A Systematic Technology Forecasting Approach for New and Emerging Science and Technology: Case Study of Nano-enhanced Biosensors

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***Abstract*- This paper addresses the topic of anticipating likely development paths for a particular "New and Emerging Science & Technology" (NES&T). Characteristics of NES&T -- technological uncertainty and contextual dynamics -- pose challenges for technology management and forecasting practices. Researchers, technologists, R&D managers, staff in funding agencies and policy makers "need to know" future prospects. This requires better ways to capture NES&T development patterns, within their socio-economic context, as well as likely innovation opportunities. A new technology forecasting framework for NES&Ts is presented, supported by a case study of nano-enhanced biosensors.**

I. INTRODUCTION

"Analysis of emerging technologies" has been of interest for many years. Recently, "New and Emerging Science & Technologies" ("NES&Ts") have drawn the attention of Future-oriented Technology Analyses ("FTA") researchers because of their uncertainty and dynamic characteristics [1]. NES&Ts challenge trusted FTA approaches, like technology roadmapping [2]. As a result, it's an intriguing methodological challenge to decide what data and methods can yield effective future projections for NES&Ts.

This paper develops a conceptual framework to depict and forecast NES&Ts. It is organized in four sections. Key concepts and development status are discussed in Section 1. In Section 2, we set up a systematic technology forecasting approach framework for NES&Ts on the basis of traditional and new FTA methods. We then apply these approaches to nano-enhanced biosensors as a case study in Section 3. At last, a discussion of advantages and disadvantages of our proposed approach gained from the case study constitutes Section 4.

II. CHALLENGES IN FORECASTING NEW AND EMERGING SCIENCE & TECHNOLOGIES

In recent decades, FTA has come forth to enrich our understanding of technological innovation within societal contexts, under highly dynamic conditions [3] (see also http://forera.jrc.ec.europa.eu/fta_2008/intro.html). FTA may combine "aims" (normative aspects) concerning particular emerging technologies and "action" dimensions, such as analytical processes that better address technological uncertainties, risks, and opportunities. FTA can serve a wide range of potential users, from corporate managers to national policy makers.

The FTA initiative blends many forms of analyzing future technology and its consequences -- for example, technology intelligence, forecasting, roadmapping, assessment, and foresight. Using these approaches, FTA analysts can inform technology management, as well as science and research policy [4]. However, NES&Ts pose new challenges for effective FTA.

Recently those engaged in FTA are beginning to distinguish science and technology development situations that warrant differentiated analytical strategies. Technology forecasting for long-established developments, with dominant platforms (e.g., silicon-based information technologies) and incrementally changing applications are more amenable to trend analyses and growth modeling than are newly advancing scientific research areas with no applications yet (e.g., many nano and bio technologies). Given their less predictable technical bases and complex societal contexts (development environment), it is very hard to anticipate the developmental paths that such technologies will follow. This requires new ways of technology forecasting that capture development patterns, interactions with the societal environment, and forecasting of likely future innovations for a given NES&T.

We distinguish four aspects of NES&Ts that bear importantly on how to do FTA. Posing these as the driving questions:

(1) How best to understand the NES&T development situation? Many existing FTA approaches focus on exploring future possibilities, neglecting to make sure that we understand key "forces and factors" of the present situation.

(2) How to convert knowledge of the present situation into the key technology management and forecasting issues to be addressed? From the viewpoint of the technology forecasting process, the starting point is really the end point---what information needs prompt this analysis and what questions

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need be resolved? Moreover, what are the empirical indicators that can be generated by our FTA actions to help answer those questions?

(3) How to adopt or adapt existing FTA methods to generate those indicators? The available data vary greatly for different NES&Ts.

(4) How to present analytical results to aid management of the NES&T development – to enhance the opportunities and decrease the risks?

NES&Ts pose special challenges as a function of many factors – factors that we are just now exploring, including:

(a) How regular is the R&D process?

Consider as one extreme the case of silicon-based microelectronics where the technology has advanced quite regularly for half a century. At the other extreme are areas where breakthrough-based research advances spur "new" science and technology (e.g., contrast genetics before and after Polymerase Chain Reaction (PCR) enabled "instant" provision of unlimited DNA copies cheaply).

(b) What applications are in place?

NES&T maturity ranges from high (e.g., modification of properties of well-developed applications and markets) to low (e.g., at the stage of fundamental research for which potential applications are barely sketched out).

These special considerations add to the inherent uncertainty of all FTA endeavors.

III. The NES&T Technology Forecasting Framework

How can we best pursue FTA for NES&Ts? We especially value "early stage" insights on likely development pathways as those provide the greatest leverage for wisely investing R&D resources. Such early stage findings also enable real time technology assessment – i.e., engaging researchers and stakeholders in consideration of potential undesirable effects of applications in advance. However, it's really a challenge to investigate future innovation prospects from limited information available for a technology at an early stage of development. Here, we approach the NES&T development situation from two angles (Fig. 1). One is to characterize the status of the technology itself ("Characterize the Technology's Nature & Maturation"); the other one ["Technology Delivery System ("TDS") Modeling"] addresses the system. The TDS approach distinguishes factors involved in taking a new technical capability to market from the contextual forces and factors affecting such technological innovation.

