Identification and Forecasting of Emerging Technology Commercialization by Reverse Salient

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***Abstract*—The identification and forecasting of reverse salients of emerging technology is becoming harder because technology is getting complex. This study presents a systematic method of identifying and forecasting reverse salients. Experts evaluation, bibliometric analysis and forecasting techniques are integrated to specify reverse salients, to figure out the gap between current and market required performance, and to forecast when a reverse salient is resolved. This study will contribute to practitioners with regard to R&D investment of private sectors and governments, planning and technology commercialization. A carbon nanotube biosensor technology was analyzed as an example.**

***Index Terms*—bibliometrics, carbon nanotube biosensor, commercialization, reverse salient**

I. Introduction

It is essential for growth of entrepreneur as well as national economy to commercialize emerging technologies successfully [1]. Emerging technologies create new growth opportunities by changing competition rules and reshaping industry structure based on disruptive innovation [2]. However, commercialization of some emerging technologies such as carbon nanotube has been slowed down than expected.

Technology commercialization can be divided into two stages [3]. The first is a period of dynamic technical change through innovation. The second is a period of technological integration and standardization. In the first, expectation on the future value of an emerging technology is formed despite various potential obstacles including technological feasibility. However, many companies drive a business based on emerging technologies, meet with a difficulty, and thus fail in businesses [4]. Jolly suggested technology commercialization procedure comprising imaging, incubating, demonstrating, promoting and sustaining [5]. This is a serial process, meaning that the success in previous phase cannot guarantee the success in the next phase. In initial phases, technological problems are important, and economics become important in later phases. Therefore, for successful technology commercialization, the first step is to overcome key technological obstacles. Despite its importance, technological issues have been overlooked.

From the methodological point of view, most were dependent on expert's assessment [6]. Yet, there is no organized method to identify key technological obstacles. Furthermore, shortened technology lifecycle and growing technological complexity have made experts' judgments less reliable. As an alternative, bibliometric analysis technique was proposed but it lacks specificity compared to expert judgment and cannot specify obstacles in R&D practice [7].

We suggest a new systematic approach to figure out key technological obstacles, and to forecast when they can be resolved. To make the concept of technological obstacles clear, reverse salience methodology is introduced. Reverse salient (RS) is a technological element, which restricts performance of the entire technology system and hinder the system advancement [8]. We define RS as technological obstacles which impede the full market potential of a technology.

Our research process consists of three phases. In the first, judgments by multiple experts are converged systematically through combination of QFD and reverse salient theory. In the second phase, key performance indicators of top priority RSs are defined through bibliometric analysis of papers and patents. Lastly, we identify the current performance gap of RS and forecast when the RS can be settled using extrapolation techniques.

Our method can overcome subjective biases of experts' judgments and the lack of specificity found in the existing bibliometric analysis technique. Furthermore, we can predict the possibility of solving future RS thereby increasing accuracy of decision making on research and development at the current time.

Manuscript received June 4, 2013; revised August 3, 2013.

doi: 10.12720/joams.1.3.282-287

As an example, carbon nanotube (CNT) biosensor is studied. CNT is a typical emerging nanotechnology. It is 100 times stronger than steel and has excellent thermal and electrical conductivity. Its application area is very wide including transparent conductive films, solar cells, semiconductors, sensors and others. However, its commercialization has been done mainly in the area of high-strength products. Commercialization in other areas has been delayed due to various RSs. Nonetheless, R&D for CNT commercialization is still actively progressing in academia as well as industries. Since CNT has similarity with other status-of-the-art nanomaterials such as grapheme in terms of applied commercialization area and material characteristics, it gives a wide range of implications for various cases for other nanotechnology commercialization.

II. Literature Review

This study focuses on technology commercialization from a wide perspective view and more particularly, it deals with technical RSs. Thus, the previous studies on RS and technology commercialization are reviewed.

A. Reverse Salient

In contrast with a unitary view, which understands the technology system integrally, a systemic view sees the technology system as multiple interactive subsystems. The RS concept is based on the systemic view. Technological elements, which restrict performance of the entire technology system and hinder the system advancement, are called reverse salient (RS). Therefore, RS must be solved in order for the technology system to work as expected and get back to the normal advancement path [9].

