Title:
A Structured Conceptual Design Approach for Complex Systems of Smart Product

Authors:
Chunlong Wu, wuchunlong@hebut.edu.cn, Hebei University of Technology
Qingjin Peng, Qingjin.Peng@umanitoba.ca, University of Manitoba
Runhua Tan, rhtan@hebut.edu.cn, Hebei University of Technology
Youcheng Zhou, zhouyoucheng@gmail.com, Hebei University of Technology
Ru Ma, maruggg@163.com, Hebei University of Technology
Jianguang Sun, sjg@hebut.edu.cn, Hebei University of Technology

Keywords:
Smart Product, System Decomposition, Function Modeling, Affordance, Multi-disciplinary Systems

DOI: 10.14733/cadconfP.2018.352-356

Introduction:

The emergence of smart products offers the potential to satisfy user needs more intelligently and appropriately. According to the definition of Smart Products Consortium [6], 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. Features of a smart product include follows [4]. It 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 language, and participate or make decisions on its behavior.

In summary, the smart product is a complex system involving mechanical, electronic, control, information, cognitive, communication and other disciplines. An important task in the conceptual design phase of the smart product is to systematically decompose the complex system. However, existing methods and tools of the classical functional decomposition, such as Pahl and Beitz's systematic functional structure method [5], are not fully applicable to the complex multidisciplinary system decomposition for smart products because of following factors:

(1) Limitation of the oriented object: The complex system of a smart product includes not only the physical structure of the smart product, but also other objects in the environment and human activities that interact with the smart product.

(2) Limitation 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 functional structure for the smart product. The design for affordance is for the behavior possibility [3] to autonomously extend its design dimensions [2] by the smart product.

(3) Limitation of representation layers: The complex system of a smart product and its components have their own purpose. The system needs to be represented not only at the behavioral level, but also at the purpose level [1].

© 2018 CAD Solutions, LLC, http://www.cad-conference.net

This paper proposes a structured approach based on the function and affordance to systematically decompose complex multidisciplinary systems of smart products for the improvement of above-mentioned limitations.

Main Idea:
The proposed method is summarized in following steps.

1. Determining the overall function of a purpose layer system
User's abilities and environment changes are identified to determine users' purpose and gap between the actual and expected future status. All action objects are represented in a form of the information flow, material flow and energy flow as the overall function of a purpose layer system as follows.

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

Where *Fp* is an overall function of the purpose layer 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 layer system into the overall functions of different carrying objects
There are three kinds of function carrying objects including the smart product to be designed, related objects in the working environment, and human activities. The conversion works from *Flow(i)* to *Flow(o)* of all the action objects corresponding to the total function of purpose level system in the three function carrying objects as follows.

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

Where *Fs* is the overall function of the smart product to be designed, *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 object
For a smart product, processes of its function structure for related objects in working environments and human activities are as follows.

(1) Forming each output flow from the behavior intention to constructing backward function chain
The required input flow and conversion are considered from an output flow to the overall function of function carrying objects. 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 object that can be a smart product *Fs*, related objects in the working environment *Fo*, or human activities *Fh*. *Itself* refer to each function carrying object, *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 object in its context. *InteractionMode(P)* includes all possible interaction modes among all entities.

© 2018 CAD Solutions, LLC, http://www.cad-conference.net

Following detailed processes are conducted in the constructing process for design dimensions of the behavior possibility.

- *Check availability of the required input flow*

If any required input flow is not 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.

- *Consider 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).*

- *Investigate 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 object into its function structure

According to the relationship of function chains of carrying objects, all functional chains are systematically combined into a complete function structure of *Fc*.

5. Integrating function structures of all function carrying objects into a complete function structure of the purpose layer 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.

<u>Case study:</u>

A nursing-care walking assistant robot is introduced as an example to apply the proposed method as follows.

1. Determining the overall function of the purpose layer system

The overall function of the purpose layer system of the walking assistant robot is to provide the most suitable, safe and ergonomic walking assistant to elders according to their location and destination.

2. Decomposing the overall function of purpose layer system into the overall functions of different carrying objects

Function carrying objects and their overall functions of the walking assistant robot are as follows.

(1) Walking assistant robot: It is aware of a user and working environment, automatically changes the walking assistant and path planning according to user's status.

(2) Related objects in the working environment: Monitor camera provides data of the location, activities and gesture 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 for the effect of the walking assistant robot.

