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Description	

Characterizing functions based on phase- and evolution-oriented models[#]

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Abstract. The purpose of this paper is to characterize some notions of function, mainly of artifacts in engineering and philosophy, from an engineering point of view. First, we distinguish some fundamental kinds of functions based on ontological distinctions. Then, using these kinds of functions, we present a phase-oriented model of artifact function along the product life-cycle. This model shows the changes of functions made by acts such as design, manufacturing and use. Then, we characterize the functions in the product life-cycle phases as a combination of those kinds of functions. Next, an evolution-oriented model of function is presented. This model shows how the fundamental notions of function have appeared along the evolutional history of creatures. Then, we characterize functions of artifacts, those of biological organs, and those of non-biological natural things.

Keywords: an ontology of function, functions of artifacts, biological organs, and natural things, interoperability of functional knowledge

1. Introduction

Functionality is one of main notions for describing artifacts, as well as biological organs. Thus, much research has been carried out on the notion of function in several research areas. For instance, in engineering design (Hubka & Eder, 1988, 2001; Pahl & Beitz, 1996; Umeda et al., 1996; Stone & Chakrabarti, 2005), artificial intelligence (Chandrasekaran et al., 1993; Lind, 1994; Chandrasekaran & Josephson, 2000; Goel et al., 2009), and value engineering (Miles, 1961), representation of artifact function for computer-supported design has been investigated. In philosophy (Cummins, 1975; Perlman, 2004; Wouters, 2005; Vermaas & Houkes, 2006), the notion of function, mainly of biological organs, has been extensively discussed. In ontology research as well, much research has been carried out, such as (Garbacz, 2006; Arp & Smith, 2008; Borgo et al., 2009; Borgo et al., 2011a).

The problem here is that there are many definitions of function without any clear relationship among them (Hubka & Eder, 2001; Perlman, 2004; Stone & Chakrabarti, 2005). Specifically, there is a large gap between the definitions of functions in engineering and those in philosophy. For example, in engineering, Umeda et al. (1996) define a function as “a description of behavior abstracted by human through recognition of the behavior in order to utilize it”. In this definition, a function is directly related to a physical process performed by an artifact when it is used. A similar perception can be found in many definitions in engineering (e.g., (Chandrasekaran et al., 1993; Lind, 1994; Pahl & Beitz, 1996; Hirtz et al., 2002)). On the other hand, in philosophy, a function is typically a special feature of a thing (Perlman, 2004). For example, in causal-role function analysis (Cummins, 1975) and ICE theory (Vermaas & Houkes, 2006), a technical (artifact) function is regarded as a special kind of capacity to be ascribed to an artifact. Thus, according to the former definition in engineering, an artifact performs a function, whereas in philosophy, an artifact has a function as a property, or a function possessed by an artifact is attributed to an artifact according to the latter definition. As the readers can see, there are large gaps between them on some ontological issues such as “when a function exists” and “on what the existence of a function depends”, even when we compare two definitions of artifact functions only.

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Although the above statements, at first glance, seem contradictory, we claim that in reality these statements refer to different kinds of function. We regard that they are not superficial but real existent things. Thus, one of our goals here is not to identify a unique definition of function but to identify fundamental kinds of function and to use them to distinguish these functions and then to harmonize them with clear relationships.

In this paper, we aim at characterizing some notions of function in engineering and in philosophy based on some fundamental kinds of functions and also present two ontological models of functions: a *phase-oriented model* and an *evolution-oriented model*. The former is a macroscopic temporal model that shows what kinds of functions exist in the phases of the product life-cycle, such as design and use. It explains the relationship among different notions of function, especially in engineering and in philosophy. The latter is a macroscopic temporal model that shows how those kinds of functions have appeared along the evolutional history of creatures. It characterizes the functions of artifacts, biological organs, and non-biological natural things.

The consideration is made from an engineering point of view based on our long experience in ontological research on function in engineering design. The authors have established a suite of ontologies of artifact function and an ontology-based functional modeling framework for engineering design (Sasajima et al., 1995; Kitamura et al., 2002, 2006, 2007). The framework has been successfully deployed in some manufacturing companies (Kitamura et al., 2006). Those practical experiences provide a real engineering basis for the consideration presented in this paper.