There are different ways to characterize technology development stages. For example, Technology Readiness Level ("TRL") is a measure which is used by some United States government agencies and many of the world's major companies (and agencies) to assess the maturity of evolving technologies [5]. Here, we divide NES&Ts into two types according to the status of their applications: 1) emerging technologies with no applications at present; and 2) emerging technologies with few applications in the market. The first type is likely to show as research with minimal focus on applications – i.e., mainly fundamental, not applied, research. The second type includes R&D that begins to note applications that may not be well defined yet and others with applications that are well developed, but amenable to notable enhancement. How one forecasts likely developmental pathways will vary depending on the current stage and, consequently, the available information.

Besides understanding a technology's maturational stage, we want to know the contextual dynamics that could affect its potential innovation pathways. As we known, technology and society are interrelated, and both are changing rapidly. Changes in technology feed upon themselves, producing a stock of concepts that may be refined, developed, and used as the basis for further change. The development and dissemination of technology creates forces that can cause change in every aspect of society. On the other hand, changes in society produce conditions that influence technological change. We must understand these interrelationships to forecast and manage technology effectively [6]. Here, we take two perspectives to model this complex TDS to help realize the linkages along the "stream" from R&D toward commercial (or other) innovation [7]. "Push-to-Pull Enterprise Analyses" are used to identify the key players and their requirements to make prospective technological innovation occur. "Contextual Forces & Factors Analyses" seek to uncover factors that will drive innovation in particular ways, including any barriers that could hinder particular developments.

Understanding the NES&T development situation (Stage 1 of Fig. 1) provides a general sense of the key actors, interests, and potential innovations. That is a valued result in its own right. Such understanding should also help the analysts specify the key technology management issues. TABLE I offers a reasonable set of such issues from which to pick. It must be pointed out that these issues can vary widely, depending on the technology itself, its particular contextual situation, and the particular interests of the intended users of the FTA [8].

TABLE I
Technology Management Issues and Concerns

A.	R&D portfolio selection
B.	R&D project initiation
C.	Engineering project initiation
D.	New product development
E.	New market development
F.	Mergers
G.	Acquisitions of intellectual property ("IP")
H.	Exploiting one's own intellectual assets
I.	Collaboration in technology development
J.	Identifying and assessing competing organizations
K.	Tracking and forecasting emerging or breakthrough technologies (opportunities & threats)
L.	Strategic technology planning
M.	Technology roadmapping

Source: Tech Mining [8]

