings point to promising applications of TENG technology, from product level to industry level. Although the list of applications is not exhaustive, it gives an overview of the breadth of TENG applications.

It is important to validate the applications identified through the analysis because of the complexity of technology development and commercialization. In the study, workshops are held not only with TENG researchers, but also with experts from the electronics, automobile industry, and venture capitalists, who provide experiences or insights from the marketplace.

According to the findings, TENG may become a technology of strategic value for mankind in the future for the following reasons:

1) TENGs have high potential to be widely used in the form of sensors in automation and energy-intensive industries, such as automobile, customer electronics, medical or surgery devices, etc. These industries are developing fast and experiencing a lot of changes led by new technologies with sensor as a key element. With the massive customer foundation, the needs for sensors used in those industries are expected to grow exponentially.
2) TENGs used as self-powered sensors may be integrated with emerging technologies such as nanotechnology, robotics, drones, automatic driving cars, and medical/bioinformatics. The characteristics of TENGs empower the technology to be combined with other technologies that are becoming smaller, more adaptable and more intelligent. Therefore, those technologies also provide opportunities for TENGs to be used in massive numbers and sensor forms.
3) The identified applications of TENGs are in line with global trends of growth in the Internet of Things, big data, clean energy, and smart cities. Many applications such as signal processing, electronic elements or chemical are closely related to these industries or technology fields. We believe the thriving and lasting growth of a technology can only go with its value to the good of human beings. Once TENGs are utilized in these fields, they can be used in dealing with grand challenges such as environmental issues, security, healthcare, education, and so on.

While the analysis demonstrates opportunities for TENG technology, challenges also exist. The TENG is still in its early stage of development and many of the application studies are laboratory studies only. The technological maturity and industry readiness are yet to be tested. Given the complexity of commercialization, certain strategies and tactics are recommended to the TENG research community:

First of all, TENG researchers should increase their efforts in actively filing patents to protect their inventions and application ideas combined with publishing papers. Meanwhile, since Table 4 shows a multitude of use possibilities by combining applications on micro- to macro-scale, we suggest TENG researchers reach out and initiate collaboration with researchers from other fields and industries in the forms of joint conferences or research projects, etc. Furthermore, based on the analysis of sensor patent transactions, the top assignees are all multinational companies who tend to be more active in filing patents to accumulate technological competitiveness. Consequently, they are also more aggressive in intellectual property rights (IPR) negotiations. Therefore, it is highly recommended that TENG researchers resort to professional IP specialists or attorneys when it comes to technology transfer.

There are also limitations of this study. As the first effort in identifying potential applications for TENGs using Tech Mining methods, this study provides a new way to forecast potential applications for emerging technologies like the TENG. It is critical to understand the research goal and characteristics of an emerging technology before the same metrics can be applied for predicting possible applications. In the case of TENG, experts not only developed a technology roadmap [67] that showed a clear path for potential application directions, but also notified in the beginning of the study that TENG has a lot of application potential in the form of sensors. So, the logic of this study is relatively straightforward that by analyzing applications of sensor patents, the findings would suggest extended applications for TENGs. However, with other emerging technologies that are not developed with clear application directions, more information and methods should be collected and considered.

Another limitation of the research is the data. When forecasting innovation pathways based on Tech Mining methods, multi-database information is preferred [49] for more encompassing results. In the study, limited publication and patent transaction data might impose a slight bias.

Lastly, it is possible that not all the applications identified are applicable for TENGs as the findings are based on analyses of sensor patents. The applications are most likely to be applicable in an ideal situation for TENGs. However, since we haven't seen any work that specifies the relationship between sensor technology and TENG technology, it is suggested that researchers double check the validity of applications they aim to explore.

To summarize, the study uses Tech Mining methods to identify potential applications for TENG technology with a focus on sensor applications. The findings provide options on different application levels and directions for TENG researchers to initiate more pragmatic research, while inspiring Tech Mining researchers to further explore how Tech Mining can be utilized to facilitate the commercialization process of emerging technologies like TENG. For future study, in-depth analysis of sensor applications of TENGs in different industries such as automobile, greentech or clean energy hold appeal due to the significant meaning for mankind.

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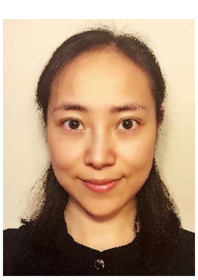

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