Using the Social Analysis Method to Examine the Evolution of Three-Dimensional Printing Materials Technology

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***Abstract*--Three-dimensional printing has seen rapid development around the world, being regarded as an important component of the third industrial revolution. The industry has focused on lowering cost and improving efficiency, while prioritizing the pursuit of innovation in material technology. This study examines the evolution of three-dimensional printing materials technology using patent searches, patent citations, and by surveying the technology's momentum. First, the study analyzes the social networking produced by the relationships among patent citations for patent technologies. Second, the evolutionary momentum of patent technology is discussed. Then, the patents emerging from the developing technologies are identified from the cited patents. The study analyzes approximately five thousand United States patents to describe the evolution in three-dimensional material technology. The study contributes to current research by analyzing the technological evolution and future development trends in the patenting of three-dimensional material technology. The main results should provide businesses and research institutes with a reference for technology development decision making.**

I. INTRODUCTION

Since the industrial revolution in the 18th century, technological advances have driven industrial manufacturing and agriculture, among others. The industrial revolution ushered in an era of innovation in production and mining methods. Machine tools, for example, enabled mass production, allowing the replacement of labor with machines, and traditional energy sources, such as wind, water, and wood, with coal-powered machines [1]. Currently, we are entering an era many believe will be similarly disruptive to the manufacturing sector—the age of 3-D printing and the digital tools that support it [2].

Three-dimensional printing technology is also known as additive manufacturing (AM). The principle of AM differs from traditional machining object manufacturing technology. AM, which emerged in the 1980s has many different names, such as rapid prototyping, rapid manufacturing, 3-D printing, and digital manufacturing. The American Society for Testing and Materials (ASTM) named the AM technology and set its relevant standards.

Currently, the industry has focused on 3-D printing as a crucial technology. Countries such as the United States, the United Kingdom, and China have begun to actively foster the development and application of 3-D printing technology. United States president Barack Obama announced the National Network of Manufacturing Innovation Bill on March 9, 2012, which plans to invest $1 million to strengthen industrial competitiveness in advanced manufacturing, including 3-D printing technology. The National Additive Manufacturing Innovation Institute was established in Ohio on August 16 of the same year [3]. The United Kingdom's government announced an investment of 8.4 million pounds to foster a 3-D printing technology development program, and private companies in the United Kingdom will invest an additional 6.3 million pounds in other relevant programs [4]. China has developed 3-D printing in aerospace components, and has actively supported the building of 3-D printing technology bases and commercial development [5].

Taiwan's Industrial Technology Research Institute (ITRI), cooperating with the Netherlands Organization for Applied Scientific Research (TNO), established additive manufacturing R&D alliances to accelerate the development of Taiwan's 3-D printing industry. Taiwan established a laser additive manufacturing industry cluster in July 2012 by gathering domestic research institutes, universities, and 36 firms that domestically produce metal powder additive manufacturing equipment. This cluster's purpose is to expand 3-D printing technology for combing materials, processes, equipment, software, and an innovative service model [6].

Many countries, which consider 3-D printing to be a critical component of the third Industrial Revolution, have begun to constructively support, prioritize, and develop this technology. Although 3-D printing is still limited, with the continuous progression in material technology and the gradual spread of both technology and application, it is predicted to have a substantial impact on the manufacturing sector and the global economy.

These emerging technology applications are currently at an initial developmental stage, but with patent-related technical information, we can understand the trend of technology development and predict a possible direction for new technology development [7]. A patent represents important information for identifying the progress of a technology [8]. Patents, through detailed analysis, can be used as the basis for investment decision making and the indication of technical details, business trends, and industrial innovation plans [9]. Patent analysis can also be used to establish corporate technology strategy and to evaluate a company's technical capability as the basis for a corporate merger and acquisition strategy. Patent analysis can contribute to an understanding of competitors and global competition trends [10], and is also an important tool for industrial development or technology forecasting [11]. At a national level, patent analysis can assist with technology development planning [12], and the simulation of specific emerging technologies' development trends [13-15].

The purpose of this study is to construct an analysis model of technology evolution, with 3-D printing material technology based on patent information. The model uses a social network analysis method to develop an analytical step that can extract useful information to analyze the evolution of technology from a patent database. Furthermore, this study identifies core patents from the technology evolution, and describes the technology's context. This study also uses the United States patent database in the processing analysis model to judge the evolution of 3-D printing material technology.

This study first explores 3-D printing material technology with a patented method, while primarily using the United States patent database to analyze trends in patented technology over several years. Moreover, the study analyzes the social networking produced by relationships among patent citations for patent technologies. Next, the evolution of the patent technology is discussed by describing its momentum. We then describe core patents, which emerge from patent technology and are estimated from patent citations through a data-mining method, to understand the technology's context. This study then proposes a model for future technology that can provide a direction for the 3-D printing industry.

II. LITERATURE REVIEW

A. 3-D printing and material technology

Various materials are used in the creation of 3-D printing products. For example, polyvinylchloride, polycarbonate, and metal or ceramic powder are all used as raw materials in 3-D printing. However, the technical production process is the same. Generally, 3-D printing consists in forming objects through a computer-aided program or scanner, production materials, and a production printer. The production process originates with the use of the assisting computer program or infrared scanner to design the object's shape. Subsequently, the object's production materials are chosen according to its type and, finally, a three-dimensional object is manufactured using the printer. A design diagram must be in place before printing, as in traditional production, and the 3-D printer must receive a three-dimensional design diagram before production.

