A Structured Approach to Function and Affordance Based Decomposition for Complex Multi-disciplinary Systems of Smart Product

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ABSTRACT

A smart product integrates product's physical and information representations in a unique entity forming a complex system to interact with users and environments. As its autonomic behavior, a smart product's unintended behaviors may occur during its application. It is therefore different from a general product in design to decide the function structure of smart products. This paper proposes a structure modeling method based on product function and affordance. It uses concepts of the function as a basis of the intention realm in smart product design and affordance as the basis of physical realm in the perspective of environments for the smart product. The function structure is expanded from the physical product to entire system to meet customer's demand. The method is applied in the development of a walking assistive robotic suit system.

Keywords: Smart product, System decomposition, Function modeling, Affordance, Multi-disciplinary system
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1 INTRODUCTION

The emergence of smart products offers the potential to meet user needs intelligently and appropriately. According to the definition of Smart Products Consortium [25], a smart product is an autonomous object that is designed for self-organized embedding into different environments in the course of its life cycle to allow a natural interaction of the product and human. Smart products are able to proactively approach users by using sensing input and output capabilities of the environment for the self-, situational-, and context-aware. The related knowledge and functionality can be shared and distributed among multiple smart products and updated over time. Therefore, a smart product is the close integration of the product's physical and information representation, enhancing with environments as a unique entity. A smart product has a unique identifier to effectively communicate with its environment and retained or stored data about itself. It can show its characteristics and operating requirements in some languages, and participate or make decisions on its behavior [4, 21].

Therefore, the conceptual design of a smart product is different from a general product [16, 29]. A smart product is a complex system to interact with people and environment. As its autonomic behavior, its unintended behaviors may occur with the environment and user. Since construction of the product function structure is an important task in the conceptual design phase [3], a systematic method is necessary to form the function structure of smart products.

Pahl and Beitz proposed a systematic theory of the product function structure [24]. Construction of the function structure is based on definition of a system boundary of the product according to customer's requirement. The input and output of the system boundary are identified as flows in three categories: material flow, energy flow and information flow. For a function to carry the flow transformation, all the input and output flows are analyzed across the system boundary to obtain tasks of flow converting, or the overall function of the product. This process is then repeated at the subsystem level, from the overall function to several sub-functions. The process is refined gradually until sub-functions of the product can intuitively correspond to the existing solution. At this point, all the material, energy, information flows with the decomposition function form a network diagram, called the function structure model. A detail procedure of function structure modeling method is as follows.

(1) Identifying flows that correspond to customer’s needs: All the material flow, energy flow and information flow related to customer's needs are searched.

(2) Generating a black box model: A desired product is considered as a black box, the overall product function is formed from input to output flows in a moving message phrase in the black box.

(3) Drawing a function chain for each input flow: An input flow is selected to imagine the flow from input to leave the product system boundary. The whole process of the various transformations is presented by the flow and sub-functions of the function chain.

(4) Combining function chains into a mesh function structure: According to the interaction of function chains, all the function chains are aggregated into a function structure model. This process sometimes requires the addition of auxiliary sub-functions.

(5) Verifying function structure model comparing with customer requirements: The existing methods and tools of function structure used for the general product are checked to be applicable for the high autonomy and close environmental interactivity of the smart products.

As the concept ambiguity of the function may lead to ambiguous in the product system level of function structure modeling [11], it is necessary to clarify the basic concept of function as a key to the development of function structure modeling method for smart products. Product design is a process that maps the design intention into real world [1]. If the function is only considered from the perspective of a personal user, it will not be able to cover the entire need of the design activity of a smart product.

Therefore, this paper uses the concept of function as a basis of the intention realm in design to introduce a concept of affordance as the basis of physical realm to consider the perspective of environment for the smart product. Following contents of the paper will firstly review the concept of function, the method of function structure modeling is then extended with the co-use of function and affordance. After then, a complete function structure modeling method is proposed and verified in the development of a smart product. Conclusions and further work are discussed at the end of the paper.

