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Patent-based QFD framework development for identification of emerging technologies and related business models: A case of robot technology in Korea

Yonghan Ju, So Young Sohn *

Dept. of Information and Industrial Engineering, Yonsei University, 134 Shinchon-dong, Seoul, Republic of Korea

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ABSTRACT

R&D planning for emerging technologies that reflect customers' future needs has a crucial role in national economies. In this paper, we propose a hierarchical quality function deployment (QFD) framework that enables one to set R&D priorities and then develop corresponding business models to meet future societal needs. The proposed QFD framework consists of a hierarchical structure with three house-of-quality (HOQ) stages, which are based on patent analysis and opinions of specialists and generalists. Based on the results of the HOQ and the convergence of iterated correlation analysis, prospective technology was identified. We applied the proposed framework to robotics technology in Korea and found that, for robotics R&D, position sensors are the most important emerging technologies, followed by distance sensors and motor-driven technologies. In addition, by utilizing reverse QFD, we suggest business models for cleaning, entertainment, and pet robots. We expect this research to open a new avenue in the R&D planning process.

1. Introduction

Research and development (R&D) planning for emerging technologies that reflect customers' future needs has a crucial role in enhancing national competitiveness. For selecting prospective technologies, previous studies suggested various methodologies, such as Delphi surveys [10,12], bibliometrics [13], and patent analysis [1,25]. However, a systematic selection method must reflect customers' needs holistically, which those methodologies fail to do. In addition, selecting emerging technology is challenging because there are many candidate technologies which are not directly related to the final product and service [29]. To find emerging technology which satisfies with respondent's needs, we propose a quality function deployment (QFD) framework and set R&D planning priorities at the lowest level of technology classification. QFD has been described as a "method to transform users' demands into design quality" and "to deploy the functions forming quality" [2]. According to Caetano and Amaral [8], it is used to identify gaps in the relationship between customers' needs and a given technology and to discover key elements contributing to new technologies' competitiveness. This concept is based on the theory of attractive quality, which was proposed by Kano et al. [21]. According to this theory, the fulfillment of attributes in two categories—one-dimensional quality and attractive quality—increases customer satisfaction. One-dimensional quality represents that attributes are linearly related to customer satisfaction. Attractive quality gives satisfaction to customer if present, but that produces no dissatisfaction if absent [37]. The proposed QFD framework consists of three house-of-quality (HOQ) stages.

The first HOQ stage relates megatrends of customers' needs to technological products. In this step, attributes of megatrends are developed by reflecting one-dimensional quality. In the second HOQ stage, using relevant patent information, an HOQ

* Corresponding author. Tel.: +82 2 2123 4014; fax: +82 2 364 7807.
E-mail address: sohns@yonsei.ac.kr (S.Y. Sohn).

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is developed to clarify the relationship between products/services and the primary level of technology classification, and the second HOQ stage reflects the prioritization of products in the first HOQ. In the third stage, an HOQ is constructed to present the relationship between the primary and secondary levels of technology classification based on patent information. The results of the second HOQ stage influence the third HOQ stage. Based on the third QFD, it ultimately becomes possible to evaluate the importance of prospective secondary-level technologies in reflecting future needs. As a result, importance of megatrends which are involved in one-dimensional quality is reflected in the second and third HOQ stages.

After identifying emerging technology in the third HOQ, we perform the HOQ process in reverse to construct a list of important megatrends only in relation to the technological services/products selected based on priority. Using this approach, one can suggest business models to reflect prospective technologies as well as customers' needs.

We apply the proposed QFD framework to robotics technology in Korea in an effort to identify related R&D priorities. According to Daim et al. [13], technology forecasting should reflect technical, personal, and organizational factors. To incorporate these three perspectives, we use patent information, survey analysis, and technology classification/technology development capacity, respectively.

This paper is organized as follows. Section 2 summarizes the relevant literature. Section 3 introduces the proposed three-stage QFD framework based on patents, while Section 4 applies the proposed framework to robotics technology. Lastly, Section 5 offers conclusions and suggests areas for future research.

2. Literature review

In this section, we review studies related to technology foresight, QFD, and patent network analysis.

2.1. Technology foresight

Formulating R&D strategies through technology foresight is a critical means of increasing national competitiveness and securing R&D funding. As methods of forecasting prospective technologies, some researchers have used qualitative approaches such as Delphi surveys, brainstorming, and technology roadmapping. The Delphi method involves the solicitation of expert views by means of successive iterations of a given questionnaire in order to identify opinion convergence as well as areas of dissent or non-convergence [16]. Brainstorming is a group technique for generating new, useful ideas and promoting creative thinking to solve a problem. It is an effective tool for predicting what is likely to happen in the future, as it benefits from a multitude of perspectives [18]. Technology roadmapping is a needs-driven technology planning process used to identify, select, and develop technological alternatives to satisfy a set of product needs [35]. While these qualitative approaches to technology foresight focus on expert opinions, the incorporation of quantitative data along with a qualitative approach will enable greater reliability and accuracy in the selection of prospective technologies.

Among various quantitative data resources that are available, scientific publications and patents are useful sources of science and technology research for R&D planning [3]. As patents are major outputs of R&D activities and represent the characteristics of new technology [11], many researchers have approached technology foresight using patent information [15,27]. Trajtenberg [34] proposed that patents be weighted based on citations as an indicator of the value of innovations. More recently, Daim et al. [13] suggested three emerging technology areas by integrating the use of patent analysis and technology foresight tools such as scenario planning and growth curve analysis. In addition, Kim et al. [22] proposed a method of visualizing patent information based on keywords from patent documents in a target field. Shen et al. [29] suggested a hybrid selection model for prospective technology, with a selection framework based on the fuzzy Delphi method, the analytic hierarchical process, and principal component analysis. Using various forecasting analyses including Gompertz curve, Bengisu and Nekhili [3] found 20 emerging technologies under the machine and materials category for Turkey. Small et al. [31] suggested framework for identifying emerging topics in science and technology based on citation-based modeling. The authors develop citation network utilizing citation information from Scopus database. Yu and Lee [38] proposed a hybrid approach for selecting emerging technology based on two-level self-organizing map, analytic hierarchy process, and data envelopment analysis-assurance region. Lee and Song [24] found key research areas in nanotechnology area using technology cluster analysis.

Previous studies on technology foresight and customer preferences, however, have not considered the hierarchical interrelationships among customers' needs and the primary and secondary levels of technology classification. To overcome this limitation, we apply the QFD framework to technology foresight planning based on both customer's needs and patent information.

2.2. QFD and patent network analysis

The QFD framework is used to identify technical requirements in future markets [26]. It consists of an HOQ with a matrix-like structure to translate customer requirements into technology solutions [2,28]. QFD is useful not only in traditional product quality but also in technology foresight [20]. In particular, QFD has been applied to technology valuation [39], technology selection [40], and management strategies [17]. Groenveld [41] and Phaal et al. [28] applied QFD to a technology roadmapping system, showing its potential as a technology foresight framework.

In this paper, we propose a technology foresight framework using a hierarchical HOQ based on patent information to select prospective technology for R&D planning. The hierarchical HOQ provides a detailed structure for guiding actions in different stages. In a general HOQ, WHAT and HOW represent quality and function requirements, respectively. Each WHAT and HOW can be subdivided from the HOQ to establish a new HOQ. Information can be communicated from one HOQ to another because they are linked [33]. This multi-stage approach has been adopted as a more realistic process [36].

An HOQ based on patent information requires a weighting scheme to determine the relative weight of a list of WHAT items. We considered four characteristics of a patent: importance based on citations, urgency based on trends, the ripple effect based on patent network analysis, and the priority of a prior HOQ. In general, citation frequency represents the value of patented inventions. According to Harhoff et al. [19], citations represent economic value because prior inventions cited in new patents tend to be relatively important precursors, and citations are used to check for potentially important economic externalities. Trend analysis provides insight into the market's reaction to, and the commercial success of, a technology [13]. In particular, patent trend analysis has much bearing on R&D planning and new product development [9].

Patent network analysis is used to calculate a patent's importance based on the relationships among targets, called "nodes." It has been used in various foresight research areas. Han and Park [18], for example, proposed an exploratory method of measuring inter-industrial knowledge flows, defining a knowledge flow matrix as the product of two separate matrices: the knowledge base matrix and the knowledge relation matrix, where the former is constructed based on patent counts. In patent network analysis, centrality is commonly used to determine the power of a node. Using the degree of centrality of patent citations, Shin and Park [30] proposed a new method of building a national information and communication technology (ICT) frontier for countries specializing in exporting ICT products. Sternitzke et al. [32] posited that the position of applicants within a citation network (or betweenness centrality) can explain behaviors in the marketplace such as cooperation and patent infringement litigation.