B. Patent citation

Patent citation in the literature is a source of important technical information and primarily functions to increase the awareness of existing technology. Researchers can uncover advances in existing technology to continue or revise how they promote the development of technology and the industry. According to Traitenberg [16], the number of times a patent is cited is proportional to its value, which means it is not only a patent with higher economic value but also an important invention.

Patent citation is classified as either citing or being cited. Researchers are allowed to discover key technology and provide recommendations, while making any related decisions, by using patent-cited quantitative analyses from various patent citation information perspectives and the value or status of the main patented technology in various fields.

A citation-based patent study is known as a patent citation analysis, which seeks to link patents in the same manner that science citation links references in the scientific literature [17]. Citation relationships among patents can be used to further determine the importance of certain patents, and the technical correlation among multiple patents. Therefore, patent citation analysis can be used as a tool for exploring key patents, confirming technical correlations, establishing technology development history, and discovering patent clustering.

According to Yoon and Park [18], patent citation analysis is widely used; however, there are some disadvantages: (1) it only emphasizes the frequency of citing and the number of patents, which may result in superficial misleading; (2) it uses only the citation and cited information, which may limit the scope of analysis; and (3) it requires a thorough examination of all patent references, which takes time.

C. Social network citation

A social network is a social structure composed of many nodes, which usually refer to individuals or groups and representatives of the social relationship structure. Lin et al. [19] defined the social network as a connection among a group of people in a direct or an indirect way, which forms a special group relationship, such as family and friends. Liou and Chand [20] note the structure of social networks, which have been used in anthropology, sociology, and psychology, among other fields. This structure implies that the network is a link between social groups or organizational relationships.

Social network analysis measures an individual, organization, and relationships between groups, and illustrates this with graphs. From the perspective of current studies, apart from the fields of anthropology, sociology, political science, etc., social network analysis can also be implemented for patent research; for example, researchers can use social network analyses to improve the efficiency of patent search, thereby predicting the development of future patents [21]. Another study [17,22] notes that a technical citation implies a technical connection, and any links between technologies will form a technical network.

A technology's network node implies a new technology or patent. Patent citations are credible and complete when describing the relevance of patented technology due to the Patent Office's strict examination of previous technologies [23].

D. Text mining

Text mining is regarded as a part of traditional data mining, and is used by researchers to discover meaningful information. Researchers can organize this implicit information into knowledge that can be used through various techniques, such as text analysis or feature extraction. Current text-mining applications are versatile, and include web mining, automatic classification, and clustering technologies.

The term frequency-inverse document frequency (TF-IDF) is a statistical method and a weighted technology, based on text mining and information searches, and is commonly used to assess the importance of a word in a document and the basic significance of the importance of words. However, with an increase in the number of files, the frequency of collection files will decline in an inverse proportion [24].

III. METHODS

A. Process of patent network analysis

The patent-cited micro-level social network in a technical field used by an organization cited patents to establish mutual relationships, which have an impact on technology development and resource allocation efficiency. The relationship between these networks will also change with the evolution of various technologies, so that these relationships can be used to judge patents' quality and importance.

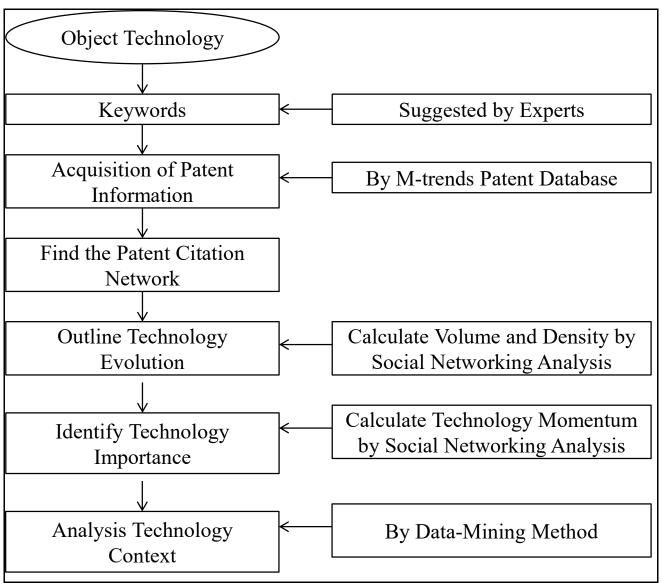

Fig. 1: Process of patent analysis.

The patent-cited social network on a macro level is the relationship of patent citation with a technology or organization; this relationship forms the flow of knowledge between various technical fields. A social network's macro level, with respect to the micro level, has a great influence on technology development. Therefore, this study uses patent analysis to obtain citation relationship information between patents. The development situation and internal characteristics of the overall patent citation network could be presented using the indicators of social network analysis. This study in particular analyzes the technology evolution of 3-D printing material technology coupling with the timeline, identifies the core patents, and analyzes the content of the technology. The results can be used as references for technology development decisions. Figure 1 demonstrates the analysis process, as well as the technology momentums and content.

B. Quantitative analysis of the patent network

Network properties are calculated after construction of the patent citation network. "Centrality" in social network theory is a key network property to estimate the simplicity of an actor retrieving from, or controlling, the network. Freeman [25] proposed three ways of measuring network centrality: the degree centrality, betweenness centrality, and closeness centrality. A higher centrality indicates more associations with actors in a network. The study used three measurement methods for obtaining centrality to understand the importance, influence, diffusivity, and convergence of a patented technology.

1) Technology centrality degree

Network nodes, or actors, directly link to a specific node, and are in the neighborhood of that specific node. The number of neighbors is defined as either the nodal degree, or degree of connection. Granovetter [26] suggested that nodal degree is proportional to the probability of obtaining a resource. Nodal degree represents to what degree a node, or actor, participates in the network. There are two degrees in which a patent is either cited or cites other patents [27].