Previous studies have used RS to investigate evolution of technology systems, and the role of RS. At first, Hughes used the concept of RS to analyze the development of a direct-current electric system generator. Similarly, Murmann and Frenken decomposed a technology system of vehicle into technological sub-elements such as a body and engine in their study on dominant design and innovation [10]. On the other hand, studies from a socio-technical viewpoint understood RS by including not only technological elements but also other external elements such as end consumers, manufacturers and related infrastructures [11].

RS concept can also be useful to understand not only RS of a current system but also dynamic changes in a technological system. For instance, Dedehayir and Mäkinen analyzed a changes of RS in PC game; hardware, the CPU and the GPU as a subsystem of a personal computer. RS of PC game in the past was the CPU but soon GPU became the RS due to rapid improvement of CPU performance and stagnant advancement of GPU technology. Moreover, prediction results of future performance of CPU and GPU showed that a CPU will become RS again in the future This study is meaningful because it attempted to predict future RS although its application scope was too narrow due to dependence on intuition for RS identification [8].

There was other attempt to systemize RS identification by dividing a commercialization process [12]. However, RS identification still depends on intuitive judgments. Their approach may have difficulty in identifying RS of sophisticated technological system. Our research is designed to overcome such subjectivity and to study dynamics of RS in a sophisticated technology system systematically.

B. Nanotechnology Commercialization

Since Dr. Richard Feynman presented the concept of nanotechnology in 1959, nanotechnology has influenced many areas including products, service, system innovation as well as society, economics and environment greatly [13]. This is because nanotechnology is interdisciplinary, disruptive and widely applicable [14]. Most of nanotechnology advancements have come from interdisciplinary R&D and technology fusion. Those are promoting innovations in many industries.

Regardless of huge R&D investments in public and private sectors over many years, nanotechnology commercialization hasn't met the initial expectations. Because of this, many previous studies have discussed the key factors of nanotechnology commercialization. US Department of Commerce in 2007 identified the core causes of the stagnant commercialization including a long period of research, large performance gap between the basic and applied science and lack of prototyping facilities [6]. Many other researchers added socio-economic factors to this list such as a large scale capital investment, highly specialized R&D personnel, research infrastructure, and network between universities and entrepreneurs [15], [16].

There were also many studies on processes and paths for nanotechnology commercialization because nanotechnology can be commercialized into various industries and products. Many researchers have studied to the co-evolution trajectories of nanotechnology, which requires multi-disciplinary convergence, research trends for nanotechnology through a quantitative bibliometric analysis, and socio-technical scenario for the future of nanotechnology.

Most studies were based on macroscopic point of views with regard to entire nanotechnology although some research studied the advancement path of specific nanoproducts. Huang analyzed possibility of commercialization for biosensors and application areas with regard to nanomaterials applied [17]. For practical implications, a microscopic approach is more appropriate over macroscopic trend analysis on commercialization process.

Many previous studies analyzed the core factors of success and failure of commercialization, but have focused on socio-economic factors rather than on technological factors. Though, technological RS should be solved before considering socio-economic factors, there has been few established method. Therefore, it is necessary to develop a practical and specific method to handle technological RSs.

III. Methodology

A. Research Framework

Our research consists of three steps as shown in Fig. 1. Reviewing related literature, commercialization processes of CNT biosensors was defined. Also, key technologies and core properties of each phase are identified. To balance technology and market perspective, three CNT experts and three nano biosensor experts participated using QFD to identify and prioritize key RSs. QFD is appropriate to converge experts' different judgments systematically way.

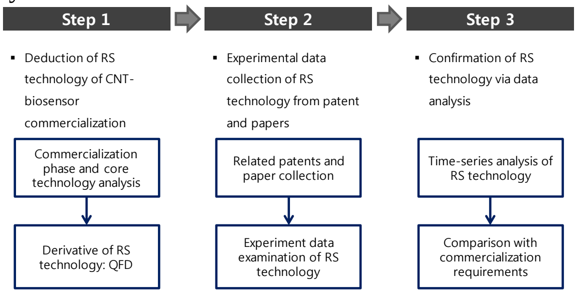

Figure 1. Research framework

In the second phase, key performance indicator (KPI) is defined. We collect the specific value of KPI from related journals and patents then analyze the changes in KPI values using bibliometric method.