The paper is organized as follows. We first discuss some ontological distinctions and fundamental kinds of functions based on our previous work (Kitamura et al., 2006, 2007; Kitamura & Mizoguchi, 2009a, 2009b; Mizoguchi & Kitamura, 2009) and compare our definition of artifact function (Kitamura et al., 2006, Kitamura & Mizoguchi, 2009a; Mizoguchi & Kitamura, 2009) to some definitions of function in the literature. Then, Section 3 presents the phase-oriented model of function, which is a revised version of the one proposed in (Kitamura & Mizoguchi, 2009b). We discuss the relationships between different notions and definitions of function introduced in Section 2 based on this model. Section 4 explains the justifications of our definition from an engineering point of view. Next, Section 5 presents the evolution-oriented model of function. Using our terminology on this model, we characterize the functions of artifacts, biological organs, and non-biological natural things and then explain some existing definitions of function, such as a philosophical definition of the function of biological organs proposed by Johansson et al. (2005), those in the Basic Formal Ontology (BFO) (Arp & Smith, 2008), and functions in the definition of artifacts in (Borgo & Vieu, 2009).

Our motivation to clarify the notion of function and the relationships among definitions of function is to develop an explicit viewpoint for describing functional knowledge in information systems and to ensure their interoperability (Kitamura et al., 2007). In practice, engineers tend to describe functional knowledge, such as functional decomposition (Pahl & Beitz, 1996), based on an implicit perception of function in an *ad hoc* manner (Kitamura et al., 2006). As a consequence of inconsistency of the implicit perceptions, it is difficult to share and reuse the functional knowledge. Moreover, it is difficult to ensure interoperability between functional knowledge based on different definitions of function in the literature due to the lack of a clear relationship among those definitions. Thus, the ontological investigation in this paper will contribute toward providing engineers with some differentiated viewpoints for consistent functional modeling. Clarification of the relationship among several definitions in the literature will contribute to interoperability. In fact, we have established a reference ontology of function (Kitamura et al., 2007) already. This paper investigates more fundamental differences of the notions of function.

2. Ontological Distinctions of Function

In this section, we discuss some fundamental kinds of functions based on ontological distinctions. These distinctions, except that between function and behavior discussed in Section 2.2, are orthogonal to each other. The target of the discussion here is mainly the function of artifacts[1], though similar distinctions can be made for biological organs and non-biological natural things, as discussed later.

[1] In this paper, we treat an artifact as a primitive notion. It is a physical object that exists in spatiotemporal space and consists of devices (components) as a system based on a device-oriented ontology (Kitamura et al., 2006; Mizoguchi & Kitamura 2009). We use the term ‘device’ for both artifacts (e.g., a hammer and a screwdriver) and components (e.g., a grip

In our definitions below, the following notions are regarded as primitives:

- (Unary) categories: artifact, device, system, intention, capacity, role, context, functional structure, (artifact's) user, (artifact's) designer, and specification
- (Binary) relations: play, intend, specify, realize (is-realization-of), induce, and satisfy.

These notions are intuitively explained below but are not exactly defined within this paper, see (Kitamura et al., 2006; Mizoguchi, 2003, 2004; Mizoguchi et al., 2007; Mizoguchi & Kitamura, 2009) for their introduction. For example, the "is-relazation-of" relation relates a thing in a real world to a specification as discussed in Section 2.5 and summarized in Table 1.

2.1. ***Actual Function and Capacity Function***

As discussed in the introduction, one of the main differences between the definitions of functions in engineering and those in philosophy is about when and where a function exists. In many definitions in engineering (e.g., (Chandrasekaran et al., 1993; Lind, 1994; Pahl & Beitz, 1996; Hirtz et al., 2002)), a function is directly related to a process performed by an artifact when the artifact is used. On the other hand, in many definitions in philosophy, a function is a special feature of an artifact (Perlman, 2004) and is what is possessed by or ascribed to the artifact. For a distinction between these two senses of function, we distinguish *actual function* and *capacity function*, as shown below. We define the actual function in the next sub-section. We here intend to explain what we mean by **actual** and **capacity** when we use them to modify "function" based on the definition of the actual function in the next sub-section:

By *actual function* (***AF***), we mean something directly related to a process that a device performs when it works in the use phase.

By *capacity function* (***CF***), we mean the capacity of a device to perform an actual function.