InDegree centrality is the number of times that patent i is cited by other patents. The higher the InDegree centrality, the more the number of times patent i is cited—that is, the greater the momentum of knowledge diffusion from patent i to other patents. The InDegree centrality index C_{ID} is defined as follows:

$$C_{ID}(n_i)=d(n_i) \quad (1)$$

where $d(n_i)$ is the number of patents that cite patent i in the network.

OutDegree centrality is the number of times that patent i cites other patents. The higher the OutDegree centrality, the more the number of times that patent i cites other patents—that is, the greater the momentum of knowledge convergence from other patents to patent i. The OutDegree centrality index C_{OD} is defined as follows:

$$C_{OD}(n_i)=d(n_i) \quad (2)$$

where $d(n_i)$is the number of patents that patent i cites in the network.

2) Technology Closeness Centrality

The Closeness centrality of an actor is defined as the inverse of the average length of the shortest paths to and from all other actors in the network. A higher Closeness centrality indicates a higher influence on other actors and, in a directed network, can be divided into InCloseness centrality and OutCloseness centrality.

InCloseness centrality is the shortest path from other patents to patent i; a higher InCloseness centrality represents a higher influence of patent i on other patents. The

InCloseness centrality index P_{IC} is defined as:

$$P_{IC}(n_i)=\Sigma^{N}_{j=1} 1/p_{ji} \quad (3)$$

where p_{ji} is the shortest path from patent j to patent i.

OutCloseness centrality is the shortest path from patent i to other patents; a higher OutCloseness centrality means patent i can be more easily influenced by other patents. The OutCloseness centrality index P_{OC} is defined as:

$$P_{OC}(n_i)=\Sigma^{N}_{j=1} 1/ \quad (4)$$

where p_{ij} is the shortest path from patent i to patent j.

3) Technology Betweenness Centrality

The concept of betweenness is a measure of how often an actor is located on the shortest path between other actors in a network. Those actors located on the shortest path between other actors are playing intermediary roles, which help any two actors without direct contact to reach each other indirectly. Actors with a higher Betweenness centrality are those located at the network's core. The Betweenness centrality index B is defined as follows:

$$B(n_i)=\Sigma_{j,\, k\neq l}\, b_{jik}/b_{jk} \quad (5)$$

where b_{jk} is the shortest path between patent j and patent k, and b_{jik} is the shortest path between patent j and patent k that contains patent i.

C. Analysis of technology context

We used a data-mining method to analyze the patents, and the characteristics of each important patent cluster, to qualitatively determine a technology's development. The process steps are as follows:

(1) We use the important patent's results and, with its forward citing and backward cited clusters, employ word extraction to identify the different words in a patent document's abstract, claim, and specifications.
(2) Subsequently, various words, such as conjunctions, are omitted to limit the word list to those that are meaningful to a specific field.
(3) Term frequency, or TF, is used to determine the technical keywords in each technology cluster. TF is an indicator typically used in data mining to determine the frequency of a word appearing in a document or database; terms with higher TFs are considered more important and more representative of the document or database [28].
(4) When the same key word appears in different clusters, the inverse document frequency, or IDF, is used to determine the relative importance of each word among the different clusters [28]. IDF is a method of calculating the number of times a word appears in all documents.
(5) Finally, the IF-IDF is IF multiplied by IDF. IF-IDF is a method of calculating the weight of a word appearing in all documents.

IV. RESEARCH RESULTS

A. Network patent sampling

This study first used the keywords of [(Additive or 3D or three dimension or rapid) and (manufacture or print or fabrication) and (material)] in an abstract for patent search within the United States patent database on granted patents in the timeframe of January 1, 1976 to December 1, 2015. This study was conducted in December 2015 and returned 5,330 patents. Out of those retrieved, 285 patents were cited twice or more in the 5,330 patents. Moreover, this study adopted manual interpretation with respect to these retrieved patents. The content for interpretation, with help from the patent background if necessary, mainly included abstracts and claims of all patents. The basis for interpretation was to examine whether or not the patent was related to the 3-D printing material technology. A total of 154 patents remained as the primary patents in this study.

A total of 154 patents were used in this analysis as primary patents, based on a total of 2,415 backward citation patents, and there were 4,409 forward citation patents retrieved from the United States patent database as secondary patents. Their contributions to primary patents can be understood by examining upstream patents; thus, the underlying knowledge flows can be analyzed. We adjusted for the double counting of 154 primary patents, as well as 2,415 backward citation patents and 4,409 forward citation patents. The total number of obtained patents was 5,809, which were defined as network patents and, therefore, were treated as network nodes, along with the network ties built by patent citation linkages. A patent citation network was constructed to understand the technology development context.

B. Patent citation network

This study used Ucinet 6-version 6.70 software for the network and graph. A computer program could plot the patent citation network, which is composed of 5,809 patents and 56,651 patent citation relationships. However, large patents are not seen in a picture; the study selected patents cited more than five times for plotting the patent citation network, as illustrated in Figure 2. Each node represents a patent, and each network tie with an arrow represents a citation relationship. The patents denoted by the network ties' arrows were cited by those located at the other ends of the network ties. Each citation relationship line consists of only one arrow point because the patent citation relationship was a one-way connection. Nearly all patents in Figure 2 were networked together, and the patents that acted as isolated nodes or actors without networking were displayed on the left strip. The overall patent network, and the close citation relationships among the patents, can be seen in Figure 2.