Drawing on the approaches of previous studies, we use patent link analysis to assess the importance of technology attributes in a hierarchical HOQ based on the concept of

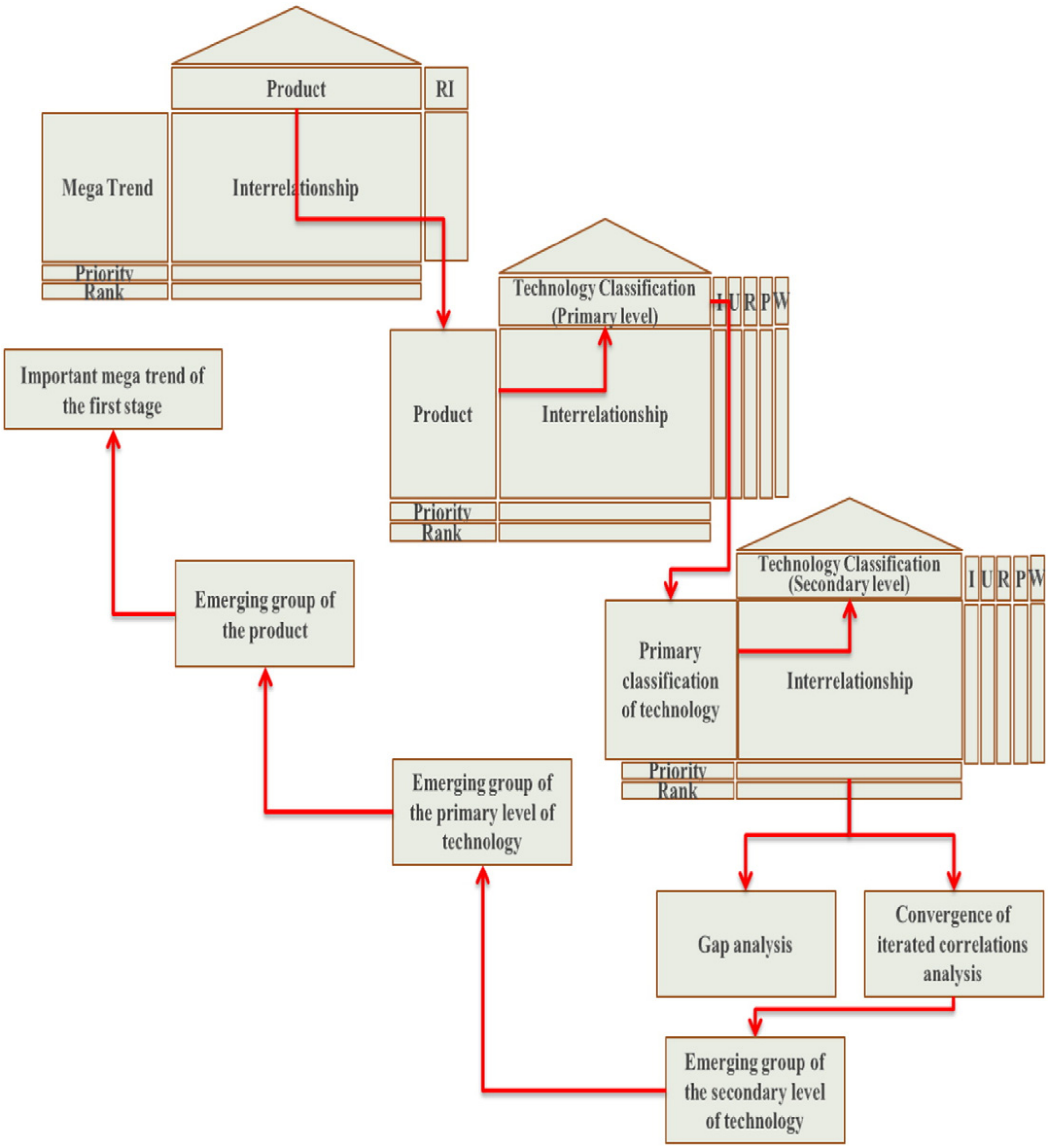

Fig. 1. Proposed hierarchical QFD framework.

eigenvector centrality. Eigenvector centrality is used to determine the general importance of each node within a network. This is done not only by counting connections, but also by weighting more heavily connections to nodes which are themselves more central than other nodes [4]. Along with eigenvector centrality, we use CONCOR (convergence of iterated correlations) analysis when selecting prospective secondary technologies to suggest business methods.

3. Proposed hierarchical QFD framework

In this section, we explain the proposed hierarchical QFD framework, which ultimately enables the development of relevant business models.

3.1. QFD framework

The proposed QFD framework has a hierarchical HOQ structure. In this framework, the definitions of WHAT and HOW change with each stage. The HOW of the first HOQ stage becomes the WHAT of the second HOQ stage, while the HOW of the second HOQ stage becomes the WHAT of the third HOQ stage. The WHAT and HOW of each stage are described below.

- The first HOQ stage: megatrends (WHAT) and products (HOW)
- The second HOQ stage: products (WHAT) and primary level of technology classification (HOW)
- The third HOQ stage: primary level of technology classification (WHAT) and secondary level of technology classification (HOW)

Fig. 1 presents the proposed hierarchical QFD framework. In the first HOQ stage, we consider megatrends in society as representing customers' needs (WHAT) and attempt to prioritize future products/services (HOW) that reflect the opinions of both generalists and specialists based on the interrelationships and importance of the WHAT elements.

The second HOQ stage is composed of both future technological products/services (WHAT) and the primary level of technology classification (HOW). Here, the future products/services are identical to the HOW attributes of the first HOQ stage. In the second stage, interrelationships are constructed based on the frequency of triadic patent families (TPF) and U.S. patents (USP). TPF are published in the U.S. Patent and Trademark Office, the European Patent Office, and the Japan Patent Office.

The third HOQ stage is composed of the primary level of technology classification (WHAT) and a more detailed secondary level of technology classification (HOW). As in the second stage, the WHAT elements of the third HOQ stage are identical to the HOW elements of the second HOQ stage. In the third stage, as in the second stage, interrelationships are formed by the TPF and USP frequencies.

Table 1 shows the content of each HOQ stage. In the first stage, the importance of WHAT elements is assessed based on surveys with generalists and specialists. Importance (I) in the second and third HOQ stages, however, reflects the frequency with which TPF are cited by other patents. Urgency (U) is based on recent TPF frequency. The ripple effect (R) utilizes centrality information obtained from the patent network analysis. Priority (P) corresponds to the priority of each element in the HOW list in the previous HOQ stage. By multiplying I, U, R, and P, one can determine the relative importance of primary-level technologies. The next section provides detailed descriptions of the weight indicators, the interrelationships, a gap analysis, the convergence of iterated correlation analysis, and the reverse HOQ approach.

3.2. The first HOQ stage

In detail, the framework of the first HOQ stage is as follows. In the first stage (k:1), the interrelationship value (IR_{ij}^{k}) between a megatrend (i: a type of WHAT) regarding needs and a future product (j: a type of HOW) is determined through surveys with both generalists (G_{ij}) and specialists (S_{ij}).

The survey used to determine the interrelationship utilizes a five-point Likert scale. A larger value represents a stronger interrelationship, whereas a smaller value represents a weaker interrelationship. If a combination is thought to have no interrelationship at all, a value of 0 is given. In order to evaluate the importance of the elements on the WHAT list, a five-point Likert scale is again used. Therefore, the first HOQ stage, which is completed through surveys, enables us to prioritize the WHAT attributes.

Table 1
Content of each HOQ stage.

Stage	WHAT	HOW	Source of interrelationship	Weight variables
First-stage HOQ	Megatrend	Future technology product	Survey	Importance of WHAT
Second-stage HOQ	Future technology product	Primary level of technology classification	TPF and U.S. patent	Importance of WHAT (I) Urgency of WHAT (U) Ripple effect of WHAT (R) Priority of HOW in the first stage (P)
Third-stage HOQ	Primary level of technology classification	Secondary level of technology classification	TPF and U.S. patent	Importance of WHAT (I) Urgency of WHAT (U) Ripple effect of WHAT (R) Priority of HOW in the second stage (P)

With respect to notation, the first-stage interrelationship (IR_{ij}^1) is calculated as follows:

$$IR_{ij}^1 = S_{ij} \times \rho + G_{ij} \times (1-\rho), \quad \text{for } i = 1, 2, \ldots, n_1; j = 1, 2, \ldots, n_2; \tag{1}$$

S_{ij} the average interrelationship of the ith row and jth column in the specialists' group;
G_{ij} the average interrelationship of the ith row and jth column in the generalists' group; and
ρ weight of the specialists' group ($0 < \rho < 1$).

We assign the weights ρ for the specialists' group and (1 − ρ) for the generalists' group. By changing ρ, sensitivity analysis can be conducted. In addition, IR_{ij}^1 is standardized from 0 to 1 by replacing x with IR_{ij}^1, as follows:

$$ST(x) = \frac{x - Min(x)}{Max(x) - Min(x)}. \tag{2}$$

$ST(IR_{ij}^1)$ represents the standardized interrelationship of the ith row and the jth column.

After estimating the standardized interrelationship, the weight (W_i^1) of WHAT is estimated by the following equation:

$$W_i^1 = \left(SRI_i^1 \times \rho\right) + \left\{GRI_i^1 \times (1-\rho)\right\} \tag{3}$$

where

SRI_i^1 is the average relative importance of the ith row (WHAT) of specialists; and
GRI_i^1 is the average relative importance of the ith row (WHAT) of generalists obtained in stage 1.

Here, we use the standardized W_i^1 by replacing x in Eq. (2) with W_i^1.

The priority of each element j of HOWs (P_j^k, k = 1) in stage 1 is estimated as follows:

$$P_j^1 = \sum_{i=1}^{n_1} ST\left(IR_{ij}^1\right) \times ST\left(W_i^1\right), \text{for all } i, j \tag{4}$$

where $ST(RI_i)$ is the standardized relative importance of the ith row (WHAT) and the jth column (HOW).

We can complete the first HOQ stage framework and obtain the priority of each HOW element j. The priority of each element is used as the weight of the WHAT elements in the second stage.

3.3. The second and third HOQ stages

The interrelationships between row i and column j in the second (IR_{ij}^2) and third (IR_{ij}^3) HOQ stages are estimated by Eq. (5) using TPF and USP. We assign the weight of α_1 for TPF and (1 − α_1) for USP. One can perform a sensitivity analysis by changing the value of α_1 to check the robustness of the HOW prioritization. In addition, we can obtain the standardized IR_{ij}^k at stage k, as follows:

$$ST\left(IR_{ij}^k\right) = ST\left(TPF_{ij}^k\right) \times \alpha_1 + ST\left(USP_{ij}^k\right) \times (1-\alpha_1), \text{for all } i, j \tag{5}$$

where TPF represents triadic patent families; USP, U.S. patents;

α_1 weight of TPF ($0 < \alpha_1 < 1$);
k 2 or 3;
i the technology product when k = 2; the primary level of technology classification when k = 3; and
j the primary level of technology classification when k = 2 or the secondary level of technology classification when k = 3.