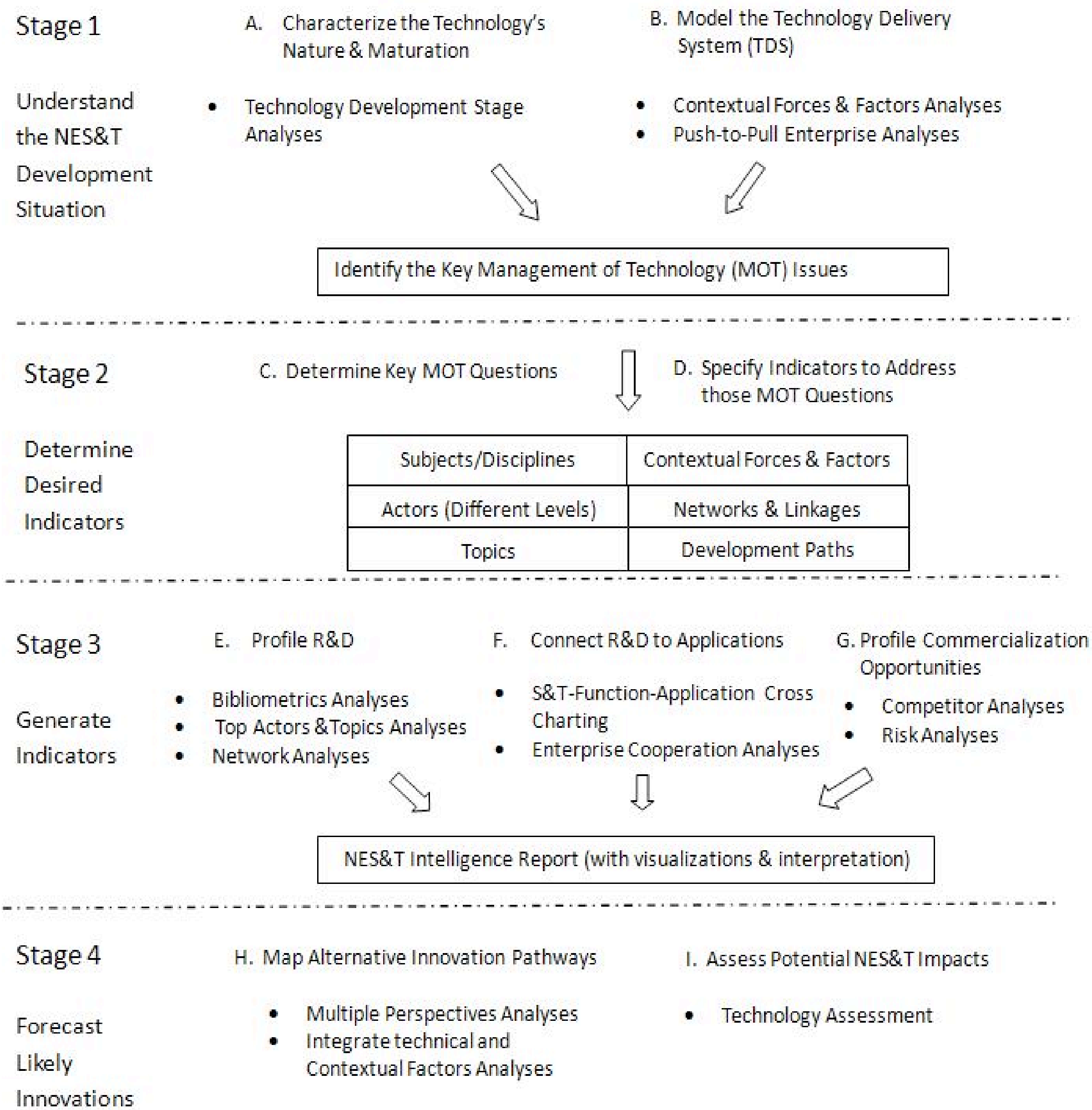

Fig.1. Future-oriented technology analyses for a new and emerging science and technology

We suggest further amplification of the objectives of the FTA endeavor. Stage 2 of Fig. 1 orients us toward particular "innovation indicators" – i.e., empirical and expert-based intelligence concerning the status and prospects of the NES&T under study. Porter and Cunningham [8] list 39 tech mining questions and more than 200 indicators based on the 13 technology management issues (TABLE I). These are just suggestive; the technology analysts need to work with the intended study users to determine what information, in what form, would be most valuable in managing the NES&T in question. Specifying particular target innovation indicators can help align FTA data selection and analytical efforts to assure that the effort is well focused.

When the indicators are spelled out, we are ready to pursue detailed profiling work – i.e., Stage 3 of Fig. 1 – "Generate Indicators." Because of the limited life of most NES&Ts, we tend to focus on the front end of the technological innovation chain. Stage 3 (Fig. 1) points us toward three facets: R&D Profiling, Connecting R&D to possible Applications, and Profiling Commercialization Opportunities.

There are many analytical tools to help profile R&D, including bibliometric analyses, social network analyses, and trend analyses. We can adopt or adapt them to facilitate our study as a function of the NES&T developmental situation (and available information) and the desired innovation indicators.

We have devised "S&T-Function-Application Cross-Charting" to bridge the gap between R&D and Applications. This is vital to understand how particular technologies might link to potential applications. In our nanobiosensors case, we began with very fuzzy notions that nanotechnology ("nano") could contribute to biosensors. After analyzing sets of R&D article abstracts and interacting with nanobiosensor researchers, we found it surprisingly helpful to systematically array the attributes of the technology (here, the features that nano offers) in terms of functional advantages, and, in turn, how those functions could translate into enhanced applications.

We are still exploring how best to do cross-charting. In this study and in companion analyses of nano-enhanced solar cells [9], we have found value in:

(1) Subdividing the technical elements (e.g., distinguishing among various nano materials);

(2) Engaging those knowledgeable about the technology in specifying the set of important, and distinctive, functions (i.e., what is important);

*(3)*Exploring which functions pertain to particular applications (in some cases requiring partitioning functions and/or application sets);

(4) Considering links between applications and commercial opportunities (users, sectors, etc.).

To date our efforts have been qualitative in nature, albeit drawing upon leads provided by R&D and contextual literature and patent compilations.

Investigating indications of cooperation between research organizations and companies is another useful way to capture early signals of commercialization intents. Tabulating "who" (e.g., active industry players) and "what" (e.g., topics being emphasized) information can constitute useful innovation indicators. Results should be well-presented with visualizations & interpretation to generate the "NES&T Intelligence Report." Well done, this should provide valuable information for technology managers and/or policy-makers.

In Stage 4, we seek to take advantage of these analyses to give insights into strategic technology planning. We want to map alternative innovation pathways. This points us to demonstrate a plausible variety of paths by which the NES&T can contribute to innovations – i.e., new or improved products, services, or systems. Such multipath mapping [2] can help articulate alternative futures. Pathways can be structured in terms of prospective innovation chains (i.e., first generation products beget second generation, and so forth). Importantly, we want to identify alternative commercialization paradigms and their likelihoods. Robinson and Propp [10] nicely counterpose a common platform "lab on a chip" innovation path versus highly specific, independent developmental options.

Furthermore, we should assess potential NES&T impacts (desirable and not) of such alternative innovation pathways, to inform early developmental choices.

IV. Case Study: Nano-Enhanced Biosensors

A. Situational Understanding

Nowadays, nanotechnology is playing an increasingly important role in the development of sensors. Biosensors represent an especially exciting opportunity for high-impact applications benefiting from nano attributes. Reviewing recent studies, we find a steep increase in the literature on nanobiosensors [11].

In this case we focus on the interesting situation of 1) novel scientifically based enhancements of 2) an emerging technology, with 3) some existing applications. "Nano-enhanced biosensors" is our NES&T. It is also of inherent interest for its highly multidisciplinary R&D and wide range of potentially important applications.