2 RELATED RESEARCH

There are various views of the function in product design. For example, Pahl and Beitz [24] considered function as the transition between input and output material, energy and information flows. The function-behavior-structure model developed by Gero [14] defines function as an intermediate between the purpose of human and the behavior of a system. Umeda and Tomiyama [26] used function as a concept in the intent field that corresponds to the behavior in the physical realm.

Erden [13] reviewed more than 80 concepts of function in product design research and enterprise practice applications, and summed up 18 different meanings. Vermass furtherly summed meanings of function in the design theory into three basic contents: behavior, effect, and purpose [28]. Vermaas argued that these three function concepts have their own role in the engineering practice, the best way is to accept different meanings of the function concept [27]. However, an ambiguity of the function concept will lead to difficulty of the design knowledge exchange and method promotion. The establishment of a clear and unified concept of function is necessary for the establishment and application of a realm system.

Chandrasekaran and Josephson named behavior meaning function as Device-Centric Function, and named the effect meaning function as Environment-Centric Function [5]. The device refers to a physical product designed in a general sense. The environment is not a natural environment but the scene where the device works. From this point of view, Chandrasekaran and Josephson focus on the boundaries of the physical product. The device-centric function focuses on the product boundary and sees the function as a property or behavior of the product. Environment-centric function focuses on the outside boundary of the product and regards the function as the effect of the product on certain parts of the environment. They also recognized the existence of the behavioral meaning function and effect meaning function considering the both importance in different stages of design activities. Designers always think about design results of effect meaning function at first, then focus on the product itself to find the solution of the behavioral meaning function. The review, from the perspective of the system boundary, of the different meanings of function is of great significance for us to differentiate and unify the different meanings.

On the one hand, the different meanings of function in their research are not unified, causing confusion in thought and difficulties in communication. The concept of function requires a single meaning, but also needs a certain way to cover different roles of different meanings at different design stages. Although the problem was considered from perspective of the system boundary, they did not strictly and carefully follow this concern. Environment-centric function is the effect of a product on other objects or people, not limited to product only. If a product does not change, but properties or abilities of the object change, the effect will change as well. For example, without paper, the effect meaning function of the pen function described as to make the visible mark on the paper would be meaningless. Thus, the effect meaning function of a product is not only a concept of the product itself, but also the intentional behavior of the system consisting of the product and its objects. Thus, the effect meaning function of a product essentially refers to the behavioral meaning function of a higher-level system of the product and its objects.

In summary, the study of an object needs to define the object system boundary firstly. The object boundary of the effect meaning function and purpose meaning function is beyond the product itself. Therefore, the concept of function is unified in the only connotation - behavioral meaning function. The different meanings of function at different stages of design process that Vermaas mentioned in fact are at different system levels in a nested system. From the perspective of different levels of nested systems [9, 10], the meanings of function could be unified into the behavioral meaning function of different levels of a system. In a design process, the function is not just the property of the product itself. At different stages of a design process, carrying agents of the function concept is the system object of different boundaries at different levels: purpose level, effect level and behavior level.

The clarification of the concept of function does not mean that the complete theoretical basis of the function structure for a smart product has been built. Design activities of a smart product are a process that maps from the human intent to real world, involving both intent and physical realms. But the basic concept of physical realm is to work together with function to constitute the complete concept basis of design. The concept of affordance, which was introduced from ecological psychology to the design field, has brought hope to solve this problem.

The concept of affordance was created by Gibson to describe the environment support for the animal [15]. Chemero added that affordance is an interaction between animal and environment [6]. Dotov summarized it as animal's behavior possibility afforded by its environment [12]. The concept of affordance was introduced by Norman into product design [22]. The behavior possibility is provided to people by a product as the physical affordance. The individual behavior is expressed in its environment perceived by users as the perceived affordance [23]. Miaer and Fadel extended the subject of affordance to non-living devices, the affordance is defined as a potential behavior that can occur between two subsystems [17-19]. Recently, the compatibility of function and affordance as a base of design have been found by more and more researchers [2, 20, 30]. Research has been conducted for the product life cycle design based on the function and affordance requirements [8]. Both function design and affordance based design were applied to construct a framework of product design [7]. A matrix product clustering method was also proposed based on the function and affordance requirement [31].