The weights (W_i^k) of the elements in the WHAT list in the second and third HOQ stages have the following four factors:

$$W_i^k = ST\left(I_i^k\right) \times ST\left(U_i^k\right) \times ST\left(R_i^k\right) \times ST\left(P_i^{k-1}\right) \tag{6}$$

I_i^k importance of the ith row at stage k;
U_i^k urgency of the ith row at stage k;
R_i^k ripple effect of the ith row at stage k; and
P_i^{k-1} priority of the ith row at stage k − 1.

The importance of a WHAT element (I_i^k) represents the fraction of the citation frequency for TPF i accounted for by other patents. We can calculate it as follows:

$$I_i^k = \frac{C_i^k}{\sum_{i=1}^{n} C_i^k} \tag{7}$$

where

C_i^k citation frequency
n the number of rows.

The urgency of a WHAT element (U_i^k) reflects TPF i's frequency. Let FY be the year of the first patent's occurrence, and let LY be the year of the last patent's occurrence:

$$YR = LY - FY;$$
$$F^1 = FY + \frac{YR}{3};$$
$$F^2 = F^1 + \frac{YR}{3}; \text{and}$$
$$F^3 = F^2 + \frac{YR}{3}.$$
$$\text{Then, } U_i^k = \left(UR_i^{k1} \times \alpha_2\right) + \left(UR_i^{k2} \times \alpha_3\right) + \left(UR_i^{k3} \times (1-\alpha_2-\alpha_3)\right) \tag{8}$$

where

LY year of the last patent's occurrence;
UR_i^{k1} TPF i's frequency from FY to F^1 for the kth stage HOQ;
UR_i^{k2} TPF i's frequency from F^1 to F^2 for the kth stage HOQ;
UR_i^{k3} TPF i's frequency from F^2 to F^3 for the kth stage HOQ;

α_2 weight of UR_i^{k1};
α_3 weight of UR_i^{k2}; and $0 \le \alpha_2 + \alpha_3 < 1$.

The ripple effect of a WHAT element is determined through patent network analysis, which uses patent data obtained by the co-word search method. Among the various measures of centrality in patent network analysis, we choose eigenvector centrality, a measure of the importance of a node; it represents each WHAT element in our research and assigns relative scores to all nodes in the network based on the following principle: connections to high-scoring nodes contribute more to the score of a node compared to an equal number of connections to low-scoring nodes. Eigenvector centrality is defined as the principal eigenvector of the adjacency matrix defining the network [6]. Using UNICET 6.0 software, this is estimated by the following equation:Let A_{lm} be a matrix of relationships. The centrality of node l is given by the following expression:

$$\lambda R_l^k = \sum_{m=l}^{N} A_{lm} R_l^k \tag{9}$$

where

λ a constant that is necessary for the equations to have a nonzero solution,
l row of the co-word matrix, and
m column of the co-word matrix.

Here, λ is the associated eigenvalue. The largest eigenvalue is usually the preferred one. In this paper, an eigenvector R of A is defined as eigenvector centrality, which is used as the ripple effect value [5].

The priority of a WHAT element (P_i^{k-1}) uses the priority identified in the previous HOQ stage.

The product of IR_{ij}^k and W_i^k yields the priorities of the second and third stages. We can obtain P_j^k, the priority of row j, as follows:

$$P_j^k = \sum_{i=1}^{n_1} ST\left(IR_{ij}^k\right) \times W_i^k \qquad k: 2 \text{ or } 3. \tag{10}$$

Through this equation, we can obtain in the third HOQ stage the prospective technology that is related to the results of the first and second HOQ stages. In addition, we can perform a sensitivity analysis by changing the values of ρ and α in Eqs. (1), (3), (5), and (8). If there are no large changes in priority among the top three technologies, these technologies are then defined as the emerging group in the third HOQ stage (EG_j^3).

Additionally, we can perform a gap analysis to confirm the difference between the percentage of international patents (U.S., Europe, and Japan) and the percentage of domestic patents in EG_j^3 by assuming that the majority of patents registered in the national patent office are granted to local people. Through this gap analysis, it is possible to assess the status of an emerging domestic group within the international arena. If the domestic group occupies a lower position relative to that of international groups, R&D should be focused on the emerging group. The gap analysis equation is

$$GAP_j^3 = \frac{IEG_j^3}{IP_j^3} - \frac{DEG_j^3}{DP_j^3}, \tag{11}$$

where

IP_j^3 the total number of patents at the secondary level of technology in three offices (USPTO, EPO, JPO);
IEG_j^3 the number of patents of emerging groups in three offices (USPTO, EPO, JPO);
DP_j^3 the total number of patents at the secondary level of technology registered in the domestic patent office; and
DEG_j^3 the number of patents of emerging groups in the domestic patent office.

In the next stage, we perform a CONCOR (CONvergence of iterated CORrelations) analysis. The CONCOR algorithm, which is a type of hierarchical clustering method, was proposed by Breiger et al. [7]. In this paper, we apply a CONCOR algorithm at the third HOQ stage. This procedure is described below.

(1) A CONCOR algorithm is conducted with a $m \times m$ co-occurrence matrix, which represents the co-occurrence frequency at the secondary level of technology at the third HOQ stage; this matrix is defined as M0.
(2) In Matrix M_0, columns will be treated as vector v_j, with $1 \le j \le m$. Vector v_j represents the co-occurrence frequency between secondary level technology j and other secondary level technologies from 1 to m (not including j). A CONCOR algorithm computes the $m \times m$ first-correlation matrix, M1, consisting of the Pearson correlation between v_j and $v_{j'}$.
(3) The algorithm then applies the same process iteratively to M1, thus obtaining M2, M3,…, etc. until the value of (j, j′) converges to 1 or −1. This value is used for clustering or blocking individual technologies. A CONCOR requires the setup of convergence tolerance (TOL). Convergence is accepted when all values are either less than −TOL or greater than +TOL. In general, the value of TOL is 0.999.
(4) In order to obtain more refined technology clusters, we repeat procedures (1), (2), and (3) with technologies having a value of either 1 or −1. The minimum size of a cluster is two entries because such a cluster cannot be split any further.

By reversing the approach of the proposed QFD, we can also suggest a business model based on an emerging group. Once EG_j^3 is identified in the previous Eq. (11), the emerging group of the first and second stage is calculated as follows:

$$EG_j^k = EG_i^{k+1} = \sum_{m=1}^{3} IR_{im}^{k+1} \times W_i^{k+1} \tag{12}$$

m emerging group of the prior step;
k 1 or 2;

Table 2
WHAT lists of first-stage HOQ.
Source: [14].

Major needs	Robotics-related customer demands (Voice of customer, VoC)
Fun	Freedom from loneliness
	Altruism and friendliness
	Creative learning ability through thinking capabilities
	More realistic expression of five senses
	Increased indirect experience
Convenience	Intelligent tools with learning ability
	Intelligent tools with thinking capability
	Convenient function without spatial restrictions
	Provision of comfortable and convenient environment
	Supplementation for the city's aging infrastructure
Safety	Healthy and abundant life
	Disaster prevention
	Guarantee of safety and security
	Clean and pleasant environment
	Technology to prevent, diagnose, and treat new diseases

i technology product when $k = 1$ or primary level of technology classification when $k = 2$; and
j primary level of technology classification when $k = 1$ or secondary level of technology classification when $k = 2$.

In addition, an important megatrend (IM) is derived from the following equation:

$$IM_i = \sum_{m=1}^{3} IR_{im}^{1} \times W_i^{1} \quad (13)$$

where m represents the emerging group of the first HOQ stage.

By combining the emerging group of each stage and the important megatrend, a business model can be identified.

Table 3
Robotics technology products.
Source: [23].

Service area	Product area	Product
Individual service	Home service	Cleaning robot
		Assistant robot
		Service robot
	Elderly/disabled	Support robot
	Fun/health support	Entertainment robot
		Pet robot
		Health care robot
	Education	Education robot
		Teaching robot
	Action support	Muscle strength robot
		Riding robot
Special service	Medical welfare	Medical robot
		Nursing robot
		Rehabilitation robot
	Safety and security	Guide-security robot
		Surveillance robot
		Rescue robot
	Special environments	Nuclear robot
		Underwater robot
		Space robot
		Construction robot

Table 4
Primary level of robotics technology classification.
Source: National IT Industry Promotion Agency in Korea, 2008.

Category of robotics technology	Primary level of robotics technology classification
Motion/mechanism technology	Mobility
	Mechanism
Recognition technology	Recognition technology
Intelligence/control technology	Intelligence technology
	Control technology
Component technology	Sensor technology
	Driving technology
	Robotics battery technology
System technology	S/W
	H/W
	N/W

Table 5
Secondary level of robotics technology classification.
Source: National IT Industry Promotion Agency in Korea, 2008.

Primary level of robotics technology classification	Secondary level of robotics technology classification
Mobility	Wheel drive
	Biped walking
	Movement to a staircase or dangerous area
Mechanism	Manipulator
	Robot arm
	Haptic device
	Robot eye or neck device
	Joint
Recognition	Visual recognition
	Voice recognition
	Cartography
	Self-localization
Intelligence	Environmental recognition
	Learning and inference
	Context/semantics
	Sensor fusion
Control	Control architecture
	Navigation control
	Walking control
	Manipulation
	Intelligence control
Sensor	Motion sensor or tactile sensor
	Visual sensor
	Auditory sensor
	Distance sensor
	Position sensor
	Biological signal sensor
	Olfactory sensor and taste sensor
Driving	Motor
	Artificial muscle
	Decelerator
Robot battery	Fuel cell
	Ion battery
	Solar fuel
SoC/fusion module	SoC (System on a Chip)
	Fusion module
S/W	Distributed object
	Development environment
H/W	Platform
	Valuation
N/W	N/W infrastructure device
	N/W-based real-time distributed control
	N/W-based robot server
	N/W-based distributed intelligence
	N/W-based service

Table 6
Weights of megatrends.