TDS modeling seeks to identify what it will take to "deliver" NES&T applications to market – in this case, for nanobiosensors. It involves multiple perspectives, including profiling R&D patterns, institutional involvements, major actors, and key markets. To anticipate the development pathways for nanobiosensors, it is also essential to identify interactions among players and to explore potential supports and barriers in the environment. This information could aid policy makers who wish to foster effective development. In order to capture more detailed information and characteristics of nanomaterial-enhanced biosensor technology, we focus on the contextual environment in one of the top nanobiosensor research countries--USA [12].

Fig. 2 characterizes a sociotechnical system composed of institutions directly or indirectly involved in developing nanomaterial-enhanced biosensor technology. At the societal level, we categorize four key players: governments, R&D groups, manufacturers, and users. We begin by thinking in terms of what will it take to translate particular nanoscience discoveries into bonafide innovations (i.e., products, processes, or services with significant commercial or other uses)? In Fig. 1, this was noted as "push-to-pull enterprise analyses." That alludes to the observation that sometimes (most times probably) NES&T interest derives from excitement emanating from a research discovery – the "push." Other times, interest is driven by an expressed need – "pull."

Government entities may address the social, political, and economic aspects of this new technology. For the R&D funding role, we note two levels: Federal agencies provide the major share of support – such as the National Science Foundation (NSF); Environmental Protection Agency (EPA); Department of Energy (DOE); and National Institutes of Health (NIH). State agencies also contribute to R&D support with relatively smaller shares (e.g., constructing new nano research facilities at universities, including Georgia Tech). Since nanobiosensor applications relate strongly to food and healthcare markets, relevant agencies are involved in regulating product development, like CDC (Centers for Disease Control and Prevention), USDA U.S. Department of Agriculture), and, especially, FDA (Food and Drug Administration).

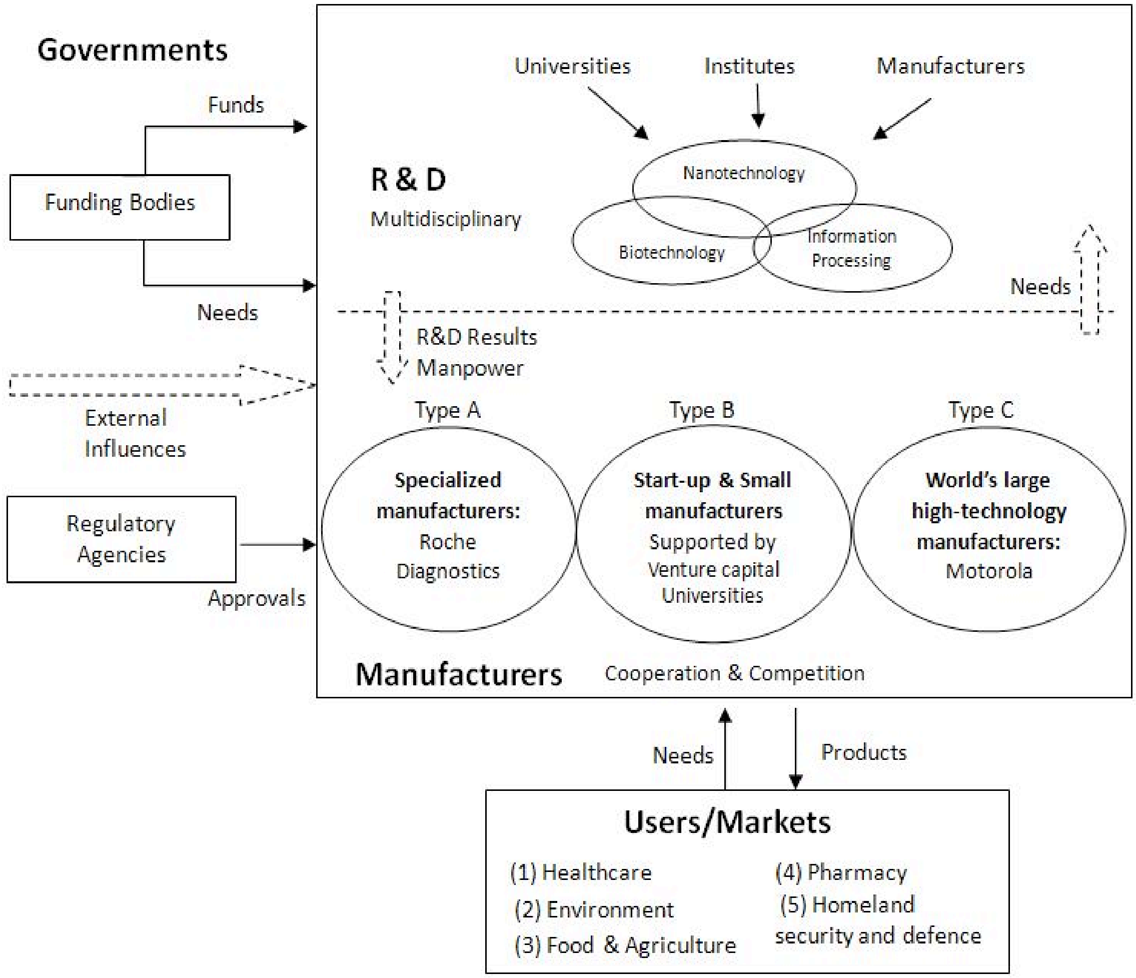

Fig.2. Nano-enhanced biosensor TDS for the USA

"Nano" research is highly multidisciplinary [13], and the nanomaterial-enhanced biosensors R&D groups really present a highly multidisciplinary research picture, reflecting integration of material sciences, molecular engineering, chemistry, biotechnology, and electrical engineering. In addition to the academic and non-profit/governmental research effort, some of the major biosensor companies are engaged in R&D programs [12].