3 FUNCTION STRUCTURE MODELING METHOD

Based on the concept of function and affordance, this paper proposes a function structure modeling method. From two dimensions of the function and affordance, the thinking process of the function structure of a smart product is decomposed. First, it starts from the function dimension backward thinking what people want to happen, to get the backward function structure modeling. Then it looks at the affordance dimension to see what may happen under the environmental support to get the forward function structure modeling. Through these two processes, the decoupling of complexity can be achieved. The proposed function structure modeling method for smart products based on function and affordance can be summarized in following steps.

1). Determining the overall function of a purpose level system

User's abilities and environment changes are identified to determine the purpose of a smart product to bridge the gap between user's actual status and expected future status. All action objects are represented in the information flow, material flow and energy flow. The overall function of a purpose level system converts all input flows into intended output flows, which can be represented as follows.

$$Fp = f[Flow(i) \rightarrow Flow(o)] \quad (1)$$

Where *Fp* is an overall function of the purpose level system, *Flow(i)* is the input flow, *Flow(o)* is the output flow, and *f(x)* represents a flow conversion mode.

2). Decomposing the overall function of purpose level system into overall functions of different carrying agents
There are three kinds of function carrying agents in smart product design: the product to be designed, related objects in the working environment and human activities. The conversion work from *Flow(i)* to *Flow(o)* of all action objects corresponding to the total function of purpose level system should be distributed among the three carrying agents. Firstly, it is to determine what is the natural items or existing related products associated with the object, and what kind of state transition of flows they can carry. Then, the remainder of the flow state transition will be allocated between the designed smart product and human activity. An allocation process of the overall function into the three function carrying agents in the purpose level system are as follows.

$$Fp = Fs+Fo+Fh \quad (2)$$

Where *Fs* is the overall function of a smart product, *Fo* is the overall function of related objects in the working environment, and *Fh* is the overall function of human activities.

3). Constructing the function structure of each function carrying agent
For complex systems of smart product, processes of forming the function structure for smart product, related objects in working environments and human activities are as follows.

(1) Forming each output flow from the behavior intention to construct backward function chain
The required input flow and conversion are considered from an output flow to the overall function of function carrying agents. A function chain is constructed with flows and sub-functions using a backward direction from Flow(o) to Flow(i) gradually until backward function chains are formed with all output flows. This step ensures design dimensions based on function requirements as follows.

$$Fc= [Entity\ (Itself),\ Entity\ (cxt)] \times InteractionMode(I) \quad (3)$$

Where Fc is a function of the function carrying agent that can be a smart product Fs, related objects in the working environment Fo, or human activities Fh. *Itself* refers to each function carrying agent, *cxt* represents its context. *InteractionMode(I)* is the intended interaction mode between entities.

(2) Design for behavior possibility to construct a forward function chain based on the constructed backward function chain
Based on the backward function chain constructed, all behavior possibility is considered in the forward direction from Flow(i) to Flow(o). Corresponding sub-functions are added to proper positions to get a complete forward function chain. This step reflects the design dimension for affordance as follows.

$$Ac= [Entity\ (Itself),\ Entity(cxt)] \times InteractionMode(P) \quad (4)$$

Where Ac is affordance of the function carrying agent in its context. InteractionMode(P) includes all possible interaction modes among all entities. Following detailed processes are conducted in the constructing process for design dimensions of the behavior possibility.

- *Checking availability of the required input flow*

If there is not any required input flow available, which means that *InteractionMode(I) is not included in the range of InteractionMode(P)*, the constructed function chain should be modified by introducing an outside input flow, or converting an existing input flow into the required input flow, or replacing by a similar input flow.

- *Considering other unintended output flows because of intended input flows*

Each required *Flow(i)* may interact with unintended objects in *Entity(cxt)* following some unintended *InteractionMode(P),* therefore the flow conversion should be examined for every sub-function to see any unintended *Flow(o)* produced accompanying with the intended *Flow(o)*. This unintended *Flow(o)* is further analyzed for any negative effect. New sub-functions will be introduced to process, eliminate or utilize the unintended *Flow(o)*.

- *Investigating the unintended accompanying input and output flows*

If there is any unintended accompanying *Flow(i)* involved in a function chain, the related unintended accompanying *Flow(o)* will be analyzed. The detrimental effect is examined to introduce new sub-functions to block, isolate or exploit the unintended accompanying *Flow(i)*.