Megatrends		Specialist (ρ)	Generalist (1 − ρ)	Total
Category	Description			
Fun	Freedom from loneliness	2.8824	3.0303	2.9415
	Altruism and friendliness	3.2353	2.9697	3.1291
	Creative learning ability through thinking capabilities	3.8235	4.1563	3.9566
	More realistic expression of five senses	3.8824	3.2424	3.6264
	Increased indirect experience	3.6471	3.3333	3.5216
Convenience	Intelligent tools with learning ability	4.0000	4.0606	4.0242
	Intelligent tools with thinking capability	3.8235	3.6061	3.7365
	Convenient function without spatial restrictions	3.8824	3.8182	3.8567
	Provision of comfortable and convenient environment	3.5882	3.7273	3.6439
	Supplementation for the city's aging infrastructure	3.0588	3.3636	3.1807
Safety	Healthy and abundant life	4.4118	3.9697	4.2349
	Disaster prevention	3.6471	3.5758	3.6185
	Guarantee of safety and security	4.5882	4.4545	4.5348
	Clean and pleasant environment	3.2941	3.4848	3.3704
	Technology to prevent, diagnose, and treat new diseases	2.9412	3.0909	3.0011

4. Empirical study

In this section, we apply the proposed QFD to robotics technology. We establish the WHAT lists of the first HOQ stage using robotics-related megatrends that reflect future customer demands [14]. Robotics-related megatrends can be divided broadly into three categories: fun, convenience, and safety [14]. Detailed information on these trends is shown in Table 2. In addition, robotics services/products that meet these megatrends are classified according to the Government Blueprint for Integrating Technology by the Korea Institute of Science and Technology Information (KISTI) [23], as displayed in Table 3.

Table 4 shows the primary level of robotics technology classification based on the Robotics Technology Level Report by

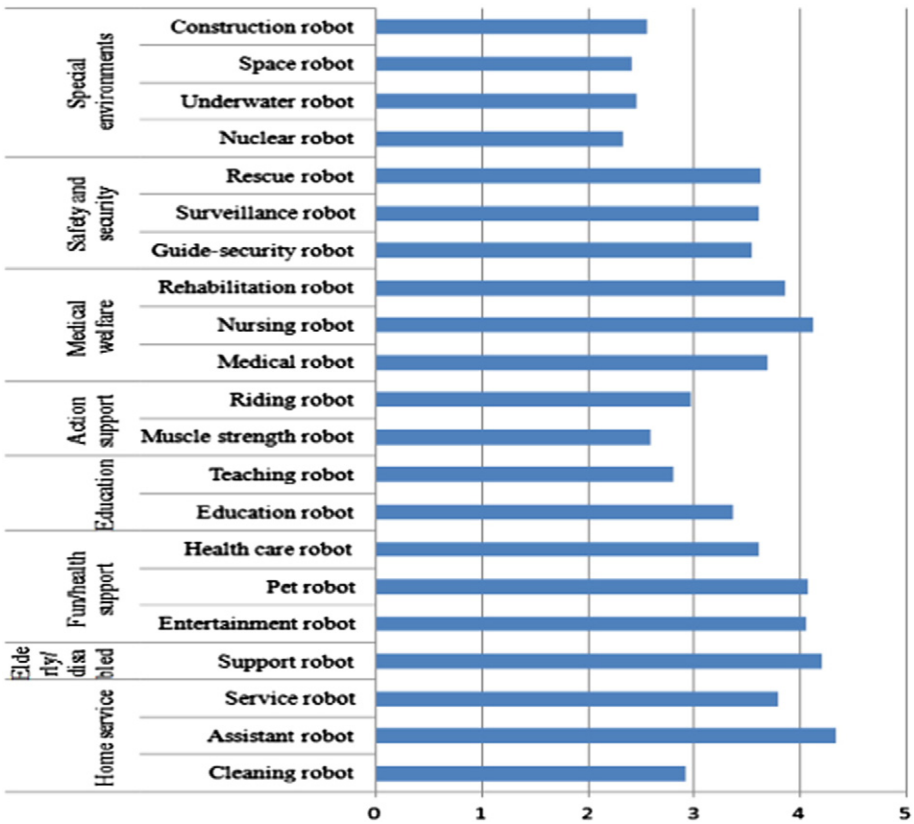

Fig. 2. Priority levels of first-stage HOQ.

the National IT Industry Promotion Agency, part of Korea's Ministry of Knowledge Economy [23]. In addition, the secondary level of technology classification is presented in Table 5. This hierarchical structure is used for each stage of the framework outlined in Section 3.

4.1. Analysis of QFD

We conducted a survey for the first HOQ stage. There were two survey groups, a specialist group composed of 17 robotics researchers and a generalist group composed of 34 graduate students in mechanical engineering and industrial engineering in Korea. The survey was conducted in July 2009. Both groups evaluated the interrelationships between WHAT and HOW elements and the relative importance of the WHAT elements. The average values of the interrelationships and the relative importance between the specialist and generalist groups were merged using the weight ρ.

We set ρ to 0.6 to assign more weight to specialists than to generalists. The resulting interrelationships between megatrends and robotics products and the weight of each megatrend are given in Appendix A and Table 6, respectively. In the sensitivity analysis, we considered various weights not only of ρ in the first HOQ stage but also of α_2, and α_3 in the second and third HOQ stages.

As shown in Table 6, 'guarantee of safety and security' was the most important megatrend to both specialists and generalists. The megatrend with the second-highest weight in the specialist group was also related to safety, but in the generalist group, the megatrend with the second-highest weight belonged to the fun category. The middle ranks for both specialists and generalists were related to the convenience category.

Fig. 2 shows the prioritization of the HOW list (robotics products) in the first HOQ stage, as estimated by Eq. (4). In addition, all information in the first HOQ stage is shown in Fig. 6 of Appendix A. The highest interrelationship value was found for the disaster prevention megatrend and the rescue robotics product, while the special environment robotics product had a lower interrelationship value compared to other areas.

Among the robotics technology products, assistant robots were found to be the most important product, followed by support robots and nursing robots. Based on this result, social welfare robotics is clearly an important group. The priority values of the first HOQ stage were used to set the weight factors after being standardized on a scale of 0 to 1 by Eq. (2).

In the second HOQ stage, we used patent data to identify interrelationships. The patent data were obtained from the SCOPUS website, and we collected TPF and U.S. patents from 1995 to 2009. Data collection was performed in August 2009. To collect the data, we used an advanced search query, entering two groups of words indicating a robotics product (second HOQ) or technology (second and third HOQ). In addition, factors used in our weight scheme were found on the SCOPUS website. When checking each patent, we can observe the publication year, title, inventor, identification number issued by the EPO, USPTO, or JPO, and number of citations. Interrelationships were derived by

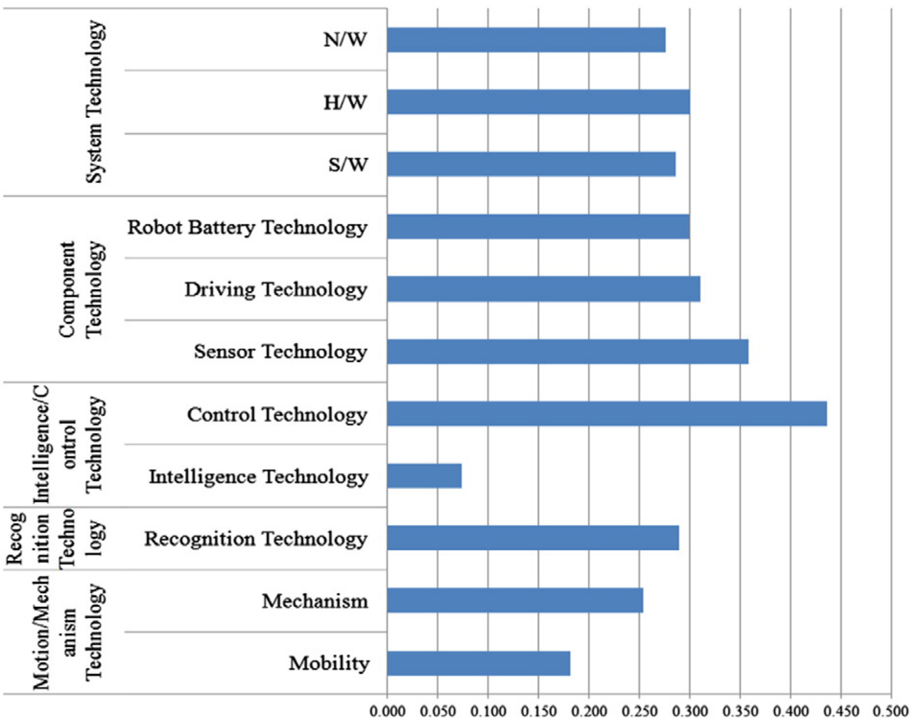

Fig. 3. Priority levels of second-stage HOQ.

Eq. (5), and the values were then standardized using Eq. (2). In Eq. (5), α_1 is assigned as 0.6. Therefore, the TPF weight is 0.6 and the USP weight is 0.4. All information on the second stage is shown in Fig. 7 of Appendix A. The highest interrelationship value was found for cleaning robots and control technology at the primary-level classification. We found no interrelationship value for nuclear robots or riding robots.

Among the four weights in Eq. (6), the lowest row is '0'. To calculate the priority of each technology, the lowest value is changed to half of the second-lowest value. In Eq. (8), we set α_2 to 0.2 and α_3 to 0.3.