Then, considering dynamic pattern of data and technology characteristics, the most appropriate growth curve is determined then future values of KPI are projected via extrapolation method. Therefore, we can figure out that what the core RS is at the current time and when the corresponding RS can be solved.

B. QFD

QFD is well known method considering both technology and market perspectives. Also it can reduce subjective biases of experts' judgments [18]. We use QFD to identify RSs. QFD was designed to correlate customer requirements with engineering characteristics. It has been used for product development in many industries.

QFD usually goes with House of Quality. Customer's requirements (required quality) are in its vertical axis and technological elements related to the requirements are placed in its horizontal axis. Through discussions of multiple experts, they score the correlation between customers' requirement and product feature by using nonsymmetrical scale of 1 (week), 3 (medium) and 9 (strong) and importance level of the required qualities are determined. The higher this importance level is, the more the corresponding technological element is important to meet the customer requirement.

In our research, customer requirements correspond to market requirements and product features correspond to core technological elements. Through the weighted sum of the importance level and relevance, we prioritize the RS for commercialization.

C. Bibliometrics

In many studies, global scale bibliometric data have been used to decrease subjective and regional biases. Bibliometric is useful for mega-trend analysis from macroscopic viewpoints whereas it is not appropriate for detailed analysis of technologies microscopically.

In order to overcome the limitation of bibliometric analysis, we use bibliometrics and QFD comprehensively. Also, for concrete analysis of technical RS, specific KPIs are defined, relevant journals and patents are collected, and the changes of performances are plotted over time. Performance gap is estimated from the difference between current and minimum required value in the market. We can identify the current difficulty of solving RS but to forecast the future RS.

Bibliometric data usually involve time lag. To minimize such truncation problem, priority date of patents and submission date of papers are used as reference date of the corresponding KPI.

IV. Empirical Analysis and Results

A. Data

In our research, experts' knowledge and experimental data of patents and papers are employed. Six experts with more than 10 years' experience were involved in the process of identifying RS and KPI through QFD.

As previously noted, we use Thompson Reuters' Web of Science and USPTO databases for bibliometric analysis between 2000 and 2011. 42,000 papers and 7,439 patents are collected by the keywords such as CNT, SWCNT, carbon nanotube and a set of similar words. Then, we extract the patents and papers with specific data about KPI.

B. RS Identification

As for the first step of RS identification, commercialization phase for CNT-biosensor is defined as four phases: material research, manufacturing technology development, application technology development, and commercialization technology development [19]. As mentioned earlier, if key technology performance in the preceding phase cannot met the minimum requirement, commercialization of CNT-biosensor products is likely to fail at a later stage.

Based on the literature review and experts' opinions, we specify key technologies of each commercialization process. Previous researches recommend key technologies comprising pure SWCNT fabrication and separation, device fabrication, sensing material combination, sample pre-processing, electrode optimization and signal processing.

Among them, pure CNT separation technology is claimed as the top priority requiring major breakthrough [20]. CNT biosensors need highly pure SWCNT with helicity. Currently, high purity SWCNT of specific helicity can be possible for an amount of a laboratory level. Not only obtaining high purity SWNT but also commercially viable production amount is essential for commercialization so that corresponding separation technology is subdivided according to purity and scale thereby deriving 13 core technologies in total as shown in Table I.

TABLE I. PROCESS-WISE KEY CNT-BIOSENSOR TECHNOLOGY

Phase 1		Phase 2						Phase 3		Phase 4		
Material research		CNT production technology development						Application technology development		Commercialization technology development		
Structure	physical property	Synthesis (quality)	Synthesis (capacity)	Shape separation (purity)	Shape separation (capacity)	Electrical property separation (purity)	Electrical property separation (capacity))	Device fabrication	Sensing material combination	Sample pre-processing	Electrode optimization	Signal processing
A1	A2	A3a	A3b	A4a	A4b	A4c	A4d	A5	A6	A7	A8	A9