4). Combining all function chains of each carrying agent into its function structure
According to the relationship of function chains of carrying agents, all functional chains are systematically combined into a complete function structure of *Fc*.

5). Integrating function structures of all function carrying agents into a complete function structure of the purpose level system
All function structures of *Fs*, *Fo* and *Fh* are systematically integrated into a complete function structure of *Fp* for a final solution of the decomposition of complex systems of the smart product.

4 CASE STUDY

A walking assistive robotic suit shown in Fig. 1 is used as an example to apply the proposed method as follows.

Figure 1: Walking assistive robotic suit.

1). Determining the overall function of the purpose level system
The overall function of the purpose level system of the walking assistive robotic suit is to provide the suitable, safe and ergonomic walking assistant to elders according to their gait characteristics, as shown in Fig. 2.

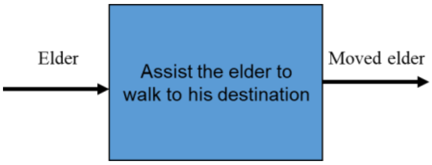

Figure 2: The overall function of walking assistive robotic suit.

2) Decomposing the overall function of purpose level system into the overall functions of different carrying agents
Function carrying agents and their overall functions of the walking assistive robotic suit are shown in Fig. 3 as follows.

(1) Walking assistive robotic suit: It helps a user walking, automatically changes the walking path according to user's status and environment.

(2) Related objects in the environment: Monitoring cameras capture data of locations, activities and gestures of the user. A smart phone provides the location and remote control of the user. A smart wristband provides the location, blood pressure, heartbeat and wrist movement data of the user.

(3) User activities: They provide the location and intended destination information, and feedback to the effect of the walking assistive robotic suit.

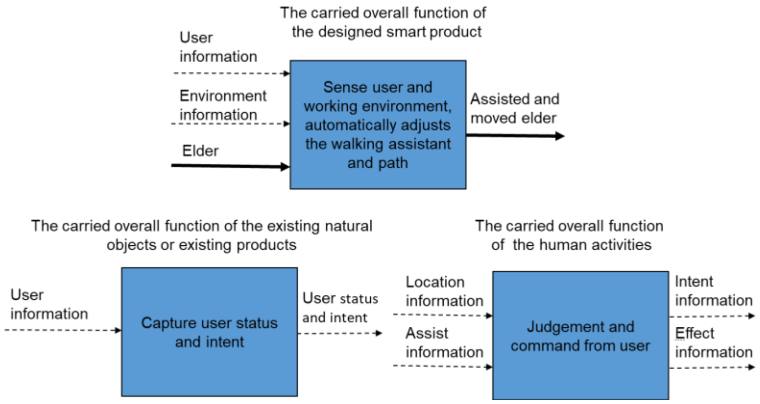

Figure 3: Three function carrying agents.

3) Constructing the function structure of each function carrying agent

(1) Design for the behavior intention to construct a backward function chain for each output flow

As the robotic suit needs to provide moving and walking assistants for a user, a walking aid belt is required to support walking of the user. A proper assistive force is provided to the user using the actuator unit and motor. The robotic suit can also automatically change the support of walking according to the walking step length and swing phase, which requires the adjustment device of the assistive force. Thus the power source, controller, control instructions, force adjusting and path planning are further needed. The generation of control instructions, force adjusting and path planning needs to sense the current status and clarify the ideal status of the robotic suit in real time. Therefore, the judgment is also required based on sensing the user status for mapping to an ideal status according to the real-time status of gait, exercise intensity and intended destination, which requires communicating collected data with other products using the self-judgment and intent information of the user to know objects in context, activity and state of the user. All above activities are from output to intended input, which forms the backward function chain as shown in Fig. 4.

(2) Design for behavior possibility to construct a forward function chain based on constructed backward function chain

- *Check availability of the required input flow*

If there are no monitoring camera in the user's context, the robot will be designed with more monitoring devices.