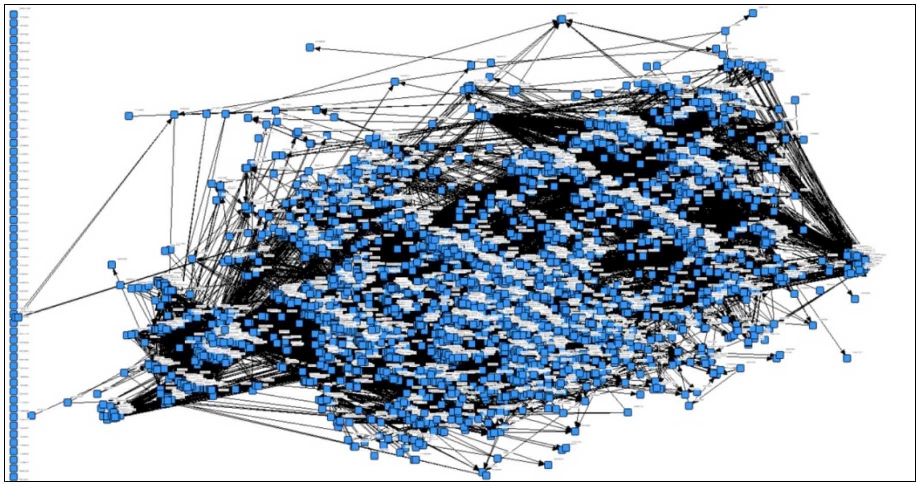

Fig. 2: Patent citation network for 3-D printing material technology.

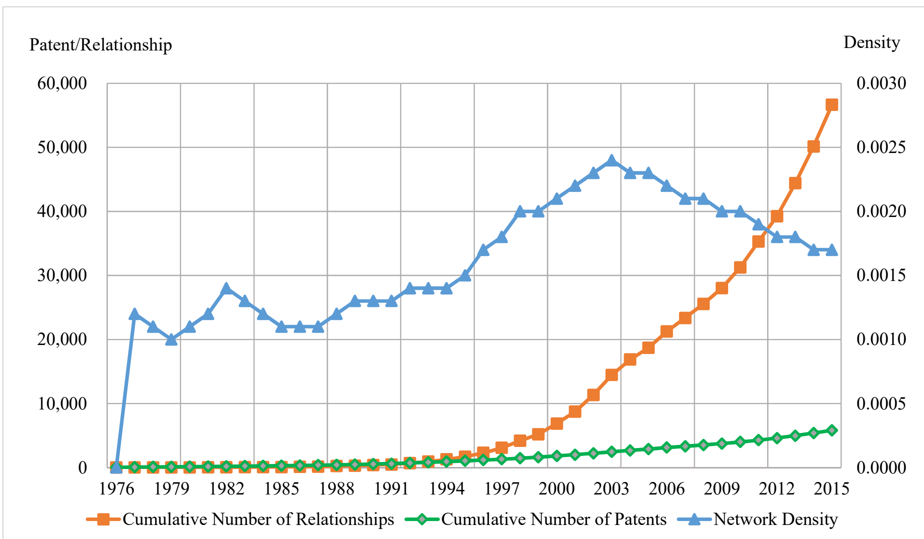

Fig. 3: Patent, relationship, and density of the patent citation network.

C. Outline technology evolution

The time direction of technology evolution runs from the past to the present, but the direction of patent citations is the opposite, that is, from new to old. A patent receives a large number of forward citations, which causes a higher value of InDegree centrality, as observed in the timeline of technology trends in patent citation. The higher InDegree centrality means that this patent serves as the foundation of many emerging patents, and is the basic patent for future technology development. The higher the InDegree centrality of a patent, the greater is the momentum of technology diffusion.

If a patent has a large number of backward citations, the value of OutDegree centrality is higher, which means that this patent converges many past patents and is an applied patent for the integration of past technology. The higher the OutDegree centrality of a patent, the greater is the momentum of technology convergence. The InDegree centrality and OutDegree centrality are the direct effects of a patent.

The InCloseness and OutCloseness centralities are indirect effects, versus the InDegree and OutDegree centralities. The InCloseness and OutCloseness centralities compute the sum of a patent's distance to other patents in the network by the patent-cited and patent-citation relationships, respectively. The distance measures the closeness of a patent to other patents in network.

A relatively higher value of Betweenness centrality in the entire network means that this patent is the key link between different patents. The role of this transition also facilitates the flow of technology between diffusion and convergence.

Figure 3 denotes potential technology evolution, as the x-axis represents the time of patent approval and the y-axis represents the cumulative of patents or nodes, the number of cumulative relationship lines, and density. The entire network in Figure 3 displays no significant changes from 1977 to 1994, which illustrates a stagnant situation. Therefore, this study suggests that this stage was the infancy period. From 1995 to 2003, the density, node, and relationship lines increase, which represents the stable development of patent technology. This study suggests that this stage is a growth period. The density from 2003 to 2015 shows decreases, representing the patent technology produced by emerging, new patents. Figure 3 displays a life cycle of infancy and growth, and demonstrates the diversity or differences of 3-D printing material technology. In the evolution during these 40 years, this technology was still in its formative stages, indicating it was still emerging.

D. Technology momentum analysis

We calculated the properties of this network, including the InDegree centrality, OutDegree centrality, InCloseness centrality, OutCloseness centrality, and Betweenness centrality of each network node. Figure 4 displays the average of InDegree centrality, OutDegree centrality, and Betweenness centrality for each year. There were significant peaks in the Betweenness centrality around 1988; further, 1997 and 1998 also witnessed increases, indicating important phases for the development of a related technology. This stage signifies that many patents were essential, having paths for any two patents or a group controlling different patents or patent groups with important knowledge or technology receiving and exchanging information for improving the overall network. Although the Betweenness centrality gradually declined in 1999, this indicates that early 3-D printing material technology was crucial for the continuing progress of this related technology.