The Manufacturers for nano-enhanced biosensors in the US can be grouped into three types: Specialized manufacturer, start-up & small manufacturers, and large, multinational companies. In the early stage of commercialization, the start-up companies are playing important roles in nanobiosensor development, and most of them are funded by venture capital and university spin-offs. A remarkable characteristic for these nano-enhanced biosensors manufacturers is strong cooperation with universities.

Biosensors have been developed for more than a half-century, but only in the last decade have commercial applications based on the new technologies become significantly available [14]. Until today, few biosensors based on nanomaterials are at work in commercial applications. Meanwhile, the emerging markets for biosensor technologies are shaping up in three dominant segments: healthcare, environment, and agriculture & food, with the healthcare markets overshadowing the others. Nanobiosensors will also likely be involved in other potential markets as well – e.g., in the field of homeland security and defense.

B. Determining FTA Indicators

Based on the nano-enhanced biosensors development situation analysis, we identify our case study's Key Management of Technology ("MOT") Issues (TABLE I) as:

I. Collaboration in technology development

K. Tracking and forecasting emerging or breakthrough technologies (opportunities & threats)

We accordingly come up with target MOT questions to address:

- What are the key nanotechnologies/nanomaterials?
- What are key technologies' competing functions?
- Which countries are the top ones for this research?
- Which organizations are the top ones for this research?

- What are those organizations' main academic and industry connections?
- What sub-topics are the top players emphasizing?
- What are the most promising opportunities for future commercialization?

Next, we should specify innovation indicators to address these MOT questions. Because nano-enhanced biosensors would enhance existing biosensor applications, it's very important to identify their commercialization opportunities at this stage. In this way, we should focus more on commercialization aspects, especially the connection between R&D and applications. Therefore, the main indicators in this case study may include:

- Locate nanobiosensor research on the map of science
- Map collaborations, looking for pointers toward potential commercial development
- Compare national R&D efforts, as possible leading indicators of commercialization strengths
- Matrix leading companies with topical research and patenting emphases
- Cross-chart nanomaterials to functions to potential applications

C. *Indicator Generation*

We now pursue the approach sketched in Fig. 1. The main dataset serving in this case study comes from global nanotechnology research publications for the time period 2001 through 2008(part year) extracted from the Science Citation Index ("SCI"), from which we have extracted 1400 records pertaining to nano-enhanced biosensors. The detailed dataset building process is described elsewhere [12].

Exploring R&D Multidisciplinary Aspects of This Research

In this paper, we apply science overlay mapping to locate nanobiosensor R&D among the disciplines [15]. This approach uses the Subject Categories that Web of Science assigns to journals. So, for a set of publications indexed by Web of Science (in this case, by SCI, which is part of Web of Science), we locate that research by the journals in which it appears. Fig. 3 overlays nanobiosensor research over a base map reflecting the 175 Subject Categories shown by the background intersecting arcs. The Subject Categories are grouped into "macro-disciplines" using Principal Components Analysis based on the degree of co-citation of the Subject Categories in a large sample of articles indexed by Web of Science [16]. Those macro-disciplines become the labels in the figure. The nanobiosensor research concentrations appear as nodes in the map, with larger nodes reflecting greater numbers of publications.

Fig. 3 illustrates that global nanobiosensor research involves a very extensive range of research fields. It is concentrated in the Materials Science and Chemistry macro-disciplines, also involving a number of Biomedical Sciences and various other fields.

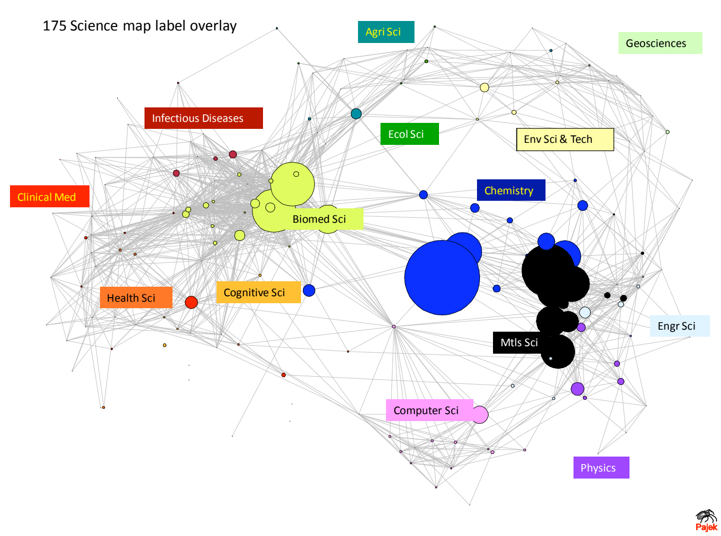

Fig.3. Locating worldwide nanobiosensor research over a base map of science (Database: SCI)

Exploring R&D to Application Connections

A general "cross-chart" from fundamental nanotechnology to market applications (Fig. 4) reveals vital links among nanomaterials, biosensors, and applications. It also explores the underlying functions of how nanomaterials can enhance biosensors, which can help future innovation path mapping.