3. Constructing the function structure of each function carrying object

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

As the robot needs to provide moving and walking assistants for a user, a walking aid gripper is required to support walking of the user. A mobile platform drives the user using motors to provide

© 2018 CAD Solutions, LLC, http://www.cad-conference.net

driving force. The robot can also automatically change the support of walking aid gripper, the walking pace and path, which requires the gripper and moving adjustment device, power source, controller, control instructions and path planning. The generation of control instructions and path planning needs to sense the current status and clarify the ideal status of the robot in real time. Therefore, the judgment is also required in the user status for mapping to an ideal status, which communicates 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.

(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.

- *Consider 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.

- *Investigate the unintended accompanying input and output flows*

Water in the user's context may splash into the walking assistant robot to affect circuits of sensing, communication and control. A waterproof cover is needed.

4. Combining all function chains of each carrying object into its function structure

For the walking assistant robot, 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 objects into a complete function structure of the purpose layer system

Figure 1 shows a complete decomposition structure of the walking assistant robot. It shows details of the design components considered in the conceptual design of the robot to meet both current and potential needs in different environments. It has not only contents of physical and digital structures of the walking assistant robot, but also the user, other objects and smart products in the context. The unintended input may influence the autonomous action of the robot, like water splash or hacker command besides the desired function.

Conclusions:

This paper proposed a structured approach to function and affordance based decomposition for complex systems of smart products, which 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 decomposition process is gradually implemented based on the need logic and rationality. The effect of decomposition can be continually improved through feedback learning. A prototype of the walking assistant robot is in building to verify the design solution. The complete structure will be used to examine the robot application in all possible interaction modes.

Acknowledgements:

This research is supported by the Open Project of Henan Key Laboratory of Intelligent Manufacturing of Mechanical Equipment, Zhengzhou University of Light Industry (No. IM201805). This research is also supported in part by the National Science and Technology Basic Project under Grant Numbers (No. 2017IM040100). And thanks for the support of National technological Innovation Method and Tool Engineering Research Center in China.

© 2018 CAD Solutions, LLC, http://www.cad-conference.net

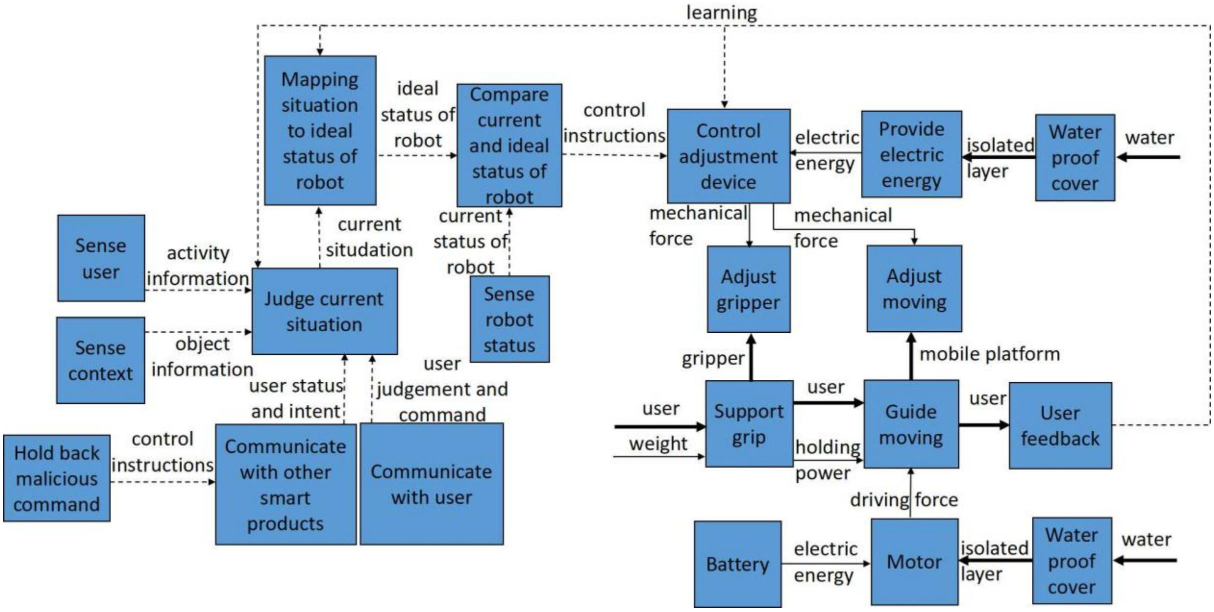

Fig. 1: Complete function structure of the purpose layer system of a walking assistant robot.

References:

[1] 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

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

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

[4] 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

[5] 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

[6] 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.

© 2018 CAD Solutions, LLC, http://www.cad-conference.net