The InDegree centrality had significant peaks in 1983 and 1993; after 1993, a gradual decline began, which represents the diffusion of earlier important patent technology into later patents. The OutDegree centrality had a slight upward trend from 1986, and in 2004, previous patents increased significantly, representing patents created in this stage cited by previous patents. Figure 4 illustrates the evolution of 3-D printing material technology over 40 years, and the different roles that patents of various periods played in the entire network.

This study used five indicators (InDegree centrality, OutDegree centrality, InCloseness centrality, OutCloseness centrality, and Betweenness centrality) throughout the network to observe the centrality change context of various patent approval years, as illustrated in Figures 5–9. An important technology network development period can be noted in Figure 5, in which the momentum of technology diffusion for the United States patent 4575330 in 1986 and United States patent 5204055 in 1993 were significantly greater than all other patents over the 40 year period. These two patents were cited by many others, and had a significant impact on other patents. Figure 5 also reveals a focusing of patent technology diffusion in 1983 to 1993, demonstrating that the important patent technology of 3-D printing material occurred in 1983 to 2011.

Significant patents in Figure 6 can be noted in 2007 to 2015, with the momentum of technology convergence, as these years exhibited a significant developmental trend. The period of 2010 to 2013, in which the momentum technology convergence of four patents was greater than that of other patents, is particularly worthy of further analysis of the detailed technical content as important research information.

Figure 7 illustrates the significant InCloseness centrality in 1978 to 1989; a patent with a greater momentum of influence was produced every year, particularly in the period 1986 to 1989, in which the momentum of influence of four patents was greater than that of other patents. Figure 8 shows significant OutCloseness centrality in 2011 to 2015; these years had five patents with a greater momentum of influence.

As Figure 9 shows, the momentum of technology transition was significantly greater for United States patent 7261542 in 2007 than for other patents in the patent network. United States patent 6401001 in 2002 ranked second in momentum of technology diffusion, and United States patent 5260009 in 1993 ranked third, which demonstrates that they are important patents in 3-D printing material technology. Several other patents cited this patent; furthermore, a number of patents also acted as an important bridge for new patents.

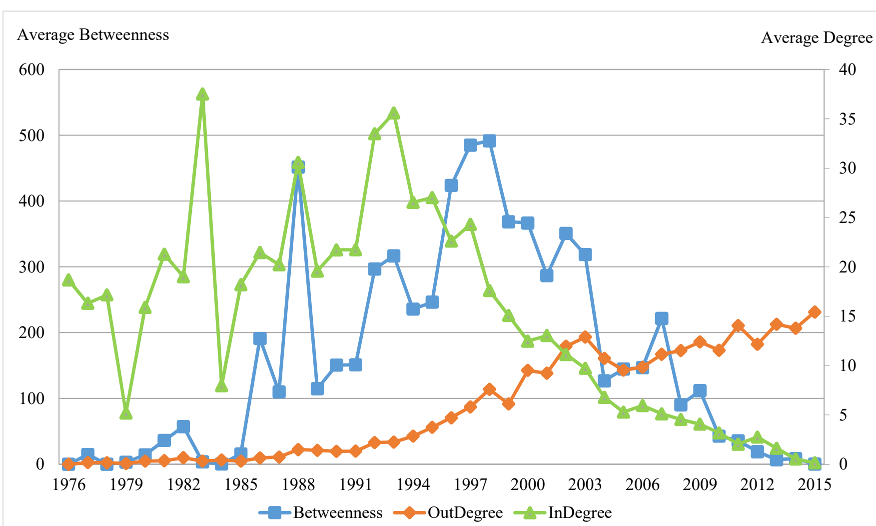

Fig. 4: InDegree Centrality, OutDegree Centrality, and Betweenness Centrality.

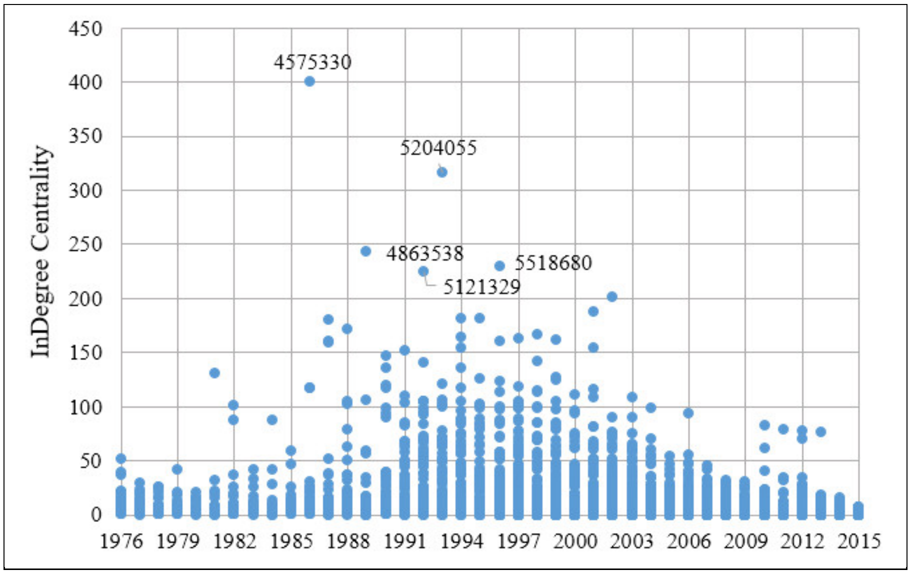

Fig. 5: Momentum of technology diffusion.