- *Considering other unintended output flows because of intended input flows*

In order to obtain the location and remote command information of a user, the assistant robot needs to communicate with user's smart phone, and generates possibility that a hacker may send the malicious command to the assistant robot through the phone. Therefore, it is necessary to set a shield to hold back the control command from the phone. When the battery and motor is worn, extra weight will add to the user, which needs to be offset. The belt for assisting hip flexion and guiding moving may restrict the range of motion in the lower limbs, which should be redistributed to lateral sides of the knee.

- *Investigating unintended accompanying input and output flows*

When the user walks outside, rain may splash into the walking assistive robotic suit to affect circuits of sensing, communication, actuator and control. A waterproof cover is therefore needed. The constructed forward function chain is shown in Fig. 5.

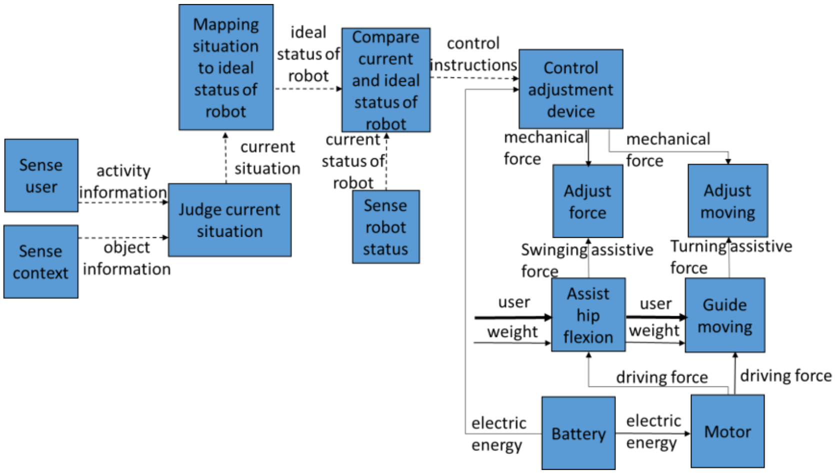

Figure 4: Backward function chain.

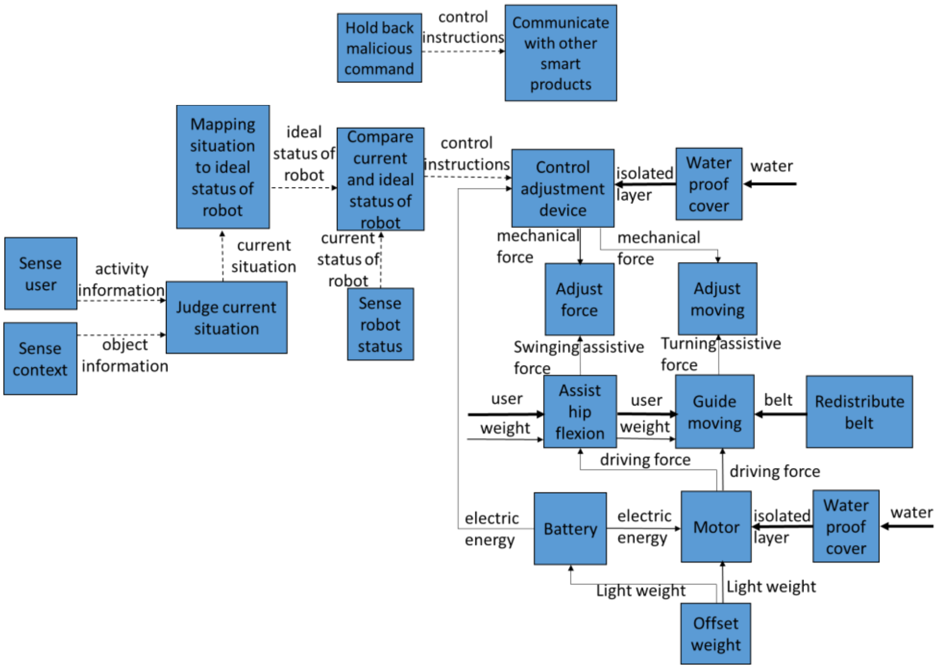

Figure 5: Forward function chain.

4） Combining all function chains of each carrying agent into its function structure

For the walking assistive robotic suit, function chains of its physical structure design, decision-making process and feedback learning process are combined into a function structure according to aligned positions of related information flows.

