Functional Ontology of Artifacts

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ABSTRACT. This article discusses a functional ontology of artifacts the author and Yoshinobu Kitamura have been developing for years. It is partly concerned with the comparison of our ontology with the ontology of biological functions which Barry Smith has been investigating. As will be indicated below, some parts of this article owes the discussion made with Barry Smith through email communications. I also discuss an on-going research on functional upper ontology.

1 Introduction

Typical knowledge systems in engineering domains include design support systems which have rich knowledge useful for designing artifacts. Among a variety of knowledge in such knowledge-intensive systems, functional knowledge plays the key role in the phase of conceptual design. The essential property of artifacts lies in its function which gives the identity of the each artifact. The reason why an artifact is meaningful to people is that the function it achieves is what people want. Considering the importance of function, I have been building functional ontology with my colleague, Yoshinobu Kitamura[Kitamura 02, 06a].

One of the most important things people need when they build an ontology is something to fix "viewpoint" consistently throughout the building process. A typical example is 3D and 4D views when building an upper ontology. What we invented for building functional ontology of artifacts is "device ontology" which I explain below. On the basis of the device ontology, we defined behavior and build a functional ontology. Comparison is made between functions of artifacts and that of biological organisms. A functional upper ontology is also discussed followed by concluding remarks.

2 Function and device ontology

2.1 Device ontology

Concerning modeling of artifacts, there exist two major viewpoints: Device-centered and Process-centered views. The device ontology specifies the former and the process ontology the latter. Device-centered view regards any artifact as composition of devices which process input to produce output which is what the users need. Process-centered view concentrates on phenomena occurring in each place(device) to obtain the output result with paying little attention to the devices existing there.

The major difference between the two is that while device ontology has an ***Agent*** which is considered as something which plays the main actor role in obtaining the output, process ontology does not have such an Agent but has ***participants*** which only participate in the phenomena being occurring. Needless to say, such an agent coincides with the device in device ontology. It is natural to consider process ontology is more basic than device ontology. Before humans had started to make artifacts, only natural phenomena had been out there in the world. Any device and/or artifact is something built by limiting the environment where phenomena of interest occur to what the device produce and by connecting them to achieve the goal set in advance. Every device utilizes several natural phenomena to realize its functions.

In spite of its less basic characteristics, device ontology has been dominant to date in modeling artifacts for many reasons as follows:

1. Device ontology is straightforward because every artifact is a device.
2. Every artifact is easily and nicely modeled as a part-whole hierarchy of devices because it can be considered as being composed of sub-devices recursively.
3. The concept of a function has to be attributed to an agent(a device) which is considered as a main actor to realize the function.
4. Theoretically, process ontology cannot have function associated with it because it has no ***Agent***.
5. Device-centered view saves a load of reasoning, it hides internal details of devices.
6. One can design almost all artifacts in the device ontology world by configuring devices, except cases where one needs innovative devices based on new combination of phenomena or new phenomena themselves.

It is important to note, however, device ontology is not almighty. Essentially, device ontology views any device as a black box. Of course, in the device ontology world, one can go into smaller grain world in which the parent device is seen as configuration of several sub-devices of smaller grain size. But, the smaller devices themselves are still devices whose internal behavior is also hidden. Process ontology is different. It is useful for explaining why a device works, since it directly explains what phenomena are occurring in the device to achieve its main function. Furthermore, process ontology is better than device ontology at modeling, say, chemical plants where chemical reactions have to be modeled as phenomena.

2.2 Constituents of device ontology

In this article, we base all of our discussion on device ontology. Top-level categories of device ontology include ***Entity, Role, Structure, Behavior*** and ***Function***. ***Entity*** represents the real and basic things existing in the world such as human, device, fluid, solid, etc. ***Role*** represents roles an entity plays during the process in which the device works. There are functional and structural roles. The former includes ***Agent*** which is an actor who does the action to cause the effect required, ***Object(operand)*** which is processed by the agent, ***Medium*** which carries something processed by the device, ***material*** which is the main source of the results output from the device and ***product*** which is the regular output of the device and is made of/from the material. The structural role has sub-roles such as ***input, output***[1] and ***component*** which is the role played by a part of any device to form the structure. Not all the ***input*** has material role, though all ***material*** have input role. Similarly, not all the ***output*** have product role, though all ***product*** have output role. ***Structure*** has sub-categories such as ***inlet***, ***outlet*** and ***connection*** which is a relational concept connecting devices. A component has inlets and outlets whose role is to connect them with other components. ***Input (output)*** is anything coming into (going out of) a device through an inlet (outlet).