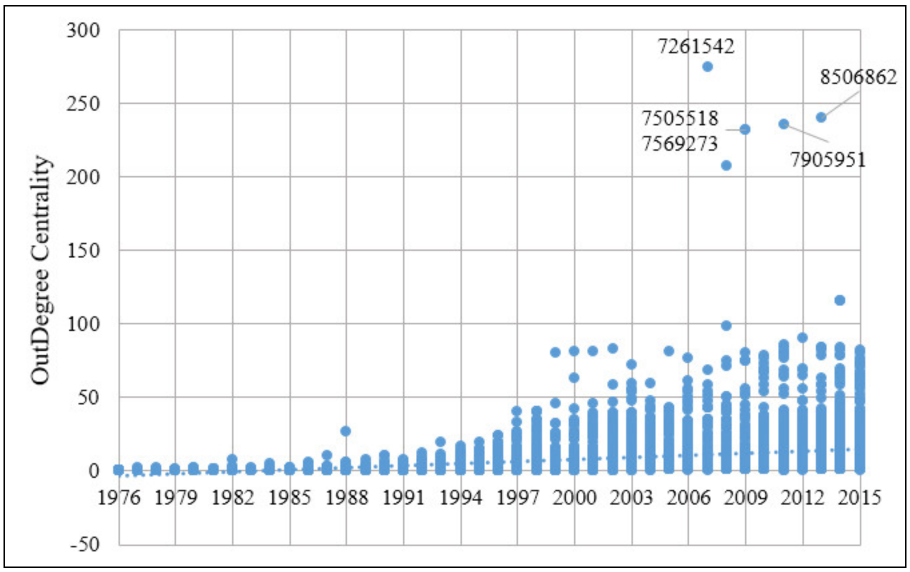

Fig. 6: Momentum of technology convergence.

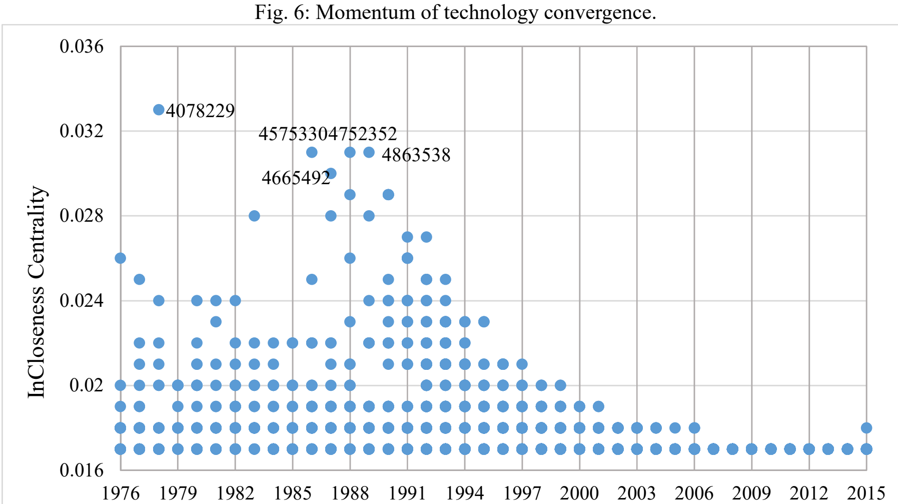

Fig. 7: Momentum of influence.

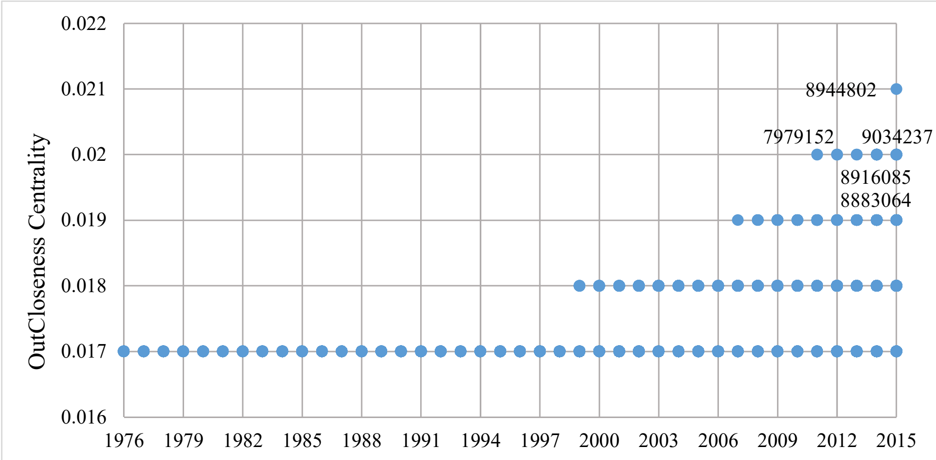

Fig. 8: Momentum of being influenced.