5） Integrating function structures of all function carrying agents into a complete function structure of the purpose level system

Fig. 6 shows a complete decomposition structure of the walking assistive robotic suit. It shows details of the design components considered in the conceptual design of the robotic suit to meet both current and potential needs in different environments. It has not only contents of physical and digital structures of the walking assistive robotic suit, but also the user, other objects and smart products in the context. The unintended input may influence the autonomous action of the robotic suit, like the water splash or hacker command besides the desired function.

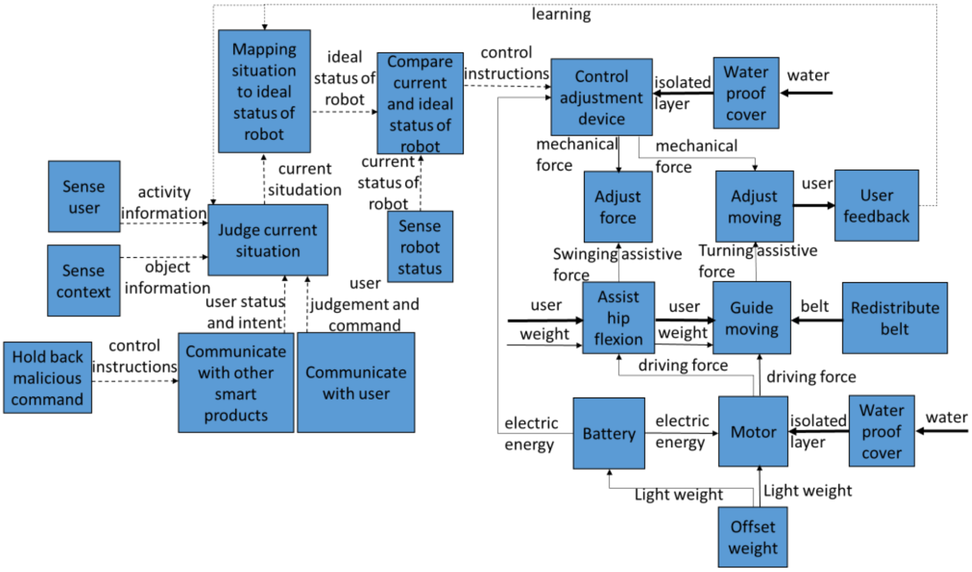

Figure 6: Completed function structure of the purpose level system of a walking assistive robotic suit.

5 METHOD EVALUATION

The function structure modeling method expands the function structure from the physical product to whole purpose level system that satisfies customer's demand, decomposes complexity of thinking in the process of constructing the function structure. Based on the function and affordance in the feedback verification, the implementation process is gradually evolved. It is a suitable method to construct the function structure for the complex system of smart products. Compared to the existing function structure modeling methods, the proposed function structure modeling method has following highlights:

1) Breakthrough of limitations of the oriented object: The overall behavior of the complex system of a smart product includes not only the physical behavior of the smart product, but also other behaviors of objects in the environment and human activities that interact with the smart product or user.

2) Breakthrough of limitations of design intents: A smart product, as an agent, can take a variety of interactive modes in its environment to carry out diverse activities besides the intended behavior. The design for functions of intended behaviors is not enough to establish a complete function structure for the smart product. The design for other behavior possibility is also needed to autonomously extend design dimensions of the smart product.

3) Breakthrough of limitations of representation levels: Function of the complex system of a smart product and its components have multiple levels. The system needs to be represented not only in the behavioral level of a smart product itself, but also in the purpose system level, considering the related activities of people and environments with related natural objects and artifacts.

6 CONCLUSIONS AND FURTHER WORK

A smart product is designed in a process of mapping users' intention to the real world, involving both intent and physical realms. In this paper, the function and affordance are introduced as basic measures of the intention and physical realms. They are used as a synergistic conceptual basis of function structure modeling method. Based on the proposed method, the design complexity of smart products is decoupled. The process is formed as a tool for the backward thinking from function dimensions of the required behavior, and forward thinking from the affordance dimension of environment effects. The function structure modeling is transferred into a process of step by step following natural thinking. The scope of the solution is expanded by considering the unintended behavior. These advantages make the proposed method practical and valuable for design of smart products. Therefore, the proposed method has following two features:

(1) The proposed function structure construction process considers the purpose level system, effect level system and behavior level system, the three levels of system objects.

