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Tracing the Evolving Trends in Electronic Skin (e-Skin) Technology Using Growth Curve and Technology Position-Based Patent Bibliometrics

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ABSTRACT Electronic skin (e-skin) technology has grown considerably over the past decade, attracting much attention as an emerging technology in the revolutionizing of the next-generation wearable devices and robots. Therefore, the tracing of the evolving characteristics of this technology up to the present time will assist researchers and R&D planners in directing their further R&D. In this paper, two patent-based bibliometric analyses are conducted to study the evolving characteristics of e-skin technology in terms of the technology life cycle and the technology position. First, a growth curve is fitted to the yearly patent registrations, thereby calculating the technology-maturity ratio, the number of potential future patents, and the expected remaining life of the e-skin technology. Second, a technology-position analysis that depicts the evolution of the core technologies and their neighborhood is performed to identify the way that new technology clusters emerge and grow over time. As a result, it is possible to identify from the inventional perspective that the technological development of the e-skin technology has entered the early maturity stage, and its expected remaining life as of the end of 2016 was estimated as 11.78 yr. In addition, several major technology clusters, including pressure-sensitive elements, semiconductor devices and fabrication, and diagnostics, which have grown considerably and show increasing technological overlaps, were identified.

INDEX TERMS Bibliometrics, electronic skin, growth curve, patent analysis, technology position.

I. INTRODUCTION

Electronic skin (e-skin) is a thin electronic device that mimics the functions and properties of human skin. Human skin has vital functions, including pressure and temperature sensing and self-healing, and unique properties, including flexibility and stretchability [1]. The prospect of creating an artificial skin with such functions and properties was, in the early days, inspired by science-fiction texts, such as the Six Million Dollar Man television series, the Star Wars series, and the Terminator movies [2]. Since the first Sensitive Skin Workshop was held in Washington D.C. just before the turn of the millennium, this technology's development pace has significantly increased owing to the increased industrial interests and investments [2]. Industrial interests in e-skin with human-like sensory capabilities can be related to artificial intelligence (AI) robots, medical diagnostics, replacement prosthetic devices, and wearable devices [2], [3]. For example, the application range of robots with a pressure sensitivity could extend to simple and manipulatory tasks for the caring of elderly people [4] and sensor skins applied on or in the body that could provide an unprecedented level of health monitoring and diagnostics [3], [5]. Due to the wide industrial-applicability potential, researchers have paid great attention to the development of new materials and fabrication processes for the e-skin functions and properties [2], [6], [7], and therefore this technology is now expected to revolutionize the next-generation wearable devices and robots. Regarding this emerging technology that is expected to make a mark in the near future, the tracing of the dynamic trends up to the present time will help the researchers and R&D planners in academia, industry, and government to better understand this technology's evolving characteristics, and it will provide them with decisive insights for the directing of further R&D.

Despite the attraction of e-skin technology and its recent growth, trend analyses have mostly relied on taxonomic analyses for which qualitative reviews of research papers have been conducted [2], [6], and for which the technical issues and application directions have been examined [7], [8]. According to the authors' best knowledge, the research so far has paid little attention to an identification of the e-skin technology's evolving technological trends that is based on objective data. In addition, a dearth exists regarding comprehensive views of the industrial competition because research papers were used as the primary analysis material for the prior trend analyses. Therefore, the present study aims to carry out two bibliometric analyses that encompass the following two dimensions: the life cycle of the technology development and the evolution of the technology positions. To this end, this study uses the patents that are related to e-skin technology as its data source. Patents are considered the most prolific and reliable technology intelligence that contains the recent technical advances in both academia and industry [9]; patent applications are published within 18 months after their first filing, regardless of their nation of origin. In addition, every patent, regardless of its commercial value, is a result of R&D activity [10], and therefore can be used in the generation of a technical insight that can offer inspirations for subsequent technology developments [11]. For these reasons, a number of patent-based bibliometric studies have been conducted for technology trend analysis. Some studies employed patent-based growth curves, which are the empirical model of the evolution of a quantify over time, and time series models to forecast recent and future trends of rapidly evolving technologies [12], [13], analyze and predict technology substitution and competition among relevant technologies [14]–[16], and forecasting research activity of emerging technologies [17]. Other studies adopted patent-based network analysis to determine convergence patterns and evolving trajectories of emerging technologies [18]–[21] and prioritize a portfolio of investment projects [22]. As made apparent, growth curve-based and network-based approaches have been widely used in many patent-based technology trend analysis studies.

In the present study, two quantified analyses are conducted to determine the evolving trends in e-skin technology, as follows: a technology development-stage analysis and a technology position analysis. First, the technology development-stage analysis, which is based on the approach by Yoon *et al.* [12], determines e-skin technology's current development stage by fitting a growth curve to the annual number of patent applications, thereby estimating the values of the following three indices from the curve: the technology-maturity ratio, the number of potential patents, and the expected remaining life. Using these indices, it is possible to illuminate the current and future technical focuses for R&D in e-skin technology in consideration of the technology life cycle. Second, the technology position analysis maps the evolving landscape of e-skin technology's technical expansion by making connections among the technology positions that have been obtained from the patents; a technology position is defined as an agglomeration of the classification codes that are assigned to a patent [23]. Therefore, the technology position analysis of e-skin technology displays the evolution of the core technology positions and their neighborhood over time, thereby identifying the growth and the spillovers of the technology clusters in e-skin technology. It is expected that this study will provide a comprehensive understanding of the evolving panorama of e-skin technology and that it will support the researchers and technology planners in the fields of e-skin technology as they determine their future R&D directions.

II. PATENT DATA

The data used in the present study are the patents related to e-skin technology. Generally, the process for collecting such patents consists of the following two steps: defining the taxonomies of a technology for the analysis, and constructing a patent retrieval query statement with the keywords that correspond to the defined taxonomies. E-skin technology embraces the technical taxonomies of the human skin's vital functions and properties, so this study considers e-skin technology as being directly related to the tactile sensors, chemical and biological sensors, and devices with additional desirable requirements such as flexibility and self-healing [2]; these taxonomies become the criteria to determine valid patents. Based on the taxonomic definition, a query statement was constructed to retrieve the e-skin patents (Table 1) that are located in the patent data from the United States Patent and Trademark Office (USPTO) database, which were then stored in an electronic file, such as a Microsoft Excel file or a text file, for the computational analysis.

The patent set that was initially obtained by the query statement contains a variety of metadata for each patent, including application numbers, application dates, inventors, applicants, and the International Patent Classification (IPC) codes, as well as the textual sections for detailed invention descriptions, including abstracts, patent specifications, and claims. Although the initial patents matched the query statement, some of them may be irrelevant to the aforementioned technical taxonomies. Such irrelevant patents, called ''noise patents,'' should be filtered out from the initial patent set by expert examination; one of the authors, who is an expert who has researched tactile sensors and chemical and biological sensors in e-skin technology, advised the noise-patent filtering task of this study. From the initial patents that were returned, the elimination of the noise patents yielded a total of 1,509 valid patents.