Behavior of a device (***DO-Behavior*** in short) is defined as "situation-independent conceptualization of the change between input and output of the device" and it has two subcategories such as ***transitive behavior*** and ***intransitive behavior*** which roughly correspond to transitive and intransitive verbs, respectively. Roughly speaking, the former is concerned with the change of the ***object*** coming into(going out of) the system and the latter with that of the ***agent***. Note here that we do not define behavior in general, that is, we only discuss behavior of a device.

We now would like to defend our definition of ***DO-Behavior*** from a possible critic that would say "it seems not compliant with what a normal simulation does". A possible counter argument against DO-Behavior would look like as follows:

> *In numerical simulation, which is the typical way of simulation, we understand simulation of the behavior of a system(device) as a trace of the change of a parameter value over time. In other words, the behavior is an interpretation of change of each parameter value. It is straightforward and convincing, since it is compatible with the basis of how a thing behaves which is not explained by DO-Behavior.*

This view is parallel to the naïve view of behavior like the idea based on "motion" such as walking and running. It is true that the above idea of numerical simulation is basic because it depends neither on device nor on process ontologies. There is, however, another kind of simulation, that is, causal simulation in qualitative reasoning. If we interpret it in the device ontology world, causal simulation is different from the numerical simulation in that it tries to simulate the change of an object between that when it exists at the inlet of the device and that when it exists at the outlet of the device, that is, causality of the change made by the device. This is what AI research needs about behavior of a system from the device-centered point of view.

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[1] By Input and Output, I mean things which are input/output to/from the system.

2.3 Definition of function

In design community, what are necessary to the researchers include the ideas of function and behavior as well as structure. In order to relate the idea of function to that of behavior, both should be based on the same ontology of artifacts. As discussed above, functional concepts inherently need device ontology because we always associate function with a device. This suggests us that behavior should be defined in terms of device ontology, that is, DO-behavior which is consistent with not the idea of numerical simulation but that of causal simulation.

On the basis of the above observation, we defined function as:

Teleological interpretation of DO-behavior under a goal[Sasajima 95]

The introduction of the device ontology together with definition of DO-behavior enables us to consistently capture any artifacts from a stable point of view for defining its functions. The device-ontology-based modeling allows recursive application to modeling artifacts in a nested device structure. We thus can represent an artifact in a necessary number of granularity layers in which the structure at the higher layer specifies goals to be achieved by the modules at the lower layer. In this way, our framework for modeling artifacts intended to capture the goal-oriented structure of an artifact naturally.

Function has been investigated in philosophy extensively mainly for biological entities(organisms). The essential difference between artifacts and organisms is that the former have a goal but the latter do not. At a first glance, it seems we cannot define function without goals, since function is essentially goal-dependent. However, as I suggested above, there are two kinds of goals in general. (1) Goal-I: One is ordinary goals which are possessed by the thing as a purpose intended by the thing itself or an outsider. (2)Goal-NI: The other is nothing to do with "intention" but something which is necessarily forced to have it from the system perspectives. That is, most biological organisms are included as parts in a system which behaves consistently by the collaborative work of parts to make the whole to be a system. Any organism is thus required to play roles necessarily defined within the context of the systematic behavior.

Both goals share a characteristic: a state to be achieved. If it is intended by the thing or not is secondary in our context. In other words, Goal-I is a goal applied to a thing as a whole and Goal-NI is one applied to parts of a whole. The definition of function shown above only needs Goal-NI. Therefore, biological function can be defined as that of function of artifacts by replacing goal by Goal-NI.

Now, the problem of defining function seems to be solved. However, it is not true. Researchers involved in biological function are not happy with the above definition because it fails to capture some essential properties of organisms.

3 Function of artifacts vs. Biological function

The most salient property of biological organisms is that they are free from human intention while artifacts are totally dependent on it. The pumping function of a heart, for example, is never used for different purposes. There is no other organ to replace it. It was born to perform the pumping function and will keep going to do so until the end of its life. On the other hand, a pump as an artifact exists in a totally request-based manner. It is designed so by a designer driven by the user requirement. More interesting is that artifacts are often used for different purposes from the designer's intention. A box can be used as a table(function of a table), a table can be used as a step(function of a step), etc. A small pump can be used as a door stop.

These essential differences brought about two different ontologies for functions of organisms and artifacts. According to Barry Smith, biological function is defined as "the disposition of a certain entity reliably to act in such a way as to achieve a goal" [Johansson 05]. Its essence is that function exists inside the thing which performs the function as a kind of an intrinsic property. This is very different from the function of artifacts defined earlier. Concerning artifacts, function as a requirement specification exists before a product has been born to realize it. This suggests that function can exist outside of artifacts. This is a serious and deep gap between biological function and function of artifacts. It seems to be very hard to fill it in.