From Fig. 4, we seek to find how nanotechnologies and nanomaterials can enhance biosensor capabilities. Nanomaterials can contribute to either the bio recognition element or the transducer of a biosensor (or both). The functions of nanomaterials used in bio recognition can be divided into two classes. The first class is referred to as "target labelling" using "0D" (zero-dimensional) or "1D" (one-dimensional) nanomaterials (e.g., using semiconductor nanoparticles). The second class of nanomaterial functions used in bio recognition elements is mainly in the form of replacing the traditional molecular recognition layers using various nanomaterials.

In generating Fig. 4 we sought to localize nano-enhancements – i.e., to see if certain nanostructures contribute to particular functions that might apply to only certain applications. For instance, if use of the 3D nanostructures might only pertain to a limited subset of functions, which contribute mainly to only one or two types of biosensors, we could then key on the organizations focusing on those to explore likely innovation prospects. Results do not localize neatly (Fig. 4). On the other hand, note that the several nano material types are not equally associated with functional advantages apt to contribute to particular biosensors. So, for instance, if we wanted to "zoom in" on one type of biosensor (say, thermal), Fig. 4 would orient us toward particular gains (e.g., patents pertaining to enhanced heat transfer or binding capacity). The broad arrows between biosensors and application sectors reflect that we have not been able to restrict types of biosensors to certain sectors.

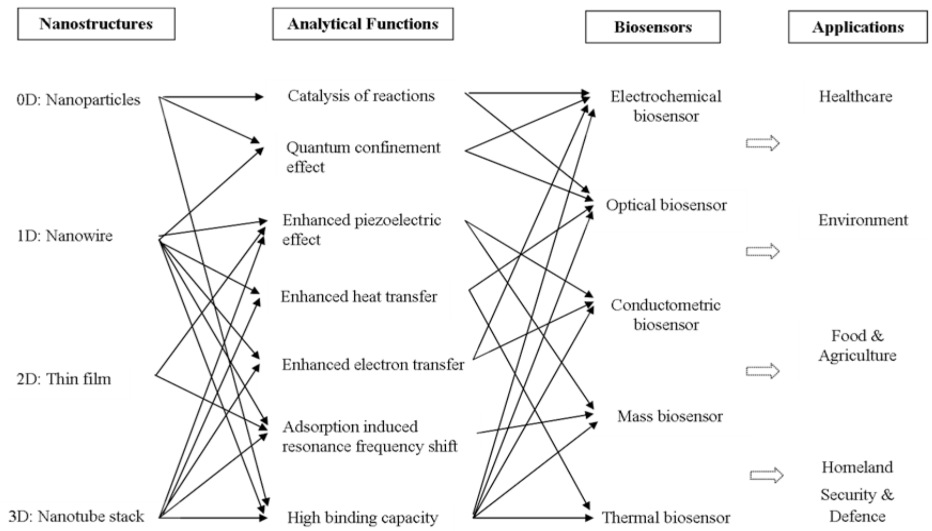

Fig.4. General nanobiosensor technology – application cross-chart [12]

Exploring Commercialization of This Research

To explore the nanobiosensor commercialization prospects, a list of top corporations around the world is shown in TABLE II (based on research publication, as indexed in SCI). From this table, we can see the countries with active industry involvement include the USA, China, Germany, Japan, Canada, and Sweden. Although the No. 1 company in the list is American, we conclude that industrial R&D on nanobiosensors is led by Japanese companies, with 5 companies in the top 15. We thus select Japan as our key focus for leading edge commercialization.

TABLE II
TOP 15 NANOBIOSNESOR CORPORATIONS IN THE WORLD (DATABASE: SCI)

No.	#Records	Affiliation	Country
1	13	Geocenters Inc	USA
2	11	Wuhan Iron & Steel Co	China
3	10	KFA Julich GmbH	Germany
4	8	Nanomix Inc	USA
5	6	BAS Co Ltd	Japan
6	6	Japan Sci & Technol Corp	Japan
7	5	FONA Technol Inc	Canada
8	5	Siemens AG	Germany
9	4	Biacore AB	Sweden
10	4	Ebiochip Syst GmbH	Germany
11	4	Eicom Ltd	Japan
12	4	NTT Adv Technol	Japan
13	3	Abgenix Inc	USA
14	3	Cent Res Labs Ltd	England
15	3	Hitachi Ltd	Japan

The map in Fig. 5 explores co-authoring among top corporations and other top R&D organizations in Japan. This can help us answer several important questions: Are there networks among key nanobiosensor research groups? How are the industry players networking with other R&D organizations? What are such networks emphasizing? Some observations:

(1) A relatively large number of Japanese corporations are publishing on nanobiosensor research;

(2) We observe notable cooperation between industry-industry and industry-academic organizations within Japan;

(3) Academic organizations comprise the core of these research networks, connecting several corporations (as circled in red in Fig. 5);

(4) Key academic organizations which are engaged with industry include: Keio University, Kyushu University, University of Tokyo, Natl Inst Adv Ind Sci & Technol, Tokyo University of Technology, University of Tsukuba.