III. METHODOLOGY

This section explains the specific methods that were used to achieve the tracing of the evolving trends in e-skin technology. The present study employs a growth-curve analysis to determine the technology development stage and technology position analysis for the display of the evolution of the core technology positions and their neighborhood over time. The following subsections describe the methods in greater detail.

TABLE 1. Patent search for e-skin technology.

Patent retrieval query statement	Initial patent set[a]	Valid patent set
(electronic ^2 skin + "e-skin" + eskin + smart ^2 skin + sensitive ^2 skin + artificial ^2 skin)+ ((tactile + chemi + bio) * (perceiv + sens + detect) * (flexib + stretch + durab)* ("PDMS" + polydimethylsiloxane + "PI" + polyimide + nano * (composite + compound) * (material + polymer) + CNT + carbon*nano*tube + graphene + NW + (nano ^2 wire) + ZnO + polymer))	21,626	1,509

[a] Patent search was conducted on July 17, 2016.

A. GROWTH CURVE ANALYSIS

A growth curve, as a type of sigmoid function, was developed from the finding that the population size of a living organism follows an S-shaped curve in which the growth is slowest at the beginning and the end of a time period [13]. Therefore, earlier studies employed growth curves to model the growth patterns of the bacteria [24] and cancer cells [25] in biology based on the historical data.

Recently, a number of studies have used this time-dependent growth curves to model a technology's life cycle and to determine the current maturity within the life cycle. Such studies assume that the evolution process in a technology follows an S-shaped growth, wherein the growth curve is fitted to identify a technology life cycle that is sequentially composed of the following 4 or 5 stages: emerging (conception and birth), growth, maturity, and saturation (or retirement) [26], [27]. The S-curve concept and patent activities over the technological lifecycle have been used together to analyze the current and future trends of a given technology and support R&D strategy formulation [12], [13], [27], [28]. In the stages of conception and birth, the development phase of a new technology is gradual because only a few researchers in academia and industry are engaged in that technology and little attention is paid to the technology due to the various technical obstacles to be solved. If, however, the technical feasibility and applicability are proven by successful inventions, the pace of the technology development increases significantly due to the increased investments into this technology, and accordingly, this technology goes through the stages of growth and maturity. As the technical opportunities for further development are exhausted, the technology finally enters the retirement stage.

As mentioned previously, the S-shaped growth curve that is used in the modeling systems saturates over time, and it has been found that it sufficiently describes the development process of a technology system. To determine the developmental stage of a given technology in terms of inventions, patent-based studies have used the number of patent applications as the input data to fit various growth curves, such as the Gompertz model, the Logistic model, the Pearl model, and the Fisher-Pry model [12], [13], [15], [29], [30].

Generally, the best model for technology growth can be chosen among those models, using prediction accuracy measures of a forecasting method, including MAPE (Mean Absolute Percentage Error) and R-squared. In addition, the characteristics of the input data such as symmetry can be considered to select a proper model. Among those growth curves, the present study elaborates the Logistic growth curve that is considered the most popular model in the trend forecasting of high technologies [28]. The Logistic growth curve is defined by Eq. (1), and it depends on the three coefficients t_0, k, and L; here, t_0 and k, determine the midpoint and the steepness of the curve, respectively, while L is the asymptotic maximum value of the curve [29]. Because an important characteristic of the Logistic growth curve is its symmetry about the point of inflection, it is easy to forecast the remaining trends if the inflection point on an S-curve occurs [31]. In the present study, a Logistic growth curve is fitted to cumulative patent registrations.

$$Y(t) = \frac{L}{1 + e^{-k(t-t_0)}} \tag{1}$$

The three unknown coefficients can be estimated by applying the ordinary-least-square regression method to the log-linearized form of Eq. (1). Given a growth curve that has been decided upon by an estimation of the coefficients, the three specific indices of the technology in terms of the technology life cycle can be computed; that is, Yoon *et al.* [12] approach is employed. These indices are the technology maturity ratio (TMR), the number of patents to appear (PPA), and the expected remaining life (ERL). The first two indices can be simply calculated using the saturation level L of the growth curve. First, the TMR has a value between 0 and 1 and indicates the degree to which a technology has approached its maximum development level. Second, the PPA is used to forecast the quantity of potential patent registrations that will appear in the future. The TMR and PPA of a technology are accordingly defined as follows:

$$TMR(t) = \frac{L_t}{L}, \tag{2}$$

$$PPA(t) = L - L_t, \tag{3}$$

where L_t is the number of cumulative patents at time t. By setting t for a specific year, analysts can predict the TMR and PPA at time t; for example, if t represents the current year, then the indices can be used to estimate the current technology maturity and the number of additional patent registrations at the current year. Next, the ERL of a technology can be computed only if a threshold value ρ for the technological advancement is given; this is because the number of cumulative patent registrations at time t never reaches the saturation level, L. Assuming, however, that the threshold value, ρ, is 0.90, the number of cumulative patents will reach the uppermost value of 90% of L at a specific time; therefore, the time required to reach this uppermost limit can be calculated using the threshold value $0 \leq \rho \leq 1$, as follows:

$$ERL(t) = T_\rho - t, \tag{4}$$

where T_ρ is the year that the number of cumulative patents is expected to be $\rho \times L$.

By using the three indices for the analysis of the technology life cycle, analysts can understand the evolving characteristics of the studied technology, whereby they can determine decisive insights for the directing of further R&D from an inventional perspective.

B. TECHNOLOGY POSITION ANALYSIS

Potential technological innovations can be understood as a landscape with potential positions, each of which corresponds to a particular configuration of technical components [32]. Some of the positions may be occupied by existing innovations, while other positions may not have been discovered by the existing innovations despite being potentially valuable or feasible; this is because the innovations within a given technology tend to agglomerate into clusters of adjacent technology positions, rather than the forming of a random distribution [23]. In the exploring of different solutions for a problem under study, the concept of recombinant search helps to identify new knowledge elements or new relationships among the knowledge elements. Recombinant refers to the fact that the creation of new knowledge is most often the product of a novel recombination of the known elements, including knowledge, problems, and solutions [33].

In terms of the patent analysis, the patent-classification codes can be used as the building blocks that constitute the technology positions, each of which is a unique combination of classification codes. The USPTO currently uses the following three classification systems for the technical classification of patents: the United States Patent Classification (USPC), the IPC, and the Cooperative Patent Classification (CPC). A prior study of the patent-based technology position analysis used the USPC codes to define the technology positions for the capturing of the technological capabilities of patents [23]; the greater focus of the USPC is the structure, function, and effect of inventions, while the IPC is an industry-focused classification [34]. As of June 1, 2015, however, patent applications are no longer published with USPC codes, with plant patents and design patents being the only exceptions; that is, the USPC was replaced and incorporated into the CPC, which is a more specific and detailed version of the IPC. Therefore, for the method reproducibility of the technology position analysis of this study, the technology positions are defined based on the IPC code that is the common dominator for both past and future patent registrations.