The priorities of the second stage are presented in Fig. 3. The most important primary-level technology is control technology, followed by sensors, driving technology, H/W, and battery technology. With the exception of control technology, these most important technologies are related to component technology.

The third HOQ stage's framework is similar to that of the second HOQ stage. We use patent data in the third stage in the same manner. The patent data again were obtained from the SCOPUS website, and we collected TPF and USP data from 1995 to 2009. Because α_1 is set to 0.6, the weight of TPF is 0.6 and the weight of USP is 0.4. We used Eq. (6) to set the foresight weights (FW) of the HOQ. In Eq. (8), we set α_2 to 0.2, α_3 to 0.3, and $(1 - \alpha_2 - \alpha_3)$ to 0.5. All information regarding the third HOQ stage is shown in Figs. 8 and 9 of Appendix A. The highest interrelationship values were found for control technology at the primary-level classification and for position sensors at the secondary-level classification. In addition, we found no interrelationship value for self-localization or artificial muscle at the secondary-level classification.

The results of the third stage are presented in Figs. 4 and 5. Position sensor technology is the most important emerging secondary-level technology, followed by distance sensor technology and motor technology.

To validate our proposed approach, we compared the rankings of the secondary-level technologies obtained using the proposed framework using data up to 2009 with rankings obtained from a test dataset consisting of patents registered from 2009 to January 2014. This approach is based on assumption that patenting activities reflect market demand and are to protect their business area. The top three emerging technologies obtained from the proposed framework were found to be the same as the technology fields of the patents obtained from the test data. The Spearman's rank correlation coefficient of the rankings of 45 secondary technologies is

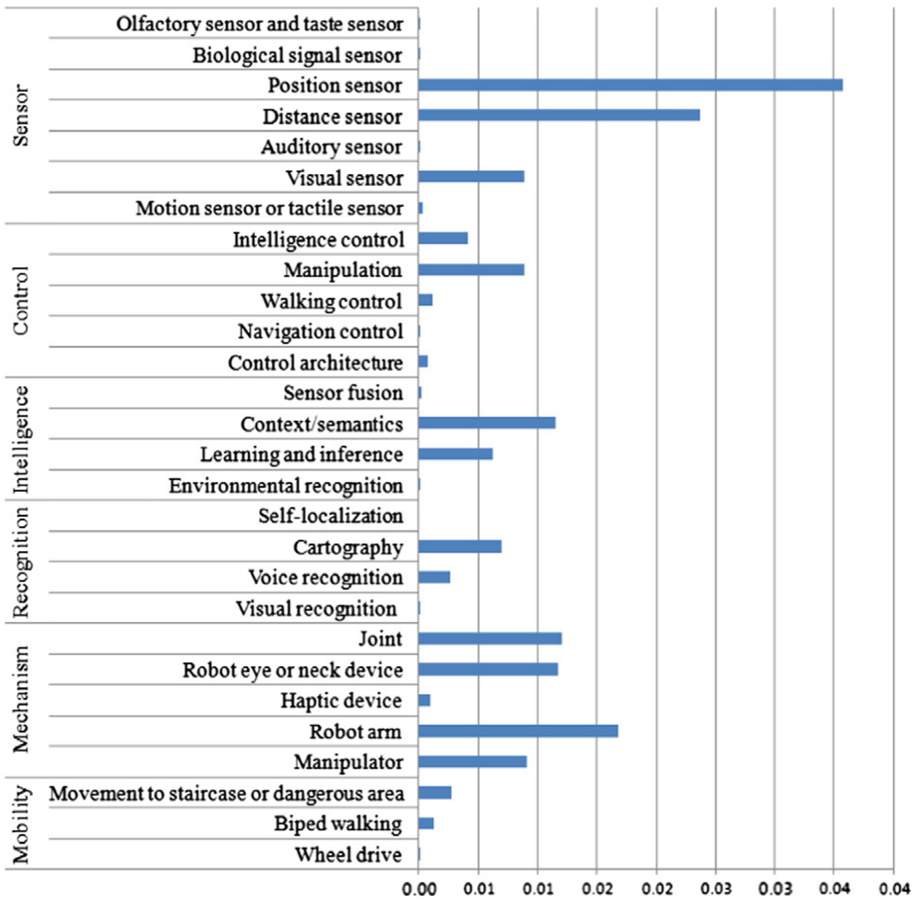

Fig. 4. Priority levels of third-stage HOQ (1).

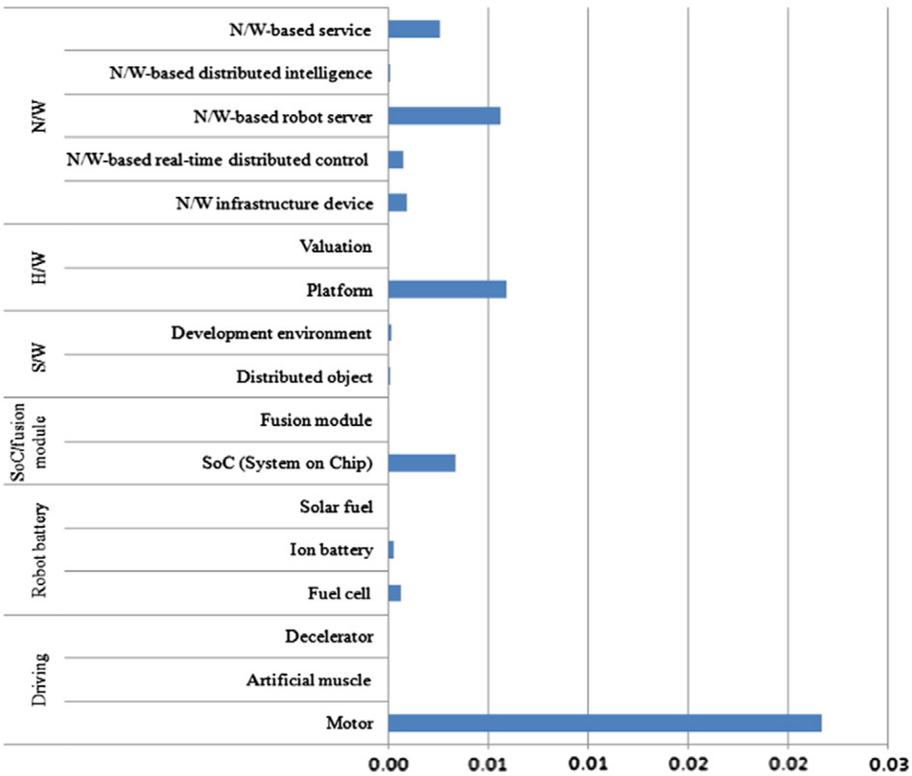

Fig. 5. Priority levels of third-stage HOQ (2).

0.65. For the top 50% technologies, the correlation is 0.74. This information validates our proposed framework.

4.2. Sensitivity analysis, gap analysis, and business model

We applied various weight values in Eqs. (1), (3), (5), and (8) for a sensitivity analysis. The results, shown in Appendix B, allow us to examine the priority values' reliability.

In the first stage, we changed ρ to 0.5 and 0.7 in Eqs. (1) and (3) and did not find a change in rankings. Next, we changed the α_1 value to 0.5 or 0.7 in Eq. (5) and did not observe many changes in the rankings of secondary-level technologies. In particular, the top 10% of secondary-level technology items did not change.

When ρ and α_1 are fixed at default scores of 0.6 and 0.6, α_2 and α_3 in Eq. (8) are changed in two cases. In the first case, α_2 and α_3 are changed to 0.33 and 0.33, and in the second case, α_2 and α_3 are changed to 0.1 and 0.2, respectively. As a result of the first case, we found many ranking changes. On the other hand, the second case did not result in many changes. However, the top three secondary technologies did not change in either case. Therefore, these three secondary-level robotics technologies are defined as an emerging group, and they have strong reliability.

We performed a gap analysis, and Table 7 shows the results. We confirm a significantly different ratio between international patent offices and the Korea Intellectual Property Office (KIPO). Therefore, Korean firms and inventors have to develop emerging technologies.

The three emerging technologies that were finally obtained from the third HOQ stage depended on the weight parameters used in all three HOQ stages. Therefore, it would be wise to identify clusters of technologies associated with these three emerging technologies, which can be insensitive to changes in those parameters. We conducted a CONCOR analysis for clustering. The sequence of clustering is displayed in Table 8 along with the cluster number. As shown in Table 8, position sensor and distance sensor technologies are grouped together, while motor technology is grouped with robot arm technology,

Table 7
Gap analysis results.

in the secondary technology	Number of patents in international offices (based on SCOPUS)	Ratio of patents in international offices	Number of patents in the domestic (Korean) office	Ratio of patents in the domestic office	Gap
Position sensor	25,187	0.28	600	0.09	0.19
Distance sensor	17,926	0.20	214	0.03	0.17
Motor	18,908	0.21	549	0.08	0.13
Total	90,011	1.00	6740	1	1.00

Table 8
CONCOR results (cluster number).