(2) The thinking process in the construction of function structure is clearly divided into two dimensions, function dimension and affordance dimension.

The function structure modeling method is in conformity with features of smart products such as multi-interaction objects, complex representation levels and wide range of behavior possibility. The logic of the modeling process is gradually implemented based on the need logic and rationality. The effect of process modeling will be continually improved through feedback learning. A prototype of the walking assistive robotic suit is in building to verify the function structure modeling method. The complete structure will be used to further examine the proposed method.

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REFERENCES

[1] Bohm M. R.; Nagel R. L.; Riggs M. K.: Utilizing design intent information to aid in the synthesis of multi-domain systems, Computer-Aided Design and Applications, 14(1), 2017, 17-27. https://doi.org/10.1080/16864360.2016.1199752

[2] Brown, D. C.; Blessing, L.: The relationship between function and affordance, Proceedings of ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, USA: ASME, Long Beach, California, 2005, 155-160. https://doi.org/10.1115/DETC2005-85017

[3] Cao DX.; Fu MW.: A knowledge-based prototype system to support product conceptual design, Computer-Aided Design and Applications, 8(1), 2011, 129-147. https://doi.org/10.3722/cadaps.2011.129-147

[4] Cena, F.; Console, L.; Matassa, A.; Torre, I.: Principles to Design Smart Physical Objects as Adaptive Recommenders, IEEE Access, 5, 2017, 23532-23549. https://doi.org/10.1109/ACCESS.2017.2765746

[5] Chandrasekaran, B.; Josephson, J. R.: Function in device representation, Engineering with Computers, 16(3-4), 2000, 162-177. https://doi.org/10.1007/s003660070003

[6] Chemero, A.: An outline of a theory of affordances, Ecological Psychology, 15(2), 2003, 181-195. https://doi.org/10.1207/S15326969ECO1502_5

[7] Ciavola, B. T.; Gershenson, J. K.: Affordance theory for engineering design, Research in Engineering Design, 27(3), 2016, 251-263. https://doi.org/10.1007/s00163-016-0216-5

[8] Ciavola, B. T.; Wu, CL.; Gershenson, J. K.: Integrating function- and affordance-based design representations, Journal of Mechanical Design, 137(5), 2015, 051101. https://doi.org/10.1115/1.4029519

[9] Crilly, N.: Function propagation through nested systems, Design Studies, 34(2), 2013, 216-242. https://doi.org/10.1016/j.destud.2012.10.003

[10] Crilly, N.: The proliferation of functions: Multiple systems playing multiple roles in multiple supersystems, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 29(1), 2015, 83-92. https://doi.org/10.1017/S0890060414000626

[11] Deng, YM.: Function and behavior representation in conceptual mechanical design, Artificial Intelligence for Engineering, Design, Analysis and Manufacturing, 16(5), 2002, 343-362. https://doi.org/10.1017/S0890060402165024

[12] Dotov, D. G.; de Wit, M. M.; Nie, L.: Understanding affordances: history and contemporary development of Gibson's central concept, Avant: the Journal of the Philosophical-Interdisciplinary Vanguard, 2012(2), 2012, 28-39. http://avant.edu.pl/wp-content/uploads/DDLNMW-Understanding-affordances.pdf

[13] Erden, M. S.; Komoto, H; van Beek, T. J.; D'Amelio, V.; Echavarria, E.; Tomiyama, T.: A review of function modeling: approaches and applications [J]. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 2008, 22(2):147-169. https://doi.org/10.1017/S0890060408000103

[14] Gero J S, Kannengiesser U. The situated function-behaviour-structure framework[J]. Design studies, 2004, 25(4): 373-391. https://doi.org/10.1016/j.destud.2003.10.010

[15] Gibson, J.: The Theory of affordances in Perceiving, Acting and Knowing: Toward an Ecological Psychology, eds. Robert Shaw and John Bransford, NJ: Lawrence Erlbaum, Hillsdale, 1977, 67-82.