The IPC is a global patent-classification system that is used to classify and search for patents according to the technical fields they pertain. The IPC is a hierarchical structure and each IPC code consists of sections (one of the capital letters A through H), classes (two-digit number), subclasses (a capital letter), main groups (a one-to-three-digit number), and subgroups in the order of detail (at least two digits) (Fig. 1). Subclass IPC codes represent the technology fields from a broad perspective, while the main-group IPC codes can precisely define a subject-matter field within the scope of its subclass IPC; the main-group IPC codes indicate specific products, processes, and mechanisms in terms of the level of detail.

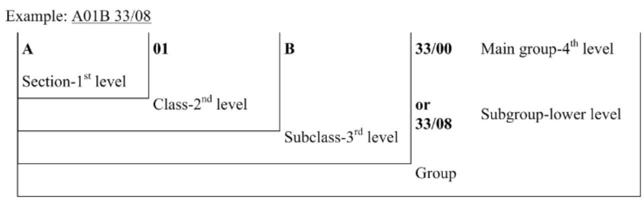

FIGURE 1. Hierarchical structure of the IPC [35].

In the present study, a main-group IPC code is considered as a technical element, and the configuration of the IPC codes is assigned to a patent as the patent's technology position. Then, a patent's technology position can be structured as an array of IPC codes. In addition, given the two technology positions p and q in an n-dimensional vector space, the distance between them can be measured using the Manhattan distance [36] (also known as the rectilinear distance) given by Eq. (2), as follows:

$$d(\boldsymbol{p}, \boldsymbol{q}) = |\boldsymbol{p} - \boldsymbol{q}| = \sum_{i=1}^{n} |p_i - q_i|. \tag{5}$$

Two technology positions are considered as adjacent (distance = 1) when they differ by only one vector element; for example, the two vectors 11100 and 11000 are adjacent because the value obtained by the third element is the difference between them. In this way, the distances between all of the pairs of technology positions from a patent dataset can be measured (Fig. 2). When the adjacency among the technology positions is identified, a technology-position landscape of e-skin technology's technical expansion can be depicted. In addition, by using the longitudinal data of the technology positions, the evolving process of the core technology positions and their neighborhood over time in terms of e-skin technology can be depicted. Therefore, the mapping of the technology positions and their adjacency provides technology experts with insight into the way that technology positions newly emerge and how different technology positions construct the technology clusters [23]. In particular, for a firm that is attempting to innovate with their technology positions, the technology-position landscape can be used as an aid to identify new technology opportunities and to extend technology-based businesses through the exploration of the firm's adjacent technology positions.

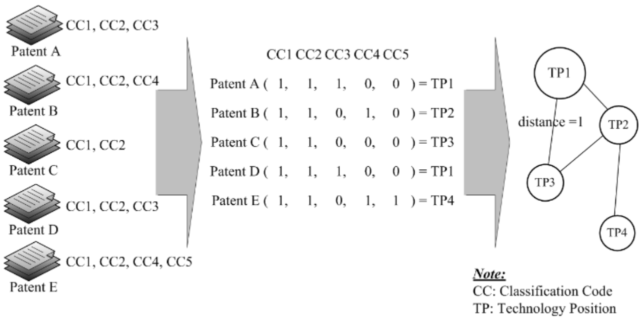

FIGURE 2. Concepts of the technology position analysis.

IV. RESULTS

A. DESCRIPTIVE STATISTICAL ANALYSES

It was possible to identify an overall trend in the number of annual patent registrations regarding e-skin technology (Table 2); to organize the patent registrations, their application date was used instead of their registered date because the filing date of a patent indicates the clear origin date of the patent's public disclosure. For the statistics of the annual patent registrations, the patents after 2014 were excluded because a patent application is published within 18 months after its first filing and the e-skin patents were collected at the beginning of 2016. Overall, the annual patents are fairly constant until 1990 (average between 1974 and 1990: 6.48), and they gradually increased thereafter until 2000 (average between 1991 and 2000: 22.89; the rate of increase: 0.09). From 2001 to 2009, the production of new intellectual property in e-skin technology started to dramatically increase (average between 2001 and 2009: 82.22; the rate of increase: 0.14); however, between 2010 and 2013, many annual patents were filed, but their numbers started to decrease slowly (average between 2010 and 2013: 101.25; the rate of increase: −0.10).

Based on this analysis of the yearly patent-application trends, it is possible to conclude that a great deal of technological advance occurred in e-skin technology during the period from 2006 to 2012. In addition, one might intuitively imagine that e-skin technology likely reached the last stage of growth or the early stage of maturity from the gradual decrease of patent applications near 2013. However, this prediction based on the simple statistics of the annual patent applications are fragmentary and logically weak, so deeper analysis is required to provide researchers and R&D planners with decisive technological implications regarding the future R&D directions of e-skin technology; therefore, a further discussion of the characteristics of the technology life cycle of e-skin technology occurs in the section "Technology development-stage analysis."

Next, the number of patents was identified by the main-group IPC code (Table 3); a patent should have at least one IPC code. Among the top-20 IPC codes, the IPC codes that are related to the pressure-measurement method of a fluid or a fluent solid material for which electric, magnetic, or mechanical sensitive elements are used were

TABLE 2. Patent applications ordered by application year in e-skin technology.

Year	# of patents	% of patents	Year	# of patents	% of patents
1974	1	0.07%	1995	23	1.52%
1975	2	0.13%	1996	15	0.99%
1976	2	0.13%	1997	19	1.26%
1977	2	0.13%	1998	28	1.86%
1978	2	0.13%	1999	23	1.52%
1979	5	0.33%	2000	36	2.39%
1980	3	0.20%	2001	40	2.65%
1981	4	0.27%	2002	59	3.91%
1982	5	0.33%	2003	76	5.04%
1983	9	0.60%	2004	73	4.84%
1984	9	0.60%	2005	80	5.30%
1985	10	0.66%	2006	96	6.36%
1986	9	0.60%	2007	99	6.56%
1987	12	0.80%	2008	100	6.63%
1988	6	0.40%	2009	117	7.75%
1989	22	1.46%	2010	107	7.09%
1990	7	0.46%	2011	109	7.22%
1991	16	1.06%	2012	112	7.42%
1992	24	1.59%	2013	77	5.10%
1993	13	0.86%	2014	31	2.05%
1994	25	1.66%	2015	1	0.07%
			Total	1509	100.00%

Note: The 2014 and 2015 patents are excluded because a patent application is published within 18 months after its first filing and the e-skin patents of this study were collected at the beginning of 2016.