Furthermore, we also investigate more deeply to find what these networks are doing through the text analysis of their co-authored papers.

(1) Network around Keio University appears to focus on the enhancement of biosensor sensitivity via improving catalytic ability of nanoparticles in electrochemical sensing [17];

(2) Network circled around Kyushu University seems to focus on the enhancement of biosensor sensitivity via using the magnetic field of magnetic nanoparticles [18];

(3) Network circled around the University of Tokyo: focus on the enhancement of SPR biosensor sensitivity and stability via using thin film and SAM (a 2D nanostructure)[19];

(4) Network circled around the National Institute of Advanced Industrial Science & Technology: focus on the enhancement of biosensor sensitivity via taking advantage of the biocompatibility of polymer nanoparticles in mass/piezoelectric sensing [20].

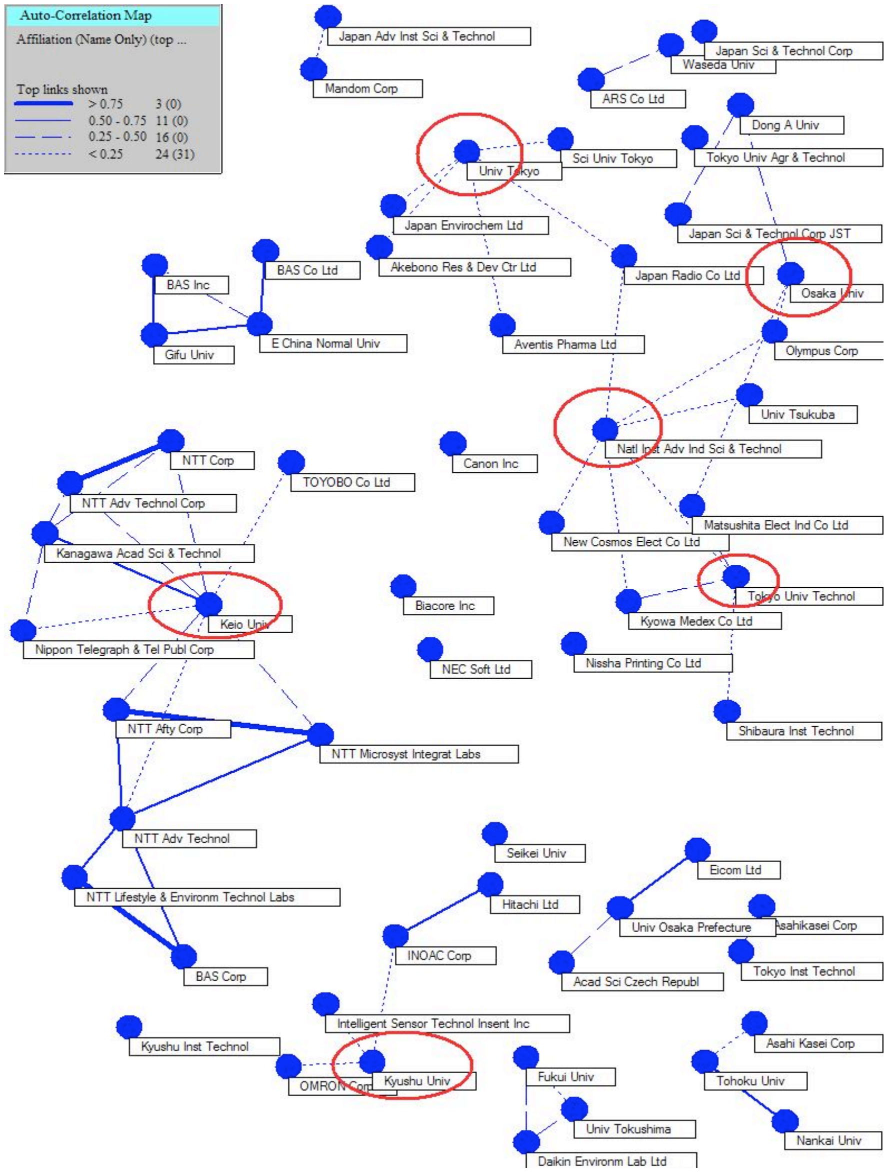

Fig.5. Cooperation between companies and other organizations in Japanese nanobiosensor research (Database: SCI)

In addition, we match the top 10 Corporations in Japan with the Subject Categories most associated with their research publication (Fig. 6).

Results suggest that the Japanese nanobiosensor companies are heavily involved with Analytical Chemistry. This concentration contrasts with the pattern seen for US companies publishing on nanobiosensors (not shown); their topical emphases vary more widely.