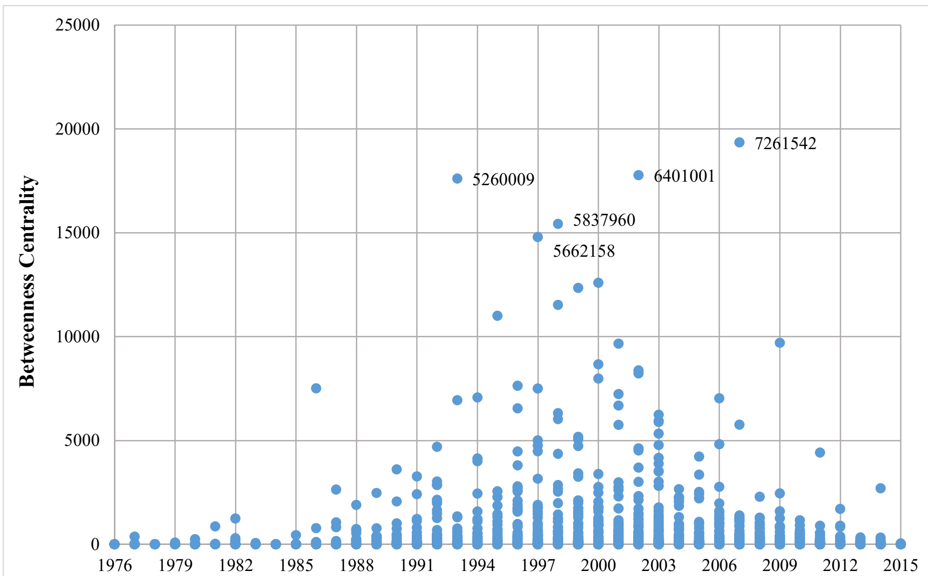

Fig. 9: Momentum of technology transition.

E. Identify Core Patents

The patents with top network properties are core patents, or key technologies that are classified by the aforementioned momentums of technology development, that is, technology diffusion, technology convergence, influence, influence, and technology transition (see Table 1). This study indicates that United States patent 7261542 ranked first in both technology convergence and technology transition; United States patent 4575330 ranked first in technology diffusion and second in influence. Through this analysis, regardless of the role of these patents, they can provide researchers with the most critical or promising starting points.

F. Analysis Technology Context

1) Technology diffusion

In technology diffusion, the important patent and its patents in the backward and forward clusters were also clustered. For example, United States patent 4575330 and its backward and forward patents total 614 patents for Cluster #1, 446 patents for Cluster #2 (US 5204055), 358 patents for Cluster #3 (US 4863538), and 242 patents for Cluster #4 (US 5518680). Based on the TF-IDF analysis results, the top values in this cluster were "powder," "material," "surface," "bone," "liquid," "composition," "teeth," and "laser", as noted in Table 2. This study, as demonstrated in Table 2, could find that 3-D printing material technology focuses on powder material and liquid material, such as resin. Moreover, the study found that patents with relatively greater momentum of technology diffusion are related to the medical industry, with values such as "bone" and "teeth," as noted in Table 3. We can find keywords for technology diffusion by using these higher-weighted values. Therefore, this study found that the 3-D printing material technology applies in the medical industry. The future application of 3-D printing technology could involve medical technology development.

TABLE 1: PATENTS WITH TOP NETWORK PROPERTIES.

InDegree Centrality-Momentum of technology diffusion			
Ranking	Patent Number	Tile	Assignee
1	4575330 (1986)	Apparatus for production of three-dimensional objects by stereolithography	UVP, INC. (CALIFORNIA SAN GABRIEL US)
2	5204055 (1993)	Three-dimensional printing techniques	MASSACHUSETTS INSTITUTE OF TECHNOLOGY (MASSACHUSETTS CAMBRIDGE US)
3	4863538 (1989)	Method and apparatus for producing parts by selective sintering	DTM CORPORATION (TEXAS AUSTIN US)
4	5518680 (1996)	Tissue regeneration matrices by solid free form fabrication techniques	MASSACHUSETTS INSTITUTE OF TECHNOLOGY (MASSACHUSETTS CAMBRIDGE US)
5	5121329 (1992)	Apparatus and method for creating three-dimensional objects	STRATASYS, INC. (MINNESOTA EDINA US)
OutDegree Centrality-Momentum of technology convergence			
1	7261542 (2007)	Apparatus for three dimensional printing using image layers	3D SYSTEMS. INC. (SOUTH CAROLINA ROCK HILL US)
2	8506862 (2013)	Three dimensional printing material system and method using plasticizer-assisted sintering	3D SYSTEMS, INC. (SOUTH CAROLINA ROCK HILL US)
3	7905951 (	Three-dimensional printing material system and method using peroxide cure	3D SYSTEMS, INC. (SOUTH CAROLINA ROCK HILL US)
4	7550518 (	Methods and compositions for three-dimensional printing of solid objects	3D SYSTEMS, INC. (SOUTH CAROLINA ROCK HILL US)
5	7569273 (	Thermoplastic powder material system for appearance models from 3D printing systems	3D SYSTEMS, INC. (SOUTH CAROLINA ROCK HILL US)
InCloseness Centrality-Momentum of influence			
1	4078229 (1978)	Three-dimensional systems	Swanson; Wyn K. (CA Berkeley US)
2	4575330 (1986)	Apparatus for production of three-dimensional objects by stereolithography	UVP, INC. (CALIFORNIA SAN GABRIEL US)
3	4752352 (1988)	Apparatus and method for forming an integral object from laminations	Feygin; Michael (IL Chicago US)
4	4863538 (1989)	Method and apparatus for producing parts by selective sintering	DTM CORPORATION (TEXAS AUSTIN US)
5	4665492 (1987)	Computer automated manufacturing process and system	Masters; William E. (SC Easley US)
OutCloseness Centrality-Momentum of being influenced			
1	8944802 (2015)	Fixed printhead fused filament fabrication printer and method	RADIANT FABRICATION, INC. (WISCONSIN FITCHBURG)
2	8916085 (2014)	Process of making a component with a passageway	A. RAYMOND ET CIE (GRENOBLE FR)
3	8883064 (2014)	Method of making printed fastener	A. RAYMOND ET CIE (GRENOBLE FR)
4	7979152 (2011)	Apparatus and methods for handling materials in a 3-D printer	3D SYSTEMS, INC. (SOUTH CAROLINA ROCK HILL US)
5	9034237 (2015)	Solid imaging systems, components thereof, and methods of solid imaging	3D SYSTEMS, INC. (SOUTH CAROLINA ROCK HILL)
Betweenness Centrality-Momentum of technology transition			
1	7261542 (2007)	Apparatus for three-dimensional printing using image layers	3D SYSTEMS. INC. (SOUTH CAROLINA ROCK HILL US)
2	6401001 (2002)	Layer manufacturing using deposition of fused droplets	Nanotek Instruments, Inc. (AL Opelika US)
3	5260009 (1993)	System, method, and process for making three-dimensional objects	Texas Instruments Incorporated (TX Dallas US)
4	5837960 (1998)	Laser production of articles from powders	LOS ALAMOS NATIONAL SECURITY, LLC (NEW MEXICO LOS ALAMOS US)
5	5662158 (1997)	Self-lubricating implantable articulation member	Johnson & Johnson Professional, Inc. (MA Raynham US)