relatively high-ranked; G01L-009 (measurement for which electric or magnetic pressure-sensitive elements are used) had the most patents (6.58%), and G01L-001 (forces or stress measurement in general) and G01L-007 (measurement using mechanical or fluid pressure-sensitive elements) were ranked fourth (4.17%) and sixth (2.64%), respectively. The IPC codes H01L-029 (semiconductor devices for capacitors or resistors), H01L-021 (processes for treatment of semiconductors), and H01L-041 (piezoelectric devices), which are the patent classifications that are related to the e-skin devices and processes, were ranked second (5.69%), third (5.32%), and seventh (3.09%). Interestingly, A61B-005 (detecting, measuring, or recording for diagnostic purposes) was ranked eighth (2.05%), so it was possible to conclude that a great amount of research on the use of e-skin technology in medical diagnostics has been performed. In addition, the high ranking of the IPC codes B82Y-030 (nanotechnology for surface science), B82Y-040 (treatment of nanostructures), C01B-031 (carbon compounds), and D01F-009 (carbon filaments) suggests a great effort in the development of new nanostructures, such as carbon compounds and carbon filaments, and their treatment and manufacture. Overall, the top-20 IPC codes had 50.17% of the number of patents, and these patents are assigned to a total of 446 IPC codes; therefore, they are likely to be core IPC codes that have received much attention due to a variety of inventions. Although these statistics show the overall trends as well as the major IPC codes in terms of the patent registrations, this analysis does not consider a dynamic technological landscape, i.e., an evolving relationship among the different technologies over time, within e-skin technology. Therefore, a discussion of this dynamic technological landscape for which the technology position analysis is used is included in the section ''Technology Position Analysis.''

B. TECHNOLOGY DEVELOPMENT-STAGE ANALYSIS

The present study identifies the developmental characteristics of e-skin technology using the Logistic model, which is a popular growth model that is used to forecast rapidly evolving high technologies [28], [29]. Why we use the Logistic model is two-fold. First, the growth curve by the Logistic model showed the best prediction accuracy among the curves by the Logistic model, the Gompertz model and the Bass model; MAPE values, one of the representative forecasting accuracy measures, were 0.140 for the Logistic model, 0.158 for the Gompertz model and 0.262 for the Bass model. Second, the characteristics of the input date used for curve fitting was considered; if the inflection point of an S-curve occurs, the Logistic model is useful for the forecasting of the remaining trends due to its symmetric property. The literature suggests that the developmental pace of e-skin technology has accelerated significantly during the last decade due to the availability of new materials and processes [2]; in fact, the yearly patent registrations during the period between 2000 and 2013 shows this great growth. In addition, considering that the patents of 2013 show a decreasing-trend signal, the use of the Logistic model to fit a growth curve to the annual patent applications in e-skin technology is reasonable.

It was decided that the curve fitting would be based on the patent registrations between 1974 and 2013; the patents after 2014 are excluded from this analysis. As stated in the previous section, this is because patent applications are published within 18 months after their first filing and the e-skin patents were collected at the beginning of 2016. The three unknown coefficients of the Logistic model were estimated through the application of the ordinary-least-square regression method to the log-linearized functions of Eq. (1), and the growth curve of e-skin technology was described by the coefficients $t_0 = 2012.85$, $k = 0.15$, and $L = 2960.44$ (Fig. 3); the goodness of fit, computed as $R^2 = 0.85$, seems sufficient for the modeling of the developmental stage of e-skin technology in terms of the prediction of the patent applications.

Using this e-skin-technology growth curve, it was possible to identify the TMR, PPA, and ERL indices in terms of the technology life cycle; the present time for these indices was set to the end of 2013 or the beginning of 2014 because the patent data through to the end of 2013 was utilized.

First, according to Eq. (2), the current TMR of e-skin technology at the beginning of 2014 is approximately 49.89%; here, $L = 2960.44$ and $L_{2013} = 1,477$. This finding indicates

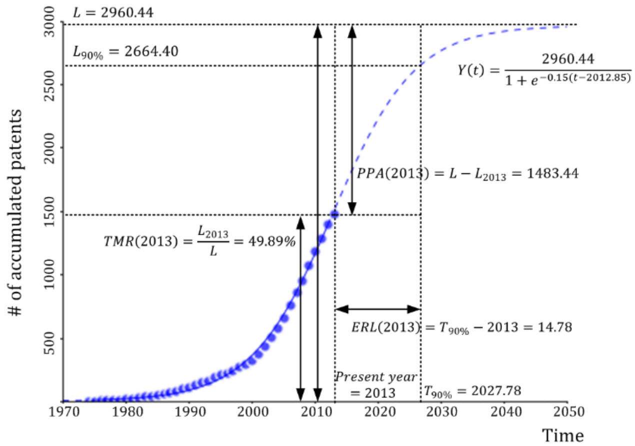

FIGURE 3. Logistic growth curve of e-skin technology.

that the future development of e-skin technology will account for approximately 50.11% of the total development. The understanding of the current S-curve location of a technology system becomes a significant clue regarding the establishment of the further technical focus of the technology [26]. As mentioned in the literature, a technology system passes sequentially through five generic stages during its life cycle, as follows: conception, birth, growth, maturity, and retirement. The R&D direction for each stage is marked by a focus on the achievement of its own technical ideality, as follows: ''make it work'' in the conception stage, ''make it properly'' in the birth stage, ''maximize performance or efficiency'' in the growth stage, ''maximize reliability'' in the maturity stage, and ''minimize cost'' in the retirement stage [26]. Based on the TMR of e-skin technology, it is possible to conclude that this technology reached the end of the growth stage and will enter the beginning of the maturity stage at the end of 2014; hereafter, the ''current year'' is the beginning of 2014. Next, using Eq. (3), the PPA of e-skin technology was estimated as 1,483.44. Compared with the 1,477 patent registrations of the past, the PPA of 1,483.44 for the future expected patent registrations suggests that the intellectual-property (IP) output from further R&D will remain active during the near future. However, it is expected that the number of future annual patent registrations will decline gradually because e-skin technology will enter the maturity stage soon; the number of patent registrations in 2013 (77 patents) can be a weak signal for this expectation.

As an early warning in terms of the technical focus, the TMR and PPA values can help researchers and R&D planners of e-skin technology in the directing of further R&D. According to the system evolution theory, the new functions and efficiencies of a system are usually the focal point during the birth and growth stages, while the system reliability and the product cost are the primary focus during the maturity and retirement stages. Based on the current TMR of 49.89%, the research into the new functions and the efficiency improvement regarding e-skin technology is likely to be less attractive from an inventional perspective. In fact,

TABLE 3. Patent applications by main-group IPC code.