[16] Horváth I.: Nucleus-Based Conceptual Design, Computer-Aided Design and Applications, 1(1-4), 2004, 649-656. https://doi.org/10.1080/16864360.2004.10738310

[17] Maier, J. R. A.: Affordance Based Design: Theoretical Foundations and Practical Applications, Berlin: VDM Publishing, 2011.

[18] Maier, J. R. A.; Fadel, G. M.: Affordance based design: a relational theory for design, Research in Engineering Design, 20(1), 2009, 13-27. https://doi.org/10.1007/s00163-008-0060-3

[19] Maier, J. R. A.; Fadel, G. M.; Battisto, D. G.: An affordance-based approach to architectural theory, design, and practice, Design Studies, 30(4), 2009, 393-414. https://doi.org/10.1016/j.destud.2009.01.002

[20] Maier, J. R. A.; Fadel, G. M.: Comparing function and affordance as bases for design, Proceedings of ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Canada: ASME, Montreal, Quebec, 2002, 315-321. https://doi.org/10.1115/DETC2002/DTM-34029

[21] McFarlane, D.; Sarma, S.; Chirn, JL.; Wong, C.; Ashton, K: Auto ID systems and intelligent manufacturing control, Engineering Applications of Artificial Intelligence, 16(4), 2003, 365-376. https://doi.org/10.1016/S0952-1976(03)00077-0

[22] Norman, D. A.: The design of everyday things, USA: Basic Books, New York, NY, 1988.

[23] Norman, D. A.: Affordance, conventions, and design, Interactions, 6(3), 1999, 38-43. https://doi.org/10.1145/301153.301168

[24] Pahl, P.; Beitz, W.; Feldusen, J.; Grote, KH.: Engineering Design: A systematic approach, 3rd edition. Springer-Verlag, London, 2007. https://doi.org/10.1007/978-1-84628-319-2

[25] Sabou, M.; Kantorovitch, J.; Nikolov, A.; Tokmakoff, A.; Zhou, X.; Motta, E.: Position paper on enabling smart products: Challenges for semantic web technologies, Proceedings of the 2nd International Conference on Semantic Sensor Networks-Volume 522.CEUR-WS. Org, 2009, 135-147. http://sunsite.informatik.rwth-aachen.de/Publications/CEUR-WS/Vol-522/p9.pdf

[26] Umeda, Y.; Takeda, H.; Tomiyama, T.: Function, behaviour, and structure. In Applications of Artificial Intelligence in Engineering V (Gero, J.S., Ed.), pp. 177-193. Berlin: Computational Mechanics Publications/Springer-Verlag, 1990.

[27] Vermaas, P. E.: Technical functions: towards accepting different engineering meanings with one overall account, The Eighth International Symposium on Tools and Methods of Competitive Engineering, Italy: TMCE, Ancona, Marche, 2010. http://pietervermaas.nl/PDF/Pieter_Vermaas_FUNENG_overall_account.pdf

[28] Vermaas, P. E.; van Eck, D.; Kroes, P.: The Conceptual Elusiveness of Engineering Functions: A Philosophical Analysis, Philosophy & Technology, 26(2), 2013, 159-185. https://doi.org/10.1007/s13347-012-0096-1

[29] Wang, MY.; Shen, LG.; Deng, YM.: An Extended Causal Behavioral Process Model for Conceptual Mechanical Product Design, Computer-Aided Design and Applications, 9(4), 2012, 419-438. https://doi.org/10.3722/cadaps.2012.419-438

[30] Wu, CL.; Ciavola, B. T.; Gershenson, J. K.: A Comparison of Function- and Affordance-Based Design, ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Portland, 2013: V005T06A001-V005T06A001. https://doi.org/10.1115/DETC2013-12349

[31] Wu, CL.; Ji, YJ.; Lu, WB.; Qi, GN.; Gu, XJ.: The modular affordance deployment method for module clustering process of the integrated service generalized product, Proceedings of the 21st ISPE Inc, International Conference on Concurrent Engineering, Beijing, 2014, 756-767. https://doi.org/10.3233/978-1-61499-440-4-756