Secondary technology	Repetition						
	M7	M6	M5	M4	M3	M2	M1
Wheel drive	1	1	1	1	1	1	1
Decelerate							
Robot arm[a]	2	2					
Motor[a]							
Joint	3	3	3				
Manipulator mechanism							
Walking control or biped control	4	4	4				
Biped walking							
Stair or hazardous	5	5	5	5			
Eye or neck							
Manipulation and control	6						
Haptic	7	7					
Motion and sense of touch sensor	8						
Visual sensor							
Position sensor[a]	9	9	9				
Distance sensor[a]							
Ion battery	10	10					
Smell or taste sensor							
Sensor fusion	11	11	11	11	11		
Navigation control							
Auditory sensor	12	12	12				
Solar fuel	13	13	13	13			
Fuel cell							
Learning or inference	14	14	14	14	14	14	
Voice recognition	15	15	15	15	15	15	
Visual recognition							
Environment recognition	16						
Intelligence	17	17					
Mapping	18	18	18				
Context or semantics							
Control architecture	19	19					
Artificial muscle	20	20	20	20			
Localization recognition							
Fusion module	21	21	21				
SoC	22	22	22	22	22		
N/W infrastructure device							
S/W development environment	23	23	23				
H/W platform							
H/W evaluation	24	24					
S/W distributed object	25	25	25	25			
N/W service							
N/W robot server	26	26					
N/W real-time distributed control							
N/W distributed intelligence	27	27	27				
Biomedical signal sensor	28	28	28	28	28	28	

[a] Emerging secondary technologies.

at the seventh repetition. Therefore, robot arm is selected as an emerging secondary technology in the robotics industry.

Based on the emerging group of the third HOQ stage, we follow a reverse QFD framework using Eqs. (11) and (13). The result of the reverse QFD is shown in Table 9. In this table, we examine different ranks between the HOQ and the reverse HOQ in the first and second HOQ stages. In addition, the selected emerging groups are placed in relation to important megatrends.

In the third HOQ stage, distance sensors, position sensors, motors, and robot arm technologies are selected as the emerging group. In the second HOQ stage, control, driving, and H/W technologies are selected as the emerging group. In the first HOQ stage, cleaning, entertainment, and pet robots are selected as the emerging group. The megatrends that we identified as important are related to intelligent tools that have learning ability, promote a healthy and abundant life, and guarantee safety and security. Based on these emerging groups, we suggest three business models that are related to each important megatrend, as follows.

- Business Model I (Entertainment robot as an intelligent tool with learning ability): To commercialize entertainment robots successfully, the R&D plan must be focused on control and hardware technologies related to distance, position, motor, and robot arm technologies.
- Business Model II (Cleaning robot for a healthy life): The R&D plan must be focused on control and driving technologies related to distance, position, motor, and robot arm technologies.
- Business Model III (Pet robot for security): The R&D plan must be focused on control and driving technologies related to distance, position, motor, and robot arm technologies.

Table 9
Results of the reverse QFD for business models.

Category	Emerging group or important megatrend	Rank of HOQ	Rank of reverse HOQ
Third-stage HOQ	Distance sensor	2	2
	Position sensor	1	1
	Motor	3	3
	Robot arm	4	4
Second-stage HOQ	Control technology	1	3
	Driving technology	3	1
	H/W	5	2
First-stage HOQ	Cleaning robot	15	3
	Entertainment robot	5	1
	Pet robot	4	2
First-stage WHAT	Intelligent tools with learning ability	10	3
	Healthy and abundant life	12	2
	Guarantee of safety and security	9	1

5. Conclusion

R&D planning based on prospective technological forecasting has a crucial role in national economic and social development. In this paper, we proposed a quality function deployment (QFD) framework that can be used for the selection of prospective technologies. The framework has a hierarchical structure. In the first stage, using surveys, a “house of quality” (HOQ) is constructed to reflect the opinions of both generalists and specialists regarding the relationship between megatrends and technological products. In the second stage, using patent information, an HOQ is constructed through a combination of products and the primary level of technology classification. In the third stage, an HOQ is constructed through a combination of the primary and secondary levels of technology classification. In this study, the second and third HOQ stages were also used to determine the weight of each WHAT element, representing an element's importance, urgency, and ripple effect. The ripple effect is obtained by means of patent network analysis. In addition, we applied the prioritization of HOW elements in the previous stage to another weight variable.

We applied the proposed QFD framework to robotics technology and identified prospective products or technologies in each stage. In the first stage, assistant robots were found to be the most important product, followed by support robots and nursing robots. In the second stage, the most important middle-level technology is control technology, followed by sensors, driving technology, H/W, and battery technology. In the third stage, location sensor technology is the most important emerging technology, followed by distance sensors and motor technology. Based on the CONCOR analysis, we added robot arm technology to the emerging technologies. In addition, based on the reverse QFD approach, we suggested an emerging group in each HOQ stage along with three business models. In the proposed business models, control and hardware technology, distance and position sensors, and motor technology are important, while entertainment, cleaning, and pet robots are emerging as important applications of robotics.

Our proposed model makes several contributions compared with the previous studies. First, we tried to develop a framework for selecting emerging technology based on responses of specialist and generalist, reflecting the theory of attractive quality. In addition, we developed a hierarchical HOQ concept enabling one to set R&D priorities based on not only the mega trend of customers needs, but also the trend of patent in related technologies. In particular, we reflected citations, trends, and riffle effect of technology in our weighting scheme to identify emerging primary and secondary technologies. A validation test using Spearman's rank correlation indicated that our proposed framework has reliability.

Our study is expected to contribute to the establishment of strategies for effective R&D planning, and we hope that the proposed QFD framework can be modified to suit specific industries based on well-defined keyword searches and the hierarchical concept. Despite the many contributions of this paper, limitations also exist. We did not consider factors influencing the market environment, such as technological infrastructure, government support policies, and manufacturing firms' technological capabilities. In subsequent research, the importance of the market environment as it relates to products should be considered in the second HOQ stage. In addition, while we measured the urgency of technological trends based on number of registered patents over a specific period, a more appropriate approach would be to use a forecasting method such as a technological diffusion model. These topics are left for further research.

Acknowledgment

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M. J. Kim participated in the data analysis and the early part of this research as a graduate research assistant. We appreciate the discussions with Dr Y. J. Kim and B. S. Jo from ETRI, which motivated this research. The main content of this study is based on a Korean patent registered with the Korean Intellectual Patent Office, with registration number 10–1198123.

Appendix A. QFD map

				Individual Service											Special Service										
				Home service			Elderly/ disabled	Fun/health support			Education		Action support		Medical welfare			Safety and security			Special environments				
				Cleaning robot	Assistant robot	Service robot	Support robot	Entertainment robot	Pet robot	Health care robot	Education robot	Teaching robot	Muscle strength robot	Riding robot	Medical robot	Nursing robot	Rehabilitation robot	Guide-security robot	Surveillance robot	Rescue robot	Nuclear robot	Underwater robot	Space robot	Construction robot	Relative Importance
Mega Trend	Aging, Nuclear families, Changes in education, Etc	Fun	Freedom from loneliness	0.02	0.60	0.56	0.51	0.89	0.99	0.30	0.29	0.23	0.16	0.19	0.28	0.50	0.35	0.27	0.12	0.08	0.01	0.00	0.01	0.01	0.02
			Altruism and friendliness	0.19	0.76	0.52	0.61	0.74	0.88	0.49	0.45	0.34	0.19	0.16	0.45	0.65	0.59	0.43	0.38	0.35	0.02	0.01	0.02	0.04	0.12
			Creative learning ability through thinking capabilities	0.22	0.66	0.69	0.67	0.65	0.72	0.41	0.70	0.56	0.20	0.23	0.47	0.57	0.43	0.46	0.44	0.41	0.14	0.24	0.27	0.17	0.64
			More realistic expression of five senses	0.09	0.64	0.57	0.61	0.91	0.89	0.44	0.55	0.40	0.19	0.19	0.36	0.57	0.46	0.37	0.23	0.20	0.06	0.11	0.11	0.08	0.43
			Increased indirect experience	0.13	0.63	0.64	0.63	0.81	0.74	0.44	0.50	0.36	0.26	0.31	0.38	0.49	0.47	0.31	0.29	0.24	0.09	0.16	0.17	0.09	0.36
		Convenience	Intelligent tools with learning ability	0.34	0.69	0.68	0.65	0.64	0.75	0.53	0.74	0.57	0.37	0.30	0.50	0.62	0.56	0.52	0.51	0.50	0.25	0.34	0.45	0.25	0.68
			Intelligent tools with thinking capability	0.30	0.75	0.64	0.63	0.63	0.71	0.51	0.67	0.47	0.29	0.23	0.47	0.57	0.50	0.52	0.50	0.52	0.23	0.33	0.44	0.29	0.50
			Convenient function without spatial restrictions	0.74	0.73	0.58	0.69	0.57	0.58	0.57	0.54	0.44	0.42	0.58	0.52	0.59	0.54	0.59	0.63	0.67	0.43	0.54	0.54	0.57	0.57
			Provision of comfortable and convenient environment	0.61	0.71	0.58	0.77	0.66	0.63	0.58	0.46	0.37	0.47	0.70	0.59	0.71	0.71	0.47	0.44	0.39	0.21	0.23	0.25	0.29	0.44
			Supplementation for the city's aging infrastructure	0.48	0.54	0.50	0.56	0.39	0.29	0.41	0.32	0.29	0.30	0.56	0.48	0.49	0.48	0.60	0.60	0.59	0.33	0.23	0.20	0.57	0.15
		Safe	Healthy and abundant life	0.67	0.76	0.65	0.74	0.93	0.63	0.87	0.53	0.44	0.67	0.63	0.89	0.90	0.88	0.59	0.59	0.59	0.34	0.31	0.25	0.39	0.81
			Disaster prevention	0.17	0.32	0.36	0.39	0.12	0.19	0.22	0.09	0.10	0.14	0.34	0.28	0.30	0.25	0.70	0.91	1.00	0.63	0.56	0.46	0.59	0.42
			Guarantee of safety and security	0.65	0.72	0.55	0.68	0.52	0.60	0.73	0.50	0.54	0.67	0.77	0.83	0.78	0.83	0.77	0.85	0.87	0.86	0.76	0.68	0.84	1.00
			Clean and pleasant environment	0.96	0.65	0.43	0.60	0.37	0.39	0.42	0.28	0.26	0.32	0.48	0.45	0.51	0.49	0.43	0.45	0.42	0.38	0.37	0.28	0.44	0.27
			Technology to prevent, diagnose, and treat new diseases	0.12	0.24	0.20	0.29	0.13	0.22	0.81	0.16	0.07	0.35	0.19	0.94	0.97	0.79	0.21	0.31	0.28	0.08	0.07	0.10	0.09	0.04
			Priority	2.92	4.33	3.79	4.21	4.06	4.07	3.61	3.37	2.80	2.58	2.97	3.69	4.12	3.86	3.54	3.62	3.62	2.33	2.45	2.41	2.57	
			Rank	15	1	7	2	5	4	11	13	16	17	14	8	3	6	12	10	9	21	19	20	18	

Fig. 6. First-stage HOQ.