However, we should not neglect a great commonality between the two. Function is intrinsic both to organisms and artifacts. It gives the identity of things of both kinds. The issue is where it is. According to Barry Smith, function is divided into two things: disposition and exhibition(functioning) process. The author and Kitamura of course believe that function is completely supported by the structure and properties of the thing. In this respect, something essential related to function exists inside things. In addition, we also believe that what is realized is the essential to what a function is. How it is different from behavior is very important for in-depth understanding of function. The biological definition of function which says that it is a kind of disposition is not appropriate for understanding the difference between function and behavior.

Viewing from the engineering point of view, biological function is very closed to capability. We suspect that their definition might accept anything that behave somehow has a function to behave so, which cannot be accepted from engineering point of view, since it tells nothing informative or meaningful to engineering.

The following would be a counterexample to the definition of biological function[2]. Imagine we are given a heat exchanger which is composed of a pair of touching pipes in which a hot liquid flows in one pipe and the cold liquid flows in the other. During the flowing process, heat energy is transmitted from the warmer flow to the cooler. This heat transmission between two flows is the behavior of a heat exchanger. It is realized

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[2] I assume that there is an intention that biological function is universally applicable to all types of function including that of artifacts.

by the touching pipes and the physical law of heat conductance. Barry Smith might say "a heat exchanger has a disposition to reliably realize such a heat transmission".

Let us imagine a situation where people focus on the warmer flow. Then, what the heat exchanger performs is cooling down the warmer flow and its function is *to cool*. On the other hand, when people focus on the cooler flow, then what it does is warming up the cooler flow and its function is *to warm*. The function of a heat exchanger is determined by the intention of its user or the designer of the whole system which has the exchanger as its part. Which flow should be focused on is totally user-dependent. This is the essential factor of function in engineering domains. Note here that the behavior is completely same in either situation. The very same behavior can play the role of warmer or cooler according to the context. While the structure and the behavior are free from the viewpoint or context where it is used, function does depend on them. We could say that such a dependency is essential to function of artifacts. It depends not only on the designer but also on user's intention. We can trace the origin of a function back to the user requirement which is often functional. Considering these observations, it is hard for us to accept the biological definition of function which is completed within the closed world inside the function bearer. Although Barry Smith explains such function that we have discussed above as "exhibition of a function", it is secondary to him. What is primary to him is "a disposition".

We now proceed further assuming we have a happy agreement on something essential to function exists inside the thing putting aside the issue if another essential to function can exist outside of things or not. Unfortunately, however, Barry Smith and I could not come to an agreement on the issue of intrinsic function and accidental function. From biological point of views, Barry Smith firmly believes only intrinsic functions exist inside things and all the accidental functions do not. On the other hand, Kitamura and I also firmly believe that both kinds of functions exist inside things. Examples are as follows[3]:

A door key: its intrinsic function is to open/close the lock of a door. It can be used to scratch your itch. It is its accidental function.

A heart: Its intrinsic function is to pump the blood. Its accidental function is producing the beat.

The problem is if scratching itch and beat production functions exist inside a key and a heart or not, respectively. The distinction between intrinsic or accidental is fairly easy. Concerning artifacts, it is determined by knowing the intention of the designer. All the intended functions are intrinsic. Other functions are accidental. Concerning biological functions, although it might look a bit difficult at first glance, it is not so difficult. As discussed earlier, each part(component) has its own Goal-NI specified by its parent part or the whole system. Therefore, if a function contributes to the achievement of the behavior of the total system through its successive contributions of its parents, then it is intrinsic. Otherwise, it is accidental. In the case of a heart, no other part(component) in

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[3] Examples are suggested by Barry Smith.

the body uses the beat, the beat producing function is accidental. Although cardiac diagnosis needs the beat, it is used by the outsiders.

The reason why we believe functions exist inside things independently of if it is intrinsic or accidental is that any function is necessarily supported by the structure and/or properties of the things. This applies also to biological organisms. Without such physical support, no concrete behavior and hence function can be produced. Nevertheless, Barry Smith claims that accidental functions are only exhibited without any disposition for realizing it. Then, the issue would be what we think exist inside things as a function. However, let us stop here on this topic.

4 An upper ontology of function

The topic I would like to discuss in this section is an upper ontology of function for use as a reference ontology intended to eventually build a unified theory of function. We recently revised our definition of function as follows[Kitamura 06b]:

Function is a role played by a behavior specified in a context

It is a refinement of the former one and there is a good analogy to "Teacher is a role played by a person specified in the context of school" Taking the example of a heat exchanger, the heat exchanging behavior plays the *to warm* function role and *to cool* function role according to the focal flow specified in a context.