Rank	Main-group IPC	Description	# of patents	% of patents
1	G01L-009	Measurement for which electric or magnetic pressure-sensitive elements are used	177	6.58
2	H01L-029	Semiconductor devices for capacitors or resistors	153	5.69
3	H01L-021	Processes for treatment of semiconductors	143	5.32
4	G01L-001	Forces or stress measurement in general	112	4.17
5	G01N-027	Investigating materials by the use of electric, electrochemical, or magnetic means	106	3.94
6	G01L-007	Measurement using mechanical or fluid pressure-sensitive elements	83	3.09
7	H01L-041	Piezoelectric devices	71	2.64
8	A61B-005	Detecting, measuring, or recording for diagnostic purposes	55	2.05
9	H01L-027	Devices consisting of a plurality of semiconductor or other solid-state components	47	1.75
10	B82Y-030	Nanotechnology for surface science	43	1.60
11	B82Y-040	Treatment of nano-structures	43	1.60
12	G06F-003	Interface arrangements for transferring data	41	1.52
13	C01B-031	Carbon compounds	40	1.49
14	H01L-023	Details of semiconductor or other solid-state devices	37	1.38
15	D01F-009	Carbon filaments	36	1.34
16	H01L-031	Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation	34	1.26
17	H01L-051	Solid state devices using organic materials	33	1.23
18	G01L-005	Apparatus for measuring force adapted for special purposes	32	1.19
19	H01B-001	Conductors or conductive bodies characterized by the conductive materials	32	1.19
20	G01N-033	Investigating materials by specific methods not covered by the preceding groups	31	1.15
Subtotal: top 20 IPC codes			1,349	50.17
Subtotal: other 426 IPC codes			1,340	49.83
Total: all 446 IPC codes			2,689	100.00

during the last 15 years (birth and growth stages), much of the R&D in e-skin technology proposed new materials based on polydimethylsiloxane, the carbon nanotube, graphene, and nanowire for their flexibility and stretchability properties, and tactile sensing based on piezoresistivity, piezoelectricity, optics, and wireless antennas. In addition, the fabrication performance of e-skin has been further optimized by fabrication processes such as vacuum filtration, spin-coating, spray-coating, and contact-printing. Consequently, there is a high likelihood that many of the inventions with a technical impact have already been patented. Therefore, at the present time, the researchers and R&D planners in academia and industry should focus their technical subjects more on the maximization of the reliability of e-skin materials and devices; for example, the achievement of a reliable operational performance during excessive and repetitive stretching.

Next, the ERL of e-skin technology was identified. Different from the previous two indices, the ERL requires the use of the threshold value ρ. We set the ρ to 0.90 through a careful examination and based on the expertise of one of the authors. The ERL according to this threshold was estimated as 14.78 yr; here, the present year = the beginning of 2014 and $T_{90\%} = 2027.78$ (late 2027). This ERL value suggests that the technological advances in e-skin technology will be mostly complete by 2028. When considering the time (the end of 2016) that this paper is being written, the practical ERL can be estimated as 11.78 yr; it seems that e-skin technology has already entered the maturity stage. In the maturity stage, technology-based firms usually compete for reliability-oriented inventions based on the previous knowledge [26]; therefore, from the perspective of technology system development lifecycle, the ERL and TMR suggest an important short-term and long-term implications for the providers of R&D investments in e-skin technology. First, as is understood intuitively, the investments into the development of new materials and their fabrication processes for the enhancement of the efficiency of e-skin devices may not be attractive in terms of the creation of valuable inventions. Rather, the near future research into the material properties or the manufacturing process to improve the reliability of e-skin devices is likely to be more effective in terms of the productivity of the inventions. Second, from a long-term perspective, there is likely to be a shift to the retirement stage in 10 years, so cost-minimization and the component modularization of e-skin devices or products could from a focal point in terms of the most valuable inventions. Therefore, as an example, the possible strategic R&D alternatives for the leading firms and researchers could be the development of patents for mass-production mechanisms and production-cost reduction through the modularization of e-skin products or components. The preoccupying of such patents that will appear in the future helps in the attainment of a patent thicket, which is described as a dense web of overlapping intellectual property rights for the commercialization of new technologies [37]. Then, by building on the future patents that are related to the retirement stage, the leading firms could differentiate their e-skin products from their competitors.

C. TECHNOLOGY POSITION ANALYSIS

The present study identifies technology positions from the patents of e-skin technology; each technology position is considered as a unique technological combination and is accordingly defined using the IPC codes contained in a patent's bibliographic data. Using the patent IPC codes as a building block, a total of 657 unique technology positions were identified from the 1,509 collected patents (Table 4). Overall, the top-20 technology positions contained approximately 40.6% of the total patents. Each of the identified technology positions represents a unique combinational technology. For example, technology position 427 (G01L-009) is related only to the measurement for which electric or magnetic pressure-sensitive elements are used, while technology position 420 not only overlaps with technology position 427, but it is also a different technical element (G01L-007); therefore, technology position 420 is a technology based on measurements for which both electric or magnetic pressure-sensitive elements and mechanical or fluid pressure-sensitive elements are used. Most of the top-20 technology positions have a single IPC code, while the two technology positions 420 (G01L-007, G01L-009) and 599 (H01L-021, H01L-029) are composed of two IPC codes.

Next, to identify the way that the technology positions in e-skin technology emerge and how their connectivity evolves, an attempt was made to visualize the maps of the technology position landscape. The historical period of e-skin technology was divided into the four specific periods for the purpose of observation; periods 1974-2000, 2001-2005, 2006-2010 and 2011-2016 (Figs. 4, 5, 6, and 7). Because the development pace of e-skin technology started to significantly increase since the turn of the millennium [2], period 1974-2000 was considered as the first period. Then, we equally divided the period between 2001 and 2016 into three periods 2001-2005,

TABLE 4. Parts of the top-20 technology positions in e-skin technology (ordered by the number of patents contained in each technology position).

Technology position	IPCs	Patents	Accumulated patents	Accumulated patents (%)
427	G01L-009	104	104	6.89%
590	H01L-021	71	175	11.60%
617	H01L-029	59	234	15.51%
470	G01N-027	55	289	19.15%
627	H01L-041	47	336	22.27%
419	G01L-007	45	381	25.25%
385	G01L-001	42	423	28.03%
7	A61B-005	31	454	30.09%
420	G01L-007, G01L-009	24	478	31.68%
311	D01F-009	17	495	32.80%
537	G06F-003	17	512	33.93%
623	H01L-031	15	527	34.92%
330	G01B-007	13	540	35.79%
448	G01L-019	12	552	36.58%
604	H01L-023	12	564	37.38%
599	H01L-021, H01L-029	11	575	38.10%
568	H01C-010	10	585	38.77%
608	H01L-027	10	595	39.43%
631	H01L-051	10	605	40.09%
656	H05K-001	10	615	40.76%

2006-2010 and 2011-2016. Each period includes the evolution of its prior periods; each period includes the cumulative patents up to its most recent year. The size and color of a node, or a technology position, indicate the number of patents belonging to the node, and a link between two nodes means that the two nodes are adjacent.