TABLE 2: KEYWORDS IN AN IMPORTANT TECHNOLOGY DIFFUSION PATENT CLUSTER.

Cluster #1		Cluster #2		Cluster #3		Cluster #4	
Keywords	TF-IDF	Keywords	TF-IDF	Keywords	TF-IDF	Keywords	TF-IDF
material	18.26	powder	14.83	powder	14.13	bone	10.52
powder	16.23	material	10.64	material	9.60	powder	7.46
surface	13.52	binder	10.63	laser	9.51	material	7.23
liquid	13.19	mold	10.52	build	8.65	dosage	6.41
composition	12.96	surface	9.65	binder	8.14	release	6.36
teeth	12.82	build	9.27	metal	7.48	device	5.33
laser	12.75	dosage	8.96	device	7.34	antibiotic	5.23
build	11.97	particles	8.51	body	7.33	particulate	4.97
model	11.91	device	8.23	bit	6.93	Semi-conductor	4.85
resin	11.49	particulate	7.79	Semi-conductor	6.27	cells	4.82
light	10.76	fluid	7.52	surface	6.12	tissue	4.45
apparatus	10.48	article	7.40	fluid	6.11	binder	4.43
mold	10.13	body	7.28	article	6.09	polymer	4.29
medium	9.29	printhead	7.07	particles	6.01	matrix	4.26
radiation	9.21	release	6.95	porous	5.92	deposition	4.18

TABLE 3: KEYWORDS IN IMPORTANT TECHNOLOGY CONVERGENCE PATENT CLUSTER.

Cluster #1		Cluster #2		Cluster #3		Cluster #4	
Keywords	TF-IDF	Keywords	TF-IDF	Keywords	TF-IDF	Keywords	TF-IDF
powder	18.44	powder	14.64	powder	12.76	powder	12.87
material	15.27	material	14.21	material	12.52	material	12.17
liquid	11.87	liquid	10.10	liquid	8.95	liquid	8.88
laser	11.43	binder	9.80	resin	8.54	resin	8.42
surface	11.27	composition	9.60	composition	8.38	composition	8.22
resin	10.77	surface	9.21	surface	8.25	surface	8.08
composition	9.36	resin	9.11	article	7.50	laser	7.37
medium	9.16	article	8.84	laser	7.42	mold	7.21
article	8.82	laser	7.96	binder	7.40	binder	7.19
build	8.73	particulate	7.80	mold	7.26	article	7.09
apparatus	8.32	medium	7.76	medium	7.11	medium	7.07
metal	8.01	mold	7.62	apparatus	6.17	apparatus	6.07
film	7.72	apparatus	7.07	support	6.04	support	5.99
particles	7.70	fluid	6.66	weight	5.71	light	5.67
temperature	7.37	weight	6.35	light	5.64	weight	5.49

2) Technology convergence

In technology convergence, the important patent and its patents in the backward and forward clusters were also clustered. For example, United States patent 7261542 and its backward and forward patents total 514 patents for Cluster #1, 417 patents for Cluster #2 (US 8506862), 370 patents for Cluster #3 (US 7905951), and 364 patents for Cluster #4 (US 7550518). Based on the TF-IDF analysis results, the top values in this cluster were “powder,” “material,” “liquid,” “laser,” “surface,” and “resin,” as noted in Table 3. We find keywords for technology convergence by using these higher-weighted values. This study, from the data presented in Table 3, could find that 3-D printing material technology focuses on powder and liquid materials, such as resin.

V. CONCLUSION AND RECOMMENDATION

This study’s primary purpose was to construct a patent citation network for 3-D printing material technology by employing patent citation relationship information. This study used a social network analysis to cultivate the technology development evolution process, based on a timeline. Moreover, this study computed the momentum of technology for playing roles in the entire network, with forward and backward patent citations. The results demonstrate that the 3-D printing material technology is in the growth stage, with the production of newer patents not based on previous patents cited; that is, a new patent is not similar to an old patent. Furthermore, the results revealed a gradually changing trend in 3-D printing material technology. The main contribution of this study was the construction a patent citation network for 3-D printing material technology and the analysis of patent roles in the network for the impact on the entire network, as well as technology evolution. This study provides a method to determine the core or key patents, and a context for technology research decision reference. This applies especially for the government, as it supports helpful technology development in its emerging stage, and with gradually evolving technology.

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