			Importance level	CNT-biosensor commercialization core technology												
				Phase 1		Phase 2						Phase 3		Phase 4		
				Material research		CNT production technology development						Application technology development		Commercialization technology development		
				A1	A2	A3a	A3b	A4a	A4b	A4c	A4d	A5	A6	A7	A8	A9
Market requirements for commercialization	Performance	B1	1	3	3	0	0	1	0	9	0	3	3	3	1	1
		B2	1	0	0	0	0	0	0	0	0	0	9	3	0	0
		B3	3	0	0	0	0	0	0	0	0	0	0	9	0	1
		B4	3	0	0	0	0	0	0	0	0	0	9	0	3	1
	Practicality	B5	9	0	0	3	0	3	0	9	0	3	1	0	0	0
		B6	3	0	0	0	0	0	0	0	0	0	0	9	0	1
		B7	3	0	0	0	0	0	0	0	0	9	3	0	0	0
	Economics	B8	9	0	0	0	3	0	3	0	9	3	3	3	3	0
	Regulation	B9	1	9	9	0	0	0	0	1	1	0	0	0	0	0
Reverse salient				12	12	27	27	28	27	91	82	84	84	87	37	10

Figure 2. QFD of CNT-biosensor

For commercialization, the performance of key technologies should meet the market requirements. Based on experts' judgments and literature study, 9 market requirements are specified and grouped into performance, practicality, economics, and regulation as shown in Table II.

TABLE II. MARKET REQUIREMENTS FOR CNT-BIOSENSOR COMMERCIALIZATION

Required items for commercialization performance	Performance	Selectivity	B1
		Sensitivity	B2
		Speed	B3
		Multiplex sensing	B4
	Practicality	Reproducibility	B5
		Miniaturization	B6
		Life cycle	B7
	Economics	Competitive price	B8
	Regulation	Safety(no toxicity)	B9

In Fig. 2, key technologies are places in the upper row and market requirements appear in the left column. Six experts score importance of market requirements, and the level of difficulty of key technologies. Thus, a weighted sum of importance and difficulty, which is RS score is calculated at the bottom.

A4c, A4d, A5, A6 and A7 are formed as a core RS group. A4c (high purity SWCNT separation with specific electrical property) gets the highest score. As mentioned earlier, CNT-biosensor commercialization cannot be succeeded without solving the RS in previous stage. Thus, A4c is the first to be addressed.

A. RS bibliometric analysis and forecasting

After identifying the key RS, we need to define its key performance indicator (KPI) to figure out the performance gap between current and market requirement. Based on literature study and the experts' opinions, KPI of A4c is defined as % purity after separation process as given in Table III.

TABLE III. KEY PERFORMANCE INDICATORS OF RS, A4C

RS KPI	RS KPI definition	Measurement
Semi-conductive SWCNT purity	A mass ratio of semi-conductive SWCNT with specific electrical	%

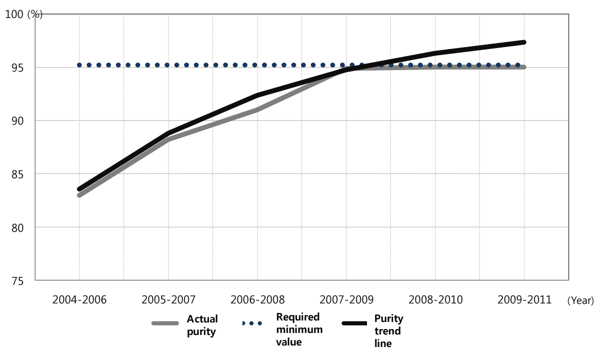

Figure 3. Semi-conductive SWCNT purity trend and future projection

For bibliometric analysis, 95 patents and 18 papers with specific KPI values are extracted from 7,439 CNT related patents in USPTO DB and 42,000 papers in Web of Science DB, respectively. Fig. 3. shows the trend of KPI over time. Since low purity and high purity study results can be published at a similar time, average value per year might be fluctuating by a few outliers. Therefore, three-year moving average is used.

Starting from 2004 of 82%, the purity of semi-conductive SWNT shows a constantly increasing trend and then stabilized at 95% since 2008. The minimum required purity for most semi-conductive SWCNT is around 95%, thus the purity of semi-conductive SWNT satisfied the minimum requirements for commercialization from 2008. Yet the minimum requirement can vary depending on applications. Some biosensors, in which a probe is inserted into a human body, require higher than 99% purity. For this restricted case, electrical property purity of semi-conductive SWCNT is RS and the performance gap of purity is 4%.