First, the map of the technology position landscape during the period 1974-2000 (Fig. 4) is sparse, because patenting activities were not active during that period. The most active technology positions in the early days are 427 (G01L-009; 28 patents), 470 (G01N-027; 22 patents), 420 (G01L-007, G01L-009; 18 patents), 385 (G01L-001; 17 patents), and 627 (H01L-041; 17 patents), and they form three major clusters as follows: generic force and stress measurement (GFSM), pressure sensitive elements (PSE), and semiconductor device and fabrication (SDF). Therefore, it seems that the early technology positions are related primarily to the measurement technology of generic force and stress and the initial sensing technology for which electric, magnetic, mechanical, or fluid pressure-sensitive elements are used. In addition, the active technology positions 627 and 617 are related to the piezoelectric devices and semiconductor devices for capacitors or resistors.

The map of the technology position landscape during the period 2001-2005 (Fig. 5) shows a gradual development

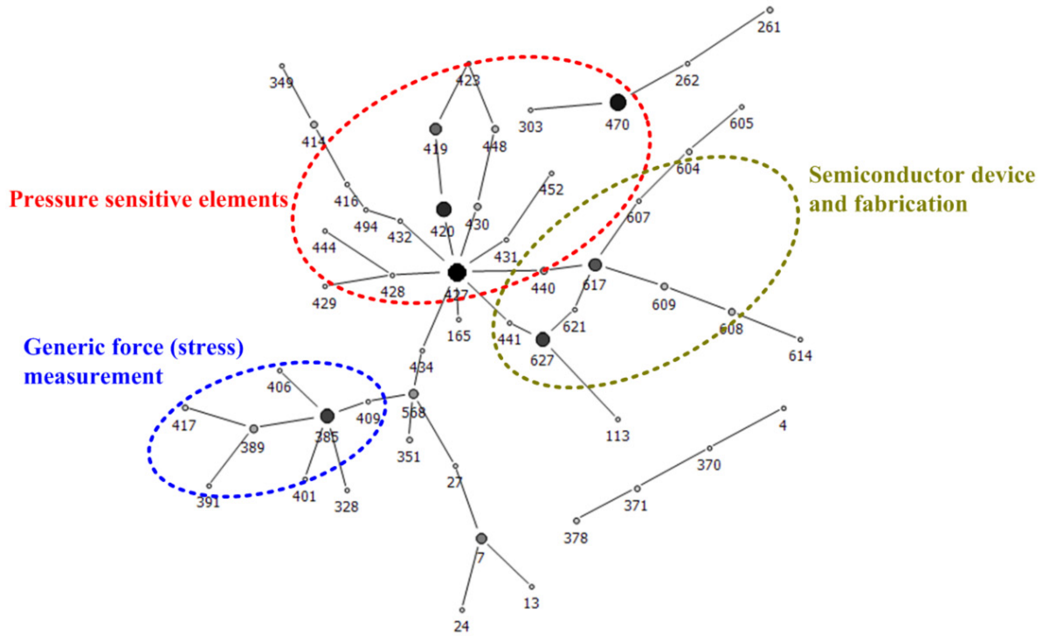

FIGURE 4. Technology position landscape during the period 1974-2000.

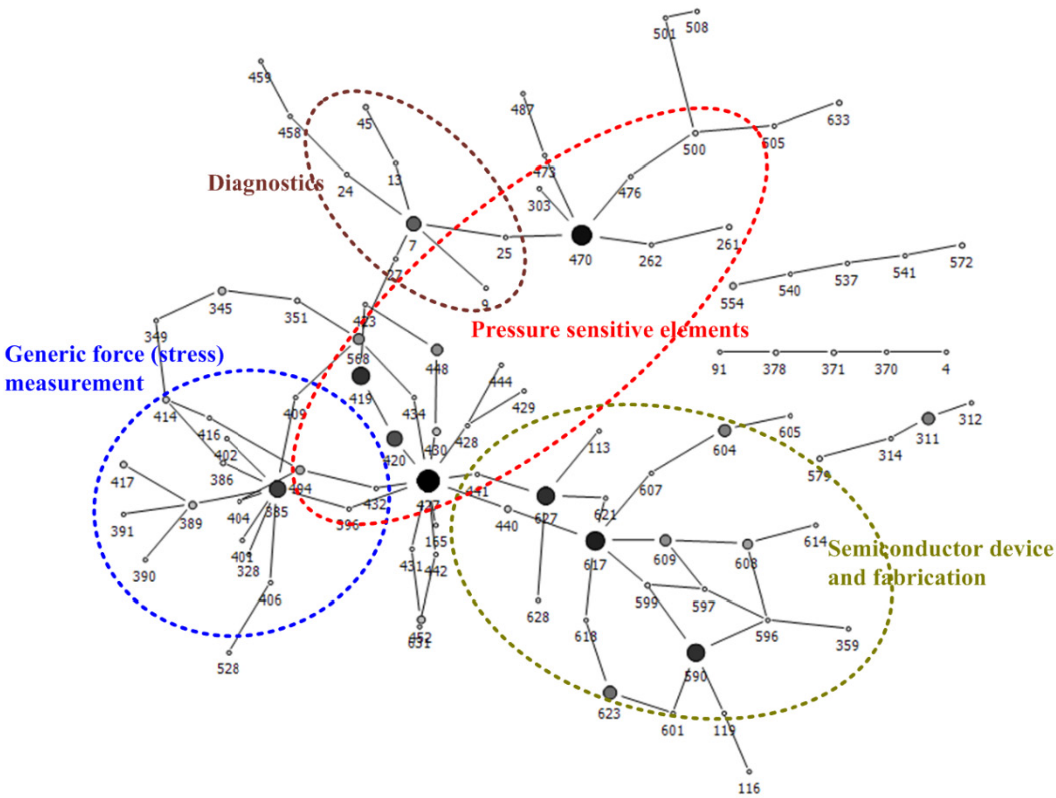

FIGURE 5. Technology position landscape during the period 2001-2005.

in e-skin technology. Interestingly, the technology positions related to diagnostics emerged to such an extent that a cluster was constructed; technology position 7 (A61B-005; 15 patents) is an application area of the detecting, measuring, or recording for diagnostic purposes. Also, the other three clusters GFSM, PSE, and SDF grew gradually. In particular, SDF grew considerably between 2001 and 2005; technology position 590 (H01L-021; 26 patents) contributed greatly