			Middle Level Technology															
			Motion/mechanism technology		Recognition technology	Intelligence/control technology		Component technology			System technology							
			Mobility	Mechanism	Recognition technology	Intelligence technology	Control technology	Sensor technology	Driving technology	Robotics battery technology	S/W	H/W	N/W	Importance	Urgent	Ripple effect	Priority of prior step	Foresight Weight
Individual service	Home service	Cleaning	0.653	0.307	0.247	0.015	1.000	0.893	0.746	0.420	0.341	0.240	0.182	0.3164	0.7653	0.4170	0.2919	0.0295
		Assistant	0.025	0.036	0.010	0.008	0.042	0.034	0.033	0.001	0.013	0.012	0.010	0.0282	0.2857	0.0043	1.0000	0.0000
		Service robot	0.036	0.070	0.102	0.012	0.154	0.128	0.081	0.067	0.066	0.046	0.077	0.0050	0.7857	0.4894	0.7296	0.0014
	Elderly/disabled	Support robot	0.056	0.039	0.025	0.000	0.049	0.031	0.028	0.009	0.025	0.018	0.026	0.0050	0.6429	0.2826	0.9396	0.0009
	Fun/health support	Entertainment robot	0.342	0.510	0.568	0.161	0.839	0.670	0.602	0.593	0.567	0.617	0.565	1.0000	0.5073	1.0000	0.8655	0.4390
		Pet robot	0.204	0.370	0.574	0.055	0.675	0.660	0.426	0.480	0.475	0.398	0.396	0.1808	0.3770	0.9554	0.8692	0.0566
		Health care robot	0.001	0.004	0.001	0.001	0.005	0.005	0.005	0.001	0.005	0.005	0.001	0.0050	0.2000	0.0011	0.6393	0.0000
	Education	Education	0.000	0.006	0.000	0.000	0.006	0.004	0.004	0.000	0.005	0.004	0.001	0.0050	0.2000	0.0645	0.5200	0.0000
		Teaching	0.077	0.055	0.027	0.001	0.046	0.056	0.052	0.008	0.095	0.038	0.006	0.1695	0.2857	0.0011	0.2343	0.0000
	Action support	Muscle strength robot	0.082	0.337	0.156	0.014	0.394	0.131	0.130	0.052	0.340	0.055	0.140	0.0050	0.5455	0.1290	0.1249	0.0000
		Riding robot	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0050	0.2000	0.0011	0.3212	0.0000
Special service	Medical welfare	Medical robot	0.051	0.061	0.006	0.000	0.110	0.068	0.063	0.004	0.025	0.008	0.039	0.0050	1.0000	0.0022	0.6789	0.0000
		Nursing robot	0.000	0.010	0.001	0.001	0.012	0.013	0.008	0.000	0.000	0.001	0.003	0.0050	0.2000	0.0539	0.8939	0.0000
		Rehabilitation robot	0.013	0.022	0.014	0.004	0.027	0.019	0.021	0.010	0.017	0.021	0.014	0.0050	0.2000	0.0248	0.7651	0.0000
	Safety and security	Guide-security robot	0.041	0.080	0.076	0.023	0.129	0.095	0.090	0.057	0.086	0.044	0.077	0.0050	0.1429	0.5452	0.6040	0.0002
		Surveillance robot	0.003	0.009	0.010	0.003	0.014	0.014	0.009	0.008	0.004	0.012	0.010	0.0050	0.2000	0.0047	0.6425	0.0000
		Rescue robot	0.003	0.015	0.006	0.004	0.019	0.018	0.010	0.008	0.009	0.005	0.015	0.0050	0.2000	0.0176	0.6452	0.0000
	Special environments	Nuclear robot	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0050	0.2000	0.0011	0.0192	0.0000
		Underwater robot	0.033	0.050	0.017	0.014	0.063	0.027	0.019	0.015	0.017	0.021	0.019	0.0113	0.2381	0.0178	0.0604	0.0000
		Space robot	0.048	0.037	0.030	0.006	0.084	0.026	0.061	0.003	0.038	0.008	0.032	0.0339	0.7143	0.0011	0.0385	0.0000
		Construction robot	0.001	0.030	0.003	0.000	0.010	0.005	0.005	0.030	0.005	0.004	0.000	0.0113	0.2857	0.0442	0.1160	0.0000
		Priority	0.181	0.254	0.289	0.074	0.436	0.358	0.310	0.300	0.28590492	0.30045821	0.27595392					
		Rank	10	9	6	11	1	2	3	5	7	4	8					

Fig. 7. Second-stage HOQ.

			Secondary Level Technology																							
			Mobility			Mechanism					Recognition				Intelligence				Control							
			Wheel drive	Biped walking	Movement to staircase or dangerous area	Manipulator	Robot arm	Haptic device	Robot eye or neck device	Joint	Visual recognition	Voice recognition	Cartography	Self-localization	Environmental recognition	Learning and inference	Context/semantics	Sensor fusion	Control architecture	Navigation control	Walking control	Manipulation	Intelligence control	Motion sensor or tactile sensor	Visual sensor	Auditory sensor
Middle Level Technology	Motion/mechanism technology	Mobility	0.0032	0.0000	0.0059	0.0141	0.0269	0.0024	0.0205	0.0354	0.0000	0.0007	0.0136	0.0000	0.0000	0.0063	0.0209	0.0001	0.0010	0.0001	0.0000	0.0182	0.0041	0.0016	0.0196	0.0000
		Mechanism	0.0000	0.0174	0.0455	0.2037	0.5555	0.0192	0.2828	0.6302	0.0017	0.0318	0.1409	0.0000	0.0045	0.1120	0.2486	0.0022	0.0123	0.0004	0.0207	0.1287	0.0683	0.0039	0.1881	0.0000
	Recognition technology	Recognition technology	0.0000	0.0043	0.0228	0.0325	0.0786	0.0076	0.1574	0.1460	0.0020	0.0663	0.1010	0.0000	0.0103	0.1312	0.1402	0.0025	0.0012	0.0004	0.0060	0.1006	0.0871	0.0019	0.1578	0.0000
	Intelligence/control technology	Intelligence technology	0.0000	0.0001	0.0068	0.0099	0.0089	0.0036	0.0497	0.0453	0.0002	0.0125	0.0298	0.0000	0.0030	0.0710	0.0584	0.0022	0.0023	0.0002	0.0059	0.0366	0.1545	0.0002	0.0817	0.0000
		Control technology	0.0000	0.0389	0.0824	0.3353	0.2542	0.0324	0.1714	0.2573	0.0020	0.0629	0.1327	0.0000	0.0005	0.1848	0.2133	0.0086	0.0160	0.0023	0.0336	0.1609	0.1475	0.0070	0.2128	0.0000
	Component technology	Sensor technology	0.0000	0.0360	0.0441	0.0742	0.1063	0.0185	0.0595	0.0899	0.0019	0.0416	0.0374	0.0000	0.0074	0.0289	0.0537	0.0101	0.0126	0.0007	0.0293	0.0471	0.0568	0.0068	0.1278	0.0044
		Driving technology	0.0000	0.0288	0.0575	0.2069	0.4063	0.0163	0.2805	0.2090	0.0003	0.0513	0.1469	0.0000	0.0017	0.1228	0.2514	0.0038	0.0138	0.0006	0.0248	0.2152	0.0697	0.0066	0.1319	0.0000
		Robotics battery technology	0.0000	0.0158	0.0136	0.0290	0.0580	0.0012	0.0917	0.1547	0.0001	0.0341	0.0295	0.0000	0.0017	0.0608	0.0560	0.0020	0.0017	0.0005	0.0161	0.0290	0.0283	0.0016	0.1075	0.0000
	System technology	S/W	0.0000	0.0016	0.0349	0.0962	0.1929	0.0149	0.1734	0.2323	0.0018	0.0459	0.1612	0.0000	0.0015	0.1469	0.2545	0.0056	0.0138	0.0006	0.0006	0.1578	0.0871	0.0039	0.2445	0.0000
		H/W	0.0000	0.0002	0.0204	0.0504	0.1119	0.0127	0.1119	0.1539	0.0003	0.0398	0.1245	0.0000	0.0002	0.1096	0.1862	0.0039	0.0110	0.0005	0.0076	0.1047	0.0707	0.0051	0.2177	0.0000
		N/W	0.0000	0.0044	0.0201	0.0537	0.0807	0.0063	0.1150	0.0955	0.0304	0.0081	0.0870	0.0000	0.0002	0.0943	0.1289	0.0026	0.0077	0.0020	0.0045	0.0886	0.0770	0.0035	0.2253	0.0000
		Priority	0.00	0.00	0.00	0.01	0.02	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00
		Rank	42	20	17	8	4	23	6	5	34	18	11	44	31	12	7	29	25	36	21	10	15	27	9	38

Fig. 8. Third-stage HOQ (1).