The actual function and the capacity function correspond to what is discussed in engineering and what is discussed in philosophy, respectively. The notion of capacity itself is primitive. By a capacity, we intuitively mean the potential ability (a property) of a device to perform some occurrent-like thing (in this case, function). A capacity function CF_x [2] is the capacity to perform a specified type of actual function AF_y. For example, a screwdriver, as a device, has CF_1, which is the capacity to perform AF_y of the type "rotating a screw (screwing)". CF_x is tightly related to the physical make-up of the device, e.g., its physical attributes, structure, geometry, and material, for realizing an instance of an actual function of the specified type; it is potential and implicit in a device. We cannot enumerate all of the capacity functions $CF_1..CF_n$ of a given device in nature. Then, CF_x, as one of $CF_1..CF_n$, is induced by a user in the use phase according to the context of use (as discussed in the next sub-section), and then AF_y, which is an instance of the specified type of function, emerges. In the example of the screwdriver, if CF_1 is induced by a user, AF_1, which is an instance of the screwing-type actual function, is performed by the device.

We can say "a device performs an actual function" but cannot say "a device has an actual function". We can say "a device has a capacity function" or "a capacity function is ascribed to a device". Thus, when we say "a device has a function", the function referred to is not an actual function but a capacity function.

In philosophy, Boorse (2002) makes a similar distinction in terms of a "weak function statement" and a "strong function statement", which roughly correspond to the actual function (*AF*) and the capacity function (*CF*), respectively. The distinction between *function* and *functioning* in (Johansson et al., 2005) is also similar, and they roughly correspond to *CF* and *AF*, respectively. *CF* is also similar to the notion of *disposition* in (Johansson et al., 2005). We will revisit these topics in Section 5.1.

Differently from most approaches, Hubka and Eder (1988) define functions as follows: "The function is a property of the technical system, and describes its ability to fulfill a purpose, namely to convert an input measure into a required output measure under precisely given conditions." In this definition, a purpose represents intended effects as output effects, whereas a function is the *ability* to perform an internal task of the technical system. Thus, the purpose and the function in their definition roughly correspond to the actual function (*AF*) and the capacity function (*CF*), respectively.

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and a head). We treat not the artistic aspects but only the physical and functional aspects of an artifact. We discuss our view on artifacts in Section 2.7.

[2] CF_x here represents an instance of the capacity function (*CF*). Variable *x* stands for the ID number of the instance. CF_1 in the next sentence is the instance of *CF* with the ID number 1. In this way, throughout this paper, such a symbol plus a suffix variable or number denotes an instance of what indicated by the symbol.

2.2. *Function and Behavior*

For the actual function performed by an artifact, the distinction between function and *behavior* is important. In both engineering and philosophy, this distinction is extensively discussed. In many definitions in engineering, a function is defined as a behavior *intended* by a user (and/or designer) and is regarded as a subset of behaviors. Such intention-relatedness is captured in the literature as “aims-means” (Hubka & Eder, 1988), “means and ends” (Lind, 1994), F-B relationship (Umeda et al., 1996), and as function in value engineering (Miles, 1961).

We model an actual function as a context-dependent entity. We define the *behavior of a device* as the changes in the attribute values of the operands between input and output (Kitamura et at., 2006; Mizoguchi & Kitamura, 2009). By operand, here we mean that a physical thing is input to a device, is changed by the device, and is then output (e.g., water in a boiler). When a behavior type is identified as the behavior of a device, its instances can play different functions (as *roles*, as discussed below) according to teleological contexts, which we call *function contexts* (*FC*), and we will discuss these in the next sub-section. For example, when we identify “to exchange (transfer) heat” as the behavior type of a heat exchanger, which is described as temporal changes of the temperature of a fluid, an instance of the heat-exchange behavior type can play either of the following functions: (1) the function “to give heat” when the heat exchanger is used as a heater with a turbine in a power plant, and (2) the function “to remove heat” when it is used as a radiator in a car engine.

The following definition of *FC* refers to a couple of notions, *Ext-FC* and *Sys-FC*, which, for presentation purposes, are given later.**Def. 1** *Function context (**FC**)* $=_{\text{def}}$ a teleological context that subsumes *External function context* (*Ext-FC*) and *System function context* (*Sys-FC*), which are defined in **Def. 3** and **Def. 6** below, respectively.