Forecasting Likely Nanobiosensor Innovations

Based on the case investigations presented, we identify some key factors affecting the development of nanobiosensors (TABLE III). Notable Supports include: the heavy R&D funding, wide involvement of highly multidisciplinary research groups, strong research cooperation between

Reset		Subject Category	1	2	3	4	5	6	7	8	9	10
		# Records	8	5	4	3	3	2	2	2	2	2
Affiliation (Name Only) (Cleaned)	# Records	Show Values >= 1 Cooccurrence # of Records	BAS Co Ltd	Japan Sci & Technol Corp	Eicom Ltd	Hitachi Ltd	NTT Adv Technol	NEC Soft Ltd	TOYOBO Co Ltd	Olympus Corp	Fujirebio Inc	Nippon Telegraph & Tel Publ Corp
1	175	Chemistry, Analytical	7	2	4		2	1	2		1	2
2	84	Electrochemistry	2				1				1	
3	44	Biotechnology & Applied Microbiology					1				2	
4	39	Materials Science, Multidisciplinary		1						2		
5	38	Physics, Applied		1		3		1		1		
6	37	Biophysics					1				2	
7	22	Nanoscience & Nanotechnology								2	1	

Fig.6. Co-occurrence matrix of corporations and Subject Categories

academic and corporate R&D groups, and the presence of potential users. Here, we have mainly analyzed fundamental nanobiosensor research; we are just pursuing "next steps" to profile patents and business publications that will speak to upcoming commercialization prospects.

TABLE III
CONTEXTUAL FORCES & FACTORS ANAYLYSES

	Supports	Barriers
Governments	• Strong financial support	• High regulatory barriers (especially where FDA approval is needed)
R&D groups	• Rapidly growing research literature • Multidisciplinary cooperation • Industry-academic cooperation in research	• Generally still distant from commercialization • Ignorance of good integration of biosensors into easy-to-use systems
Manufacturers	• Promising market prospects • Ever-growing number of companies offering nanomaterials	• Separate market segments • High standards of door-step to markets • High cost for needed performance • Scaling up manufacture of nanomaterials
Users	• Plenty of potential uses	• High needs beyond present ability (Tiny, disposal, low-cost, fast, super-sensitive, non-invasive)

Like most emerging NES&Ts, nanobiosensors also face many challenges. For example, the higher regulatory barriers and funding requirements for medical applications are notable. So, any small enterprises pursuing such innovations would confront major concerns about sufficient capitalization. Moreover, the cost of producing nanobiosensors is still a big problem at present. It is still hard for nanobiosensors to achieve high performance with low cost.

According to our framework (Fig. 1), the next step should be devoted to lay out alternative innovation pathways for further analyses. We needed to gather professional opinions from researchers with backgrounds in biosensors, nanotechnologies, and, hopefully, nanobiosensors. We first identified local technical experts, based on bibliometrics and collegial contacts. E-mail questions provided an initial step to enlist cooperation. One-on-one meetings proved very valuable to orient ourselves and the experts, and to decide how best to proceed. Co-authoring of papers has been a useful way to help develop close cooperation with technical experts.

We intend to pursue multi-path mapping analyses for nanobiosensors. If time and resources were to allow, an interactive workshop with a spectrum of relevant experts (technical and business) would be most attractive [2].

V. CONCLUSION

The aim of this paper is to explore a framework to help characterize the new and emerging science & technology at its early stage. The resulting approach can then serve to inform strategic technology planning and management.

With the nanobiosensors case study, we see advantages of using this framework for NES&T Future-oriented Technology Analyses (FTA). Setting forth the four stages seems vital to gain perspective on what is entailed in possible technological innovation here. In the past, we may have been too ready to delve into detailed analyses of R&D activity without being clear on the broader system involved. It is also useful to set forth the questions to be answered by the FTA effort ahead of data gathering and analyses. In practice, iteration is useful. That is, investigation of R&D and contextual data can suggest refinements to the innovation indicators and management of technology (MOT) questions.

Technology development stage analyses and TDS modeling complement each other to help understand the developmental situation for the target NES&T. Simple "boxes and arrows" TDS modeling helps identify the key actors likely to pursue biosensor innovations based on nanomaterials.

We adapt tech mining tools to help identify key R&D players and to study their interactions (research networks). "Mining" the R&D abstract records proved a fruitful source of ideas on possible nanobiosensor functions and applications. However, engaging technical experts was essential to establish valid sets of these, and important links, in the cross-charting activity.

Our framework to analyze NES&Ts is a work in progress. As this and other case analyses show, NES&Ts can take on a variety of types. The relative importance of particular technology management issues and questions should vary greatly. MOT questions and the pertinent innovation indicators seem specific to each FTA. In the present case illustration, we have mainly used only a limited spectrum of R&D information, with a special focus on linkages pointing toward potential commercialization. We recognize the need to extend to patent and richer contextual information resources to round out these analyses. That represents considerable work.

We will continue to develop this approach to forecasting likely innovation pathways for NES&Ts. With support to explore nano prospects, that constitutes our focal domain, but we recognize the need to test the approach on other new and emerging technologies. In particular, we point to variation in the extent of existing applications as a key factor in determining how to go about such FTA analyses.

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