Sensor				Driving			Robot battery			SoC/fusion module		S/W		H/W		N/W									
Distance sensor	Position sensor	Biological signal sensor	Olfactory sensor and taste sensor	Motor	Artificial muscle	Decelerator	Fuel cell	Ion battery	Solar fuel	SoC (System on Chip)	Fusion module	Distributed object	Development environment	Platform	Valuation	N/W infrastructure device	N/W-based real-time distributed control	N/W-based robot server	N/W-based distributed intelligence	N/W-based service	Importance	Urgent	Ripple effect	Priority of prior step	Foresight Weight
0.0798	0.1086	0.0000	0.0000	0.0551	0.0000	0.0003	0.0010	0.0016	0.0000	0.0087	0.0000	0.0001	0.0001	0.0203	0.0001	0.0026	0.0030	0.0098	0.0000	0.0084	0.0500	1.0000	0.0199	0.2953	0.0003
0.3175	0.5514	0.0001	0.0001	0.4426	0.0000	0.0000	0.0113	0.0048	0.0000	0.0699	0.0015	0.0021	0.0000	0.2063	0.0000	0.0115	0.0131	0.0738	0.0023	0.0298	1.0000	0.0552	0.1400	0.4962	0.0038
0.3165	0.4718	0.0062	0.0000	0.1678	0.0000	0.0000	0.0010	0.0003	0.0020	0.0724	0.0001	0.0003	0.0004	0.0615	0.0009	0.0086	0.0076	0.0547	0.0023	0.0270	0.5272	0.0622	0.0627	0.5940	0.0012
0.0952	0.1294	0.0000	0.0000	0.0493	0.0000	0.0000	0.0004	0.0002	0.0000	0.0130	0.0000	0.0017	0.0001	0.0216	0.0005	0.0045	0.0032	0.0226	0.0023	0.0122	0.1053	0.1952	0.0207	0.1476	0.0001
0.6632	0.9568	0.0001	0.0001	0.4788	0.0000	0.0000	0.0223	0.0081	0.0000	0.0629	0.0015	0.0022	0.0035	0.1626	0.0026	0.0246	0.0200	0.0967	0.0023	0.0308	0.2110	0.1000	0.1769	1.0000	0.0037
0.2307	0.3425	0.0001	0.0001	0.1772	0.0000	0.0000	0.0128	0.0079	0.0000	0.0482	0.0015	0.0002	0.0019	0.0740	0.0004	0.0180	0.0132	0.0282	0.0000	0.0085	0.1543	0.4832	0.1233	0.7843	0.0072
0.4449	0.6805	0.0001	0.0000	0.4586	0.0000	0.0000	0.0125	0.0059	0.0000	0.0680	0.0001	0.0019	0.0034	0.0966	0.0006	0.0149	0.0137	0.1294	0.0023	0.0660	0.5874	0.5442	0.1342	0.6525	0.0280
0.2632	0.3855	0.0000	0.0000	0.2638	0.0000	0.0000	0.0169	0.0081	0.0000	0.0092	0.0014	0.0001	0.0001	0.0257	0.0002	0.0063	0.0054	0.0377	0.0000	0.0205	0.3751	0.1795	0.0358	0.6239	0.0015
0.5250	0.7694	0.0000	0.0000	0.3828	0.0000	0.0000	0.0023	0.0018	0.0000	0.0599	0.0015	0.0021	0.0034	0.1026	0.0011	0.0198	0.0095	0.0957	0.0000	0.0140	0.9206	0.0518	0.1180	0.5846	0.0033
0.4559	0.6569	0.0000	0.0000	0.3145	0.0000	0.0000	0.0030	0.0031	0.0000	0.0414	0.0015	0.0020	0.0034	0.1137	0.0008	0.0247	0.0109	0.1256	0.0023	0.0539	0.7417	0.1519	0.0850	0.6248	0.0060
0.4311	0.6600	0.0001	0.0000	0.2615	0.0000	0.0000	0.0032	0.0019	0.0000	0.0482	0.0001	0.0022	0.0034	0.1102	0.0025	0.0221	0.0130	0.0000	0.0000	0.0102	0.5000	0.0588	0.0835	0.5571	0.0014
0.02	0.04	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00					
2	1	39	41	3	44	43	26	28	40	16	37	33	30	13	35	22	24	14	32	19					

Fig. 9. Third-stage HOQ (2).

Appendix B. Sensitivity analysis

Table 10
Sensitivity analysis of changing ρ.

Secondary level of technology classification	Rank (0.6:0.4)	Rank (0.5:0.5)	Rank (0.7:0.3)
Wheel drive	42	42	42
Biped walking	20	20	20
Movement to a staircase or dangerous area	17	17	17
Manipulator	8	8	8
Robot arm	4	4	4
Haptic device	23	23	23
Robot eye or neck device	6	5	5
Joint	5	7	7
Visual recognition	34	34	34
Voice recognition	18	19	19
Cartography	11	11	11
Self-localization	44	44	44
Environmental recognition	31	31	31
Learning and inference	12	12	12
Context/semantics	7	6	6
Sensor fusion	29	29	29
Control architecture	25	25	25
Navigation control	36	36	36
Walking control	21	21	21
Manipulation	10	9	9
Intelligence control	15	15	15
Motion sensor or tactile sensor	27	27	27
Visual sensor	9	10	10
Auditory sensor	38	38	38
Distance sensor	2	2	2
Position sensor	1	1	1
Biological signal sensor	39	39	39
Olfactory sensor and taste sensor	41	41	41
Motor	3	3	3
Artificial muscle	44	44	44
Decelerator	43	43	43
Fuel cell	26	26	26
Ion battery	28	28	28
Solar fuel	40	40	40
SoC	16	16	16
Fusion module	37	37	37
Distributed object	33	33	33
Development environment	30	30	30
Platform	13	14	14
Valuation	35	35	35
N/W infrastructure device	22	22	22
N/W-based real-time distributed control	24	24	24
N/W-based robot server	14	13	13
N/W-based distributed intelligence	32	32	32
N/W-based service	19	18	18

Table 11
Sensitivity analysis of changing α_1.

Secondary level of technology classification	Rank (0.6:0.4)	Rank (0.5:0.5)	Rank (0.7:0.3)
Wheel drive	42	42	42
Biped walking	20	20	20
Movement to a staircase or dangerous area	17	18	17
Manipulator	8	10	8
Robot arm	4	4	4
Haptic device	23	23	23
Robot eye or neck device	6	6	5
Joint	5	7	7
Visual recognition	34	34	34
Voice recognition	18	19	18
Cartography	11	11	11
Self-localization	44	44	44
Environmental recognition	31	31	31
Learning and inference	12	13	12

(continued on next page)

Table 11 (*continued*)

Secondary level of technology classification	Rank (0.6:0.4)	Rank (0.5:0.5)	Rank (0.7:0.3)
Context/semantics	7	5	6
Sensor fusion	29	29	29
Control architecture	25	25	25
Navigation control	36	36	37
Walking control	21	21	21
Manipulation	10	9	9
Intelligence control	15	15	15
Motion sensor or tactile sensor	27	27	27
Visual sensor	9	8	10
Auditory sensor	38	38	38
Distance sensor	2	2	2
Position sensor	1	1	1
Biological signal sensor	39	39	39
Olfactory sensor and taste sensor	41	40	41
Motor	3	3	3
Artificial muscle	44	44	44
Decelerator	43	43	43
Fuel cell	26	26	26
Ion battery	28	28	28
Solar fuel	40	41	40
SoC	16	17	16
Fusion module	37	37	35
Distributed object	33	33	33
Development environment	30	30	30
Platform	13	12	14
Valuation	35	35	36
N/W infrastructure device	22	22	22
N/W-based real-time distributed control	24	24	24
N/W-based robot server	14	14	13
N/W-based distributed intelligence	32	32	32
N/W-based service	19	16	19

Table 12
Sensitivity analysis of changing α_2, α_3.

Secondary level of technology classification	Rank (0.2:0.3:0.5)	Rank (0.33:0.33:0.33)	Rank (0.1:0.2:0.7)
Wheel drive	42	42	42
Biped walking	20	24	20
Movement to a staircase or dangerous area	17	18	17
Manipulator	8	13	8
Robot arm	4	7	4
Haptic device	23	21	23
Robot eye or neck device	6	8	6
Joint	5	4	5
Visual recognition	34	32	34
Voice recognition	18	17	18
Cartography	11	10	11
Self-localization	44	44	44
Environmental recognition	31	29	31
Learning and inference	12	11	12
Context/semantics	7	5	7
Sensor fusion	29	26	29
Control architecture	25	22	25
Navigation control	36	38	36
Walking control	21	25	21
Manipulation	10	9	10
Intelligence control	15	15	15
Motion sensor or tactile sensor	27	28	27
Visual sensor	9	6	9
Auditory sensor	38	40	38
Distance sensor	2	2	2
Position sensor	1	1	1
Biological signal sensor	39	34	39
Olfactory sensor and taste sensor	41	41	41
Motor	3	3	3
Artificial muscle	44	44	44
Decelerator	43	43	43

Table 12 (*continued*)

Secondary level of technology classification	Rank (0.2:0.3:0.5)	Rank (0.33:0.33:0.33)	Rank (0.1:0.2:0.7)
Fuel cell	26	27	26
Ion battery	28	31	28
Solar fuel	40	39	40
SoC	16	16	16
Fusion module	37	35	37
Distributed object	33	33	33
Development environment	30	30	30
Platform	13	12	13
Valuation	35	36	35
N/W infrastructure device	22	20	22
N/W-based real-time distributed control	24	23	24
N/W-based robot server	14	14	14
N/W-based distributed intelligence	32	37	32
N/W-based service	19	19	19

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Yonghan Ju is a graduate student at the Department of Information and Industrial Engineering, Yonsei University. His research area is IP management, quality engineering and customer relation management. Address: e-mail: juyonghan@yonsei.ac.kr.

So Young Sohn is a Professor of Industrial Engineering at Yonsei University in Korea. Her research areas include engineering education, technology management, marketing, quality and reliability engineering. Detailed information about her teaching and research areas can be found at http://isl.yonsei.ac.kr.