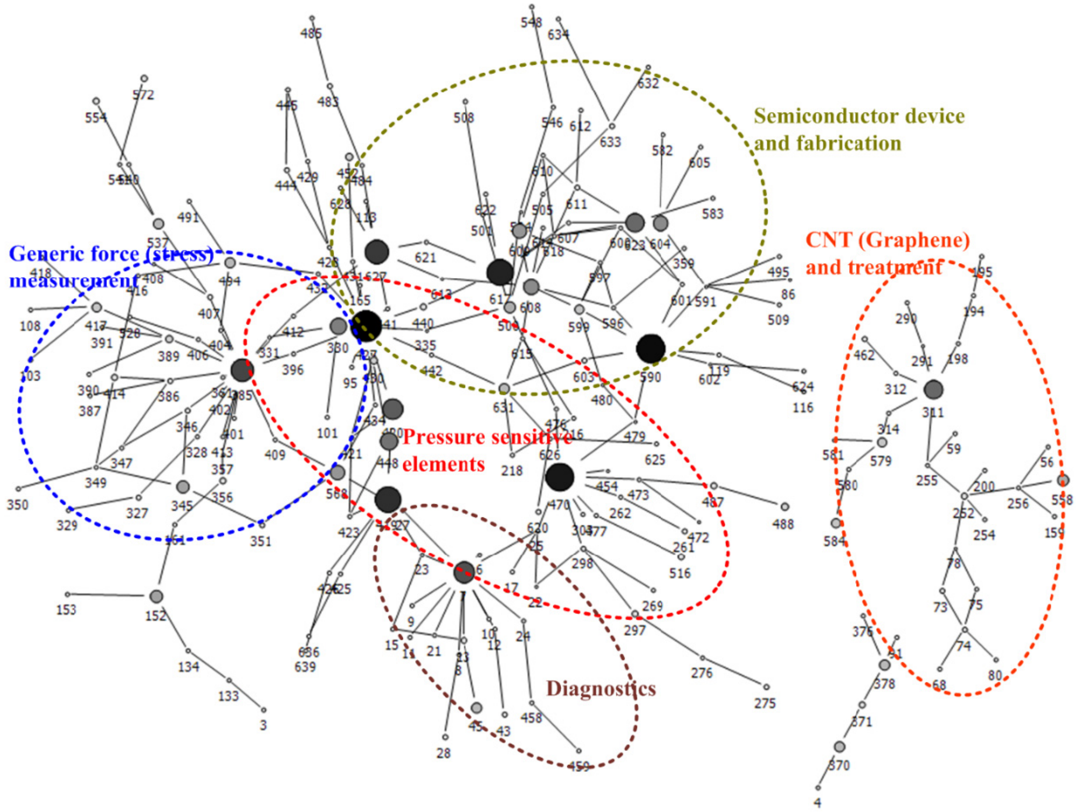

FIGURE 6. Technology position landscape during the period 2006-2010.

to the processes and apparatus that were adapted for the manufacture or treatment of the semiconductor devices in e-skin, and some process- and treatment-related technology positions, including technology positions 113, 621, 618, and 599, are variant technologies that were extended from the technology positions 627, 617, and 590.

During the periods 2006-2010 and 2011-2016 (Figs 6 and 7), the technology clusters GFSM, PSE, and SDF on the maps of the technology position landscapes grew remarkably and showed increased overlaps among them. For example, a large overlap is evident between the PSE clusters and diagnostics between 2011 and 2016, and intuitively, it is possible to conclude from this overlap that many of the application inventions for diagnostics attempted to adopt the technologies of the PSE cluster. Next, the following interesting new cluster emerged: CNT (graphene) and treatment during the period 2006-2010. In fact, several technology positions that are related to the CNT and CNT filaments, such as 311 and 312, first appeared during the period 2001-2005, but in consideration of the number of patent registrations, they were not considered as a major cluster. However, the additional technology positions, including graphene, coating, and layered treatment, were newly emerged and were connected to the CNT-related technology positions; this was followed by the construction of a major technology cluster during the period 2006-2010. In particular, the cluster of CNT (graphene) and treatment showed an increasing overlap with the PSE cluster during the period 2006-2010, and this overlap indicates that the technologies that are related to CNT and graphene started to be applied to e-skin development. It was then possible to conclude from a technological perspective that the new materials, including CNT and graphene, and their fabrication processes provided major contributions to the development of e-skin technology. In particular, during the period 2011-2016 indicates a rapid growth of CNT and graphene-based elastic electronics and its increasing overlaps towards other clusters in the near future. Therefore, technology experts and researchers working in this field should put their attention on the advancement of CNT (graphene) and its treatment.

Using the technology position analysis, the evolving landscapes of e-skin technology we were monitored over time. The technology position analysis provides analysts with the emergence of the technology clusters and their expansion and integration within e-skin technology. As examined previously, some of the core technology clusters, such as GFSM, PSE, and SDF, appeared from the early stage of e-skin technology, while some of the technology clusters, such as diagnostics during the period 2001-2005 and CNT (graphene) and treatment during the period 2006-2010, are relatively small during their first emergence and thereafter grew gradually. Next, with the significant growth of the field over the last