In order to predict the RS alleviation time for biosensor which requires higher than 99% purity, a trend extrapolation method is applied. The three-year moving average between '2004-2006' and '2007-2009' shows a typical logistic growth curve. When we assume that an upper limit (L) of purity is 99%, the equation is shown in Equation (1) and statistical parameters are estimated as below in Table IV. R2 (0.990) with p-value (0.011) indicates that the logistic curve ifits well with corresponding data.

$$y = \left(1/L + c \times b^t\right)^{-1} \quad (1)$$

TABLE IV. PARAMETER ESTIMATION RESULTS OF A SEMI-CONDUCTIVE SWCNT PURITY GROWTH CURVE

	Coefficient	Standard deviation	t	p-value	F	p-value	R^2
b	0.619	0.033	18.93	0.003	82.49	0.011	0.990
c	0.003	0.000	6.911	0.02			

According to the above logistic curve, the purity of semi-conductive SWCNT is forecasted to reach 98% at '2009-2011' and 99% at '2011-2013'. However, purity has been stagnant since 2008.

To analyze the reason, a three-year moving average of the numbers of patents and papers is plotted as shown in Fig. 4. The number of patents started to decrease from 2006, and the number of papers started to decrease from 2004. Once basic research reached the limitation, applied research also reached the limitation, which is a typical pattern. Considering this, little possibility of innovation is expected.

In early 2000s, various new separation methods were developed also the number of patents and papers were increased. However, no new separation method has been developed since stagnant periods of research. The extrapolation result of KPI and the research trend indicate that the separation purity is not likely to grow by more than 95% at a later stage. As a result, the purity of semi-conductive SWCNT will be a RS for CNT-biosensors requiring purity of 99%.

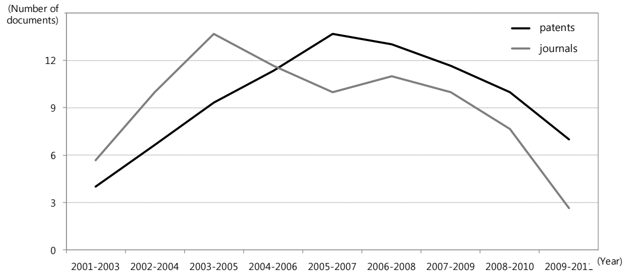

Figure 4. Number of patents and journal papers of Semi-conductive SWCNT separation technique

V. CONCLUSION

This study proposes a method of identifying and predicting the RS for commercialization of emerging technologies systematically by utilizing QFD and bibliometric analysis in combination. Empirical analysis is done with regard to CNT biosensor, a typical emerging technology but with some commercialization obstacles. The highest priority RS is identified by QFD and the performance gab of it between current value and market requirement is estimated based on bibliometric analysis and forecasting technique.

Academically, this paper contributes to expand the research scope of RS and increases the usefulness of it. This study deals with emerging technology, but previous studies have focused on commercialized products. Obviously, ex-ante identification and forecasting of RS is more meaningful to practitioners but more difficult to drive appropriate results due to involved uncertainty. Combined use of experts' judgment and bibliometric analysis makes it possible.

The study results can also be applied to RS monitoring in practice by overcoming limitation of superficial analysis of bibliometric studies as well as subjective bias of experts. Employees and researchers can apply the method to perform R&D strategy, planning, target selection and its execution effectively. It can also help to increase rationality of decision making on investment on new product and business for decision makers.

In spite of its contributions, this study has some limitations. Emerging technologies often experience disruptive technological innovation, but we assume continuous development trajectory. For better results, we should consider suitable prediction methods such as complex system techniques or scenario technique. Secondly, minimum market requirement of KPI heavily depends on expert's judgment, which could involve subjective biases. There have been many studies with regard to commercialization of emerging technologies, but none of them can ensure objectivity of setting market requirements of specific performance. Because they are substantially different depending on industrial characteristics and conditions of companies that initiate commercialization. Therefore, it is required to present judgment criteria for commercialization and need to be specified according to different characteristics of technology, industry and company size and others.

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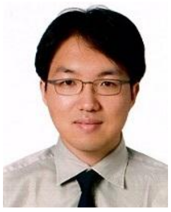

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