Let us move on to the topic of upper ontology of function. Our next example is an electric fan whose function is usually considered as *to cool* persons or *to make persons comfortable*. According to our upper ontology of function, however, it is not true. Let us examine the function of an electric fan step by step. Imagine a fan is put in a room. What it is doing is "to blow" which is the function closest to the device. It usually heads toward a person, then the wind blown at a person. The reason why he/she feels cool is the air with the same temperature as that of his/her body around him/her is moved away and new cooler air come around him/her. Furthermore, the evaporation of the water on his/her skin is promoted and hence heat absorption is promoted, he/she thereby becomes cooler. There must be this kind of a sequence of physical phenomena after the wind has been blown by the fan. This is represented in terms of function as follows:

To blow wind => to blow wind at a person => to move air away
=> to promote evaporation => to absorb heat

The example shows that after some device function is performed, many phenomena happen consecutively until some meaningful effect works out on a target. Final desirable effects are realized as a result of sequence of phenomena/actions context sensitively.

Another example is an analog clock whose function is usually understood as to show time. But, it is not correct. The function of an analog clock is just a regular rotation of long and short hands. Time is read by humans. Human interpretation plays the key role here. As these two examples show, there exist several types of functions in the world. I am afraid this important fact is not recognized well to date. The function performed by a concrete device itself seems to be just one of them. We recently enumerated possible function types and organized them as an upper ontology of function as shown in Fig. 1.

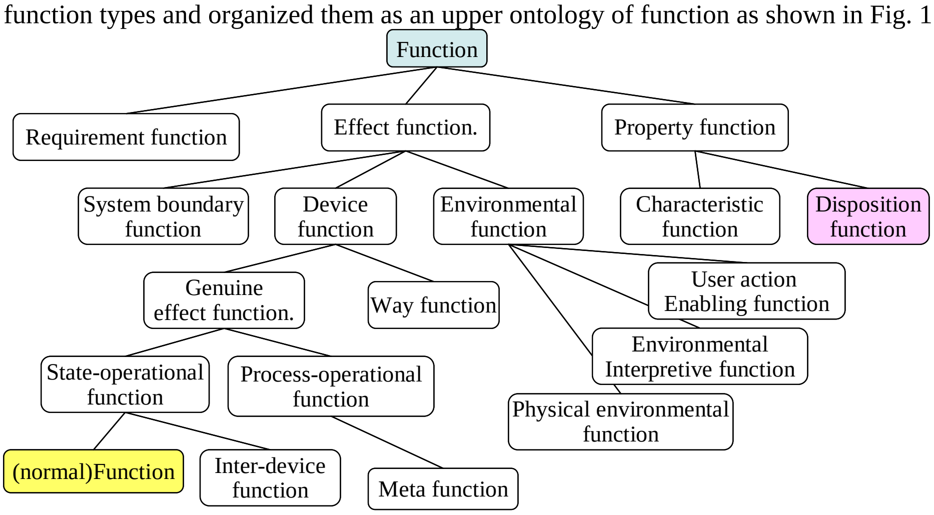

Fig. 1 An upper ontology of function(slight modified from [Kitamura 07]).

Function is divided into the three types: Requirement function, Effect function and Property function. Effect function is one which eventually brings about some effect on the target thing. Although requirement function would have exactly the same structure as Effect function, it is shown there because its origin is very different from Effect function. Property function includes Biological function and Characteristic function by which I mean what appears in functional materials in materials science such as *high conductivity function, heat-resistant function*, etc. Effect function is divided into three subclasses such as System boundary function, Device function and Environmental function. By System boundary function, we mean only two functions: *to import* and *to export*. Environmental function includes those we see above and further divided into Physical environmental function such as *to cool function* of evaporation, Environmental interpretive function such as *time reading* and User action enabling function such as *meeting-enabling function* of a meeting room. Device function consists of Genuine effect function and Way function. Way function is a composite of **what to achieve** and **how to achieve** such as *to weld* which is a composite of *to join* and *fusing way*. Although Genuine effect function might seem to be the function we want, it still needs further refinement. It consists of State-operational function and Process-operational function. The latter has what we call Meta function such as *to enable* and *to prevent* which effect on other processes(functions). The former includes Inter-device function such as *to push up* (a rod) of a cam and the Function which a device performs satisfying our definition of function based on the device ontology. Examples of the Function include ***to separate, to join, to transform,*** etc. These genuine functions are applicable to explanation of how engineering artifacts work and to configuration of them by connecting the functional modules.