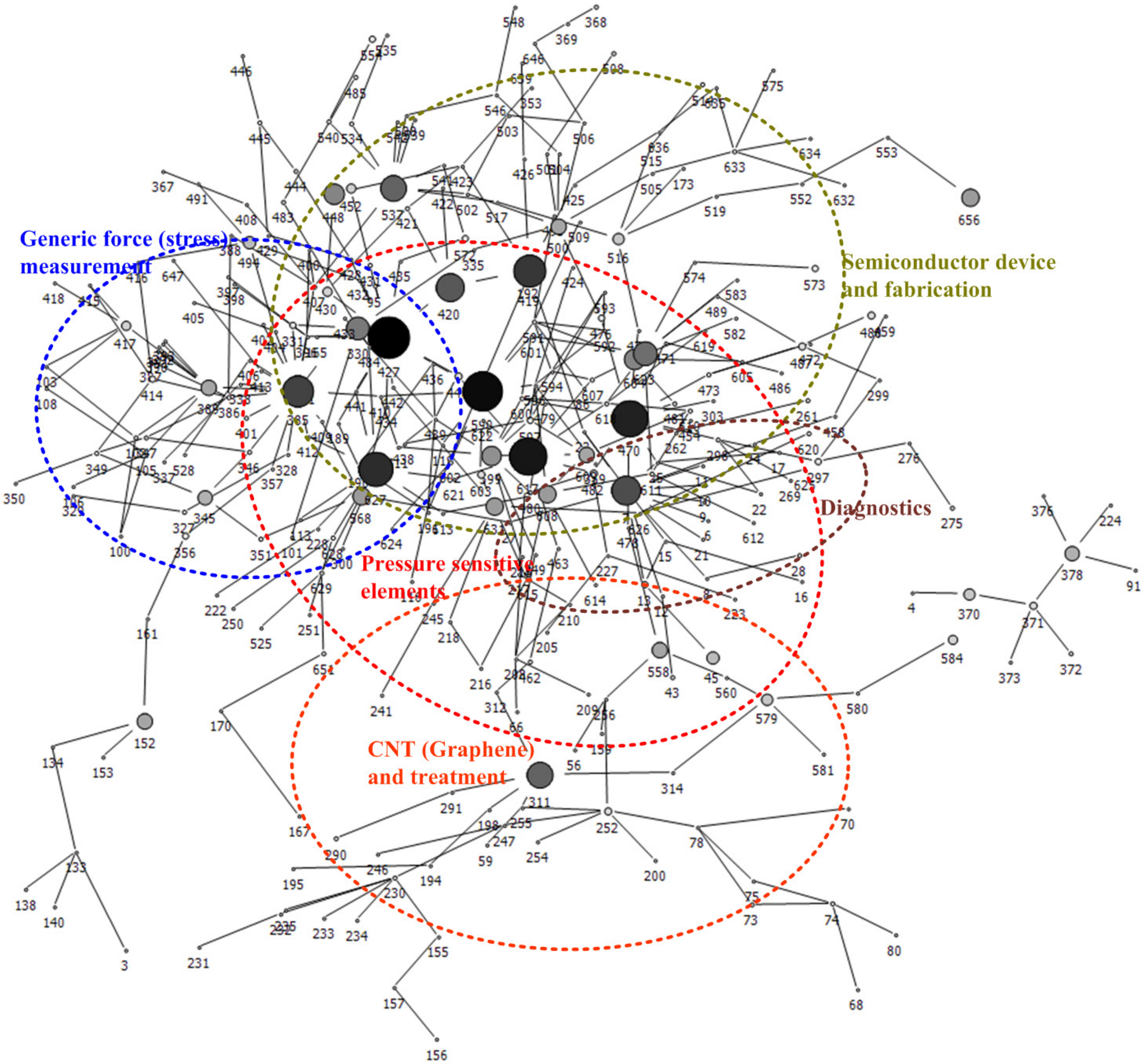

FIGURE 7. Technology position landscape during the period 2011-2016.

10 years, increasing overlaps have become evident among the technology clusters of e-skin technology.

V. DISCUSSIONS AND CONCLUDING REMARKS

In this study, the evolving trends in e-skin technology in terms of the technology development stage and the technology position were identified. To locate the current maturity stage of e-skin technology within its growth process from an inventional perspective, a growth curve was fitted to the annual patent registrations, and this shows that e-skin technology had mostly reached the end of its growth at the beginning of 2014 (TMR = 49.89%). The number of additional future patent registrations was estimated as 1,483.44 patents. In addition, the ERL of e-skin technology as of the beginning of 2014 was estimated as 14.78 yr. To understand the emergence of the technology clusters and their expansion, a technology position analysis was conducted for e-skin technology; accordingly, the core technology positions are 427, 470, and 419 for the PSE cluster; 385 for GFSM; 590, 617, and 627 for SDF; 7 for diagnostics; and 311 for CNT (graphene) and treatment. Overall, these clusters have grown significantly during the last decade, and the clusters of diagnostics and CNT (graphene) and treatment were newly constructed during the periods 2001-2005 and 2006-2010, respectively.

This study provides contributions to both industry and academia. First, from a practical perspective, the results of this study can provide insightful information to the experts who are working in the field of e-skin technology. The patent registrations used in this study constitute a comprehensive patent set of e-skin technology in terms of both academia and industry, and therefore the estimates of the TMR, PPA, and ERL and the technology-position-landscape maps for this technology can assist researchers and R&D planners in the proper directing of further R&D from an inventional perspective. Second, it is certain that much of the attraction in e-skin technology has resulted in, and will result in, the increases of the technical-data and fragmented-technology domains; it would be more difficult for human experts alone to identify comprehensive trends in e-skin technology. Therefore, the quantified analyses of this study for the technology growth and the technology positions will become an effective aid in the rapid monitoring of the evolving trends in e-skin technology. Third, the authors' approach, as a modified version of the existing growth-curve and technology-position analyses, has the potential to help in the generation of insightful information regarding various technology fields, because they are neutral with respect to the type of data that are analyzed; therefore, researchers and R&D planners could apply this approach to the analysis of patents in any technology domain of interest.

Despite the findings and insights that were obtained from the present analysis, this study is still subject to several limitations, and the consequential further research is as follows. First, the analyses were performed using only patent data, so its results relate to the technology life cycle purely from an inventional perspective. A gap exists between a technology's inventional maturity and its market adoption, so an understanding of such gaps would help to identify the evolving trends of e-skin technology more synthetically; therefore, further research should incorporate the market adoption of e-skin technology into the authors' method through the identification of the recognizable patent owners and the market size and share of these owners. In addition, open source intelligence, which exploits social data, such as blogs, community posts and Web news, could be combined with our analysis to understand market needs from anonymous people and the gap between technological development and customer needs. Second, although patents are considered the most prolific technical source that encompasses the R&D output in both industry and academia, a sole reliance upon patent data might be misleading, as they are not the only source of inventional output. For a more comprehensive analysis of e-skin technology's evolving trends, the further research should consider a wider range of technical data, including the patents of multiple patent databases, research articles, and technical reports, as the data source for an analysis. Third, the present analysis is based only on the historical data of e-skin technology, and the potential breakthroughs have been overlooked. Researchers will continually try to redouble their efforts to improve this technology, and such efforts might lead to breakthroughs. In fact, our keyword search found that various types of technologies, including tactile, chemical and biosensors, existed in the patent set we collected. For example, based on a simple keyword search for patent titles, we found that there were 58 patents for the chemical sensor, 87 patents for bio sensor and 20 patents for the gas sensor; interestingly, many of them were applied for patents during the last decade. In addition, the technical scope and keywords of e-skin technology could even change in the future. For this reason, if our analysis is conducted for the patents of e-skin technology in the future or the patents collected by a modified patent search query or a search query focusing on new or emerging technology topics, it may result in different growth curves and technology-position-landscape maps. In this regard, a follow-up study that monitors the change of e-skin technology should be conducted with an updated set of patents. In the same vein, a follow-up study that implements this approach in a software system will make the process of the rapid monitoring of the evolving technological trends efficiently. Fourth, for the method of this study, only the number of patent applications by year and during specific periods is considered, thereby neglecting the quality of the individual patents; the quality of inventions may significantly affect the advancement of e-skin technology. The quality or impact of patents can be identified using a number of typical patent measures, including the number of forward citations and the number of patent claims, or through an expert examination. Therefore, the future research should improve the applicability of the current analysis by taking into consideration the quality weighting of such patents. Finally, each technology position landscape map itself represents a network and includes the emergence and blooming of technology clusters. Therefore, in a future research topic, network analysis could be applied to identify the emergence and blooming of technology positions and their clusters and provide relevant technological insights over time.

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