One of the most significant properties which function must have is implementation-independence. Function must be equal to what people want to enjoy. They are not interested in how the function is realized. In theory, to invent an innovative way of realizing a new function is what engineers are expected to do. There must be multiple ways of realization of a function.

It is really amazing to see so many different categories of functions exist in the real world without proper recognition of the differences to date. Especially, Way function is the most dominant and dangerous type among all. *To weld, to cut, to wash, etc*. all belong to the Way function and all the experts have strongly believed that they are "functions". *To cut* implies the use of a sharp tool and *to wash* implies the use of liquid(water). Ignorance of the danger of the Way function has been the major cause of preventing from smooth reuse of functional information across domains, since how to achieve (Way functions) bears the domain-specific things.

The Function is free from the domain-dependence and is generic enough to capture essential functional structure. We currently formalize 89 functions of the Function type and defined in Hozo and OWL. They are defined as lean[4] as and as local as possible. We do not claim they are exhaustive, but our experience in tight collaboration with three companies for years suggests that they are quite adequate.

5 Ontology alignment

Using those 89 functions defined in Hozo and OWL, the author's group has developed a tool called SOFAST for representing functional structure of any artifact and has deployed it into industries since 2002. Currently, three companies use SOFAST [Kitamura 06b].

NIST(National Institute of Standards and Technology) in USA developed functional terms called Functional basis[Hirtz 02]. Although their research has started a few years later than us, the activity was done independently of us. They come up with 52 functional terms without ontological consideration. We have investigated functional basis intended to align both terms/concepts and found about 80% of their terms have correspondents in our ontology. Considering the independence of the research, such a high correspondence rate is extraordinary, which is a strong justification of the correctness of their and our achievements, though it is indirect. We found some room for improvement in Functional basis. It is partly because Functional basis is not based on ontological analysis of function. Our functional ontology contains finer-grained functional concepts than Functional basis.

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[4] I mean to exclude unnecessary properties while keeping the essentials.

6 Concluding remarks

We have discussed functional ontology from engineering point of view. Comparison of biological function and function of artifacts was also done based on the personal communication between Barry Smith and me. Although the gap between the two kinds of functions is still deep, it is worth to investigate the possibility to fill it in. One convincing task to do would be to refine the upper functional ontology or a reference ontology of function and to use it for coordinating both opinions. Another issue to pursue would be more careful examination of what exists inside things and how exhibition process and function of artifacts are different.

References

[Hirtz 02] Hirtz, J., Stone, R., McAdams, D., Szykman, S. and Wood, K., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts", Research in Engineering Design 13(2):65-82.

[Johansson 05] Johansson, I., Smith, B., Munn, K., Tsikolia, N., Elsner, K., Ernst, D., and Siebert, D., "Functional Anatomy: A Taxonomic Proposal", *Acta Biotheoretica*, 53(3), pp. 153-66, 2005.

[Kitamura 02] Kitamura, Y., Sano, T., Namba, K., & Mizoguchi, R. (2002). A functional concept ontology and its application to automatic identification of functional structures. *Advanced Engineering Informatics, 16(2)*,145-163.

[Kitamura 06a] Yoshinobu Kitamura, Roles of Ontologies of Engineering Artifacts for Design Knowledge Modeling, In Proc. of the 5th International Seminar and Workshop Engineering Design in Integrated Product Development (EDIProD 2006), Gronow, Poland, pp. 59-69, 2006. http://www.ei.sanken.osaka-u.ac.jp/%7Ekita/pub/documents/kita-ediprod06.pdf

[Kitamura 06b] Yoshinobu Kitamura, Yusuke Koji and Riichiro Mizoguchi, An Ontological Model of Device Function: Industrial Deployment and Lessons Learned, Journal of Applied Ontology (Special issue on "Formal Ontology Meets Industry"), Vol. 1, No. 3-4, pp. 237-262, 2006 http://www.ei.sanken.osaka-u.ac.jp/pub/documents/kita-AO2006-preprint.pdf

[Kirtamura 07] Yoshinobu Kitamura, Sunao Takafuji, Riichiro Mizoguchi, Toward A Reference Ontology for Functional Knowledge Interoperability, Proceedings of the ASME 2007 International Design Engineering Technical Conferences& Computers and Information in Engineering Conference, IDETC/CIE 2007, Las Vegas, Nevada, USA.

[Sasajima 95] Sasajima, M., Kitamura, Y., Ikeda, M. & Mizoguchi, R. (1995). FBRL: A Function and Behavior Representation Language. *Proc. Of IJCAI-95* (pp. 1830–1836).