Thus, we define an *actual function* as follows:

Def. 2 *Actual function (**AF**)* $=_{\text{def}}$ a role played by a device’s behavior in *a teleological (function) context (FC)* (Kitamura et al., 2006).

The actual function **Def. 2** is clearly distinguished from the capacity function (*CF*) as discussed in the previous sub-section. We call this just ‘function’, as discussed in Section 4. The notions of role and context are regarded as primitives here. By role concept, here we intuitively mean a concept that cannot be defined without a context and whose existence depends specifically on the existence of the context (Mizoguchi et al., 2007). A context for *AF* is called a function context (*FC*), which is a teleological context that subsumes two sub-kinds of contexts defined in the next sub-section. Strictly speaking, a function is a composite of a function-role concept and the behavior playing the function-role concept, which is a kind of a thing called a role-holder (Mizoguchi et al., 2007). Thus, a function is not a selected behavior. Based on the definition, we say that “a behavior plays a function role”[3]. If a device performs a behavior and the behavior plays a function role in a context, then the device plays a *function-performer role* in the context.

In some philosophical considerations (Cummins, 1975; Boorse, 2002; Vermaas & Houkes, 2006), function is regarded as a role, though the role is played by a function-performer. According to the categorization of definitions of function in (Perlman, 2004), our definition is a kind of ‘goal-contribution theory’ in the ‘recent past backward-looking reductionist category’, because our definition is ‘goal-directed’ (see the next subsection) and we need ‘reach back into history as far as the establishment of the goal’ (Perlman, 2004). The general characteristics of roles have been extensively investigated such as ‘externally-founded’, ‘anti-rigid’, and ‘dynamic and multiple’ (Masolo et al., 2004; Mizoguchi et al., 2007). We have shown that function satisfies those generic characteristics (Kitamura et al., 2006). On the other hand, in (Chandrasekaran, 1993; Pahl & Beitz, 1996; Hirtz at al., 2002), function is not distinguished explicitly from behavior based on the intention-relatedness. Some researchers distinguish purpose from function (e.g., (Chittaro et al., 1993; Rosenman & Gero, 1998)), whereby the purpose represents a human-intended goal. Chandrasekaran and Josephson (2000) discuss an environment function as an effect on the environment. While the effect of the function in our definition is local within the device performing the function, the environment function and the purpose capture the effects on the environment or human perception, which are consequences in causal or enabling relations of the local effect. We have clarified these differences in the reference ontology of function (Kitamura et al., 2007). Borgo et al. (2009) investigate a formal account of the definitions of function and behavior in (Chandrasekaran & Josephson,

[3] We know that “a behavior (a kind of occurrent) plays a role” sounds odd as an English expression. Please note that “play a role” here is a technical notion in role theory (Mizoguchi et al., 2007).

2000). Garbacz (2006) points out that a function is a state of affairs that represents a connection between objects and processes. Our definition tries to define the connection in terms of the context from a device-oriented point of view

2.3. ***External Function and Component Function***

When an artifact is performing an actual function (AF_x), the function is dependent on a function context (FC_y), as discussed above. In this section, we introduce another dimension for characterizing FC_y to explain the distinction between *external* and *component functions*. The dimension is related to what determines FC_y. The distinction is based on the system boundary (interface) between a system and an intentional agent. Based on such a boundary, we call such a system and an agent the *whole system* and the *end-user* (or just "user"), respectively, and say that the user 'uses' the whole system[4] . So, by the whole system, here we mean the system (1) that is composed of sub-systems and/or components (as a device-oriented system), (2) that is the largest and outermost device that has an interface to an end-user, and (3) (if the system is an artifact) that is directly operated by the end-user for his/hers specific purpose (e.g., a tool is operated by an end-user). The detailed distinction is explained below. Based on this distinction, we categorize actual function into external actual functions *(Ext-AF)*, relative to *external function contexts*, and component actual functions *(Cmp-AF)*, relative to *system function contexts*, as below. The goal state to be realized by performing the *Ext-AF* is intended by the end-user (called Intentional-goal (I-goal) in (Mizoguchi & Kitamura, 2009)). By the word "external" here, we mean that its *context* is *external* to the whole system in the sense above. Thus, all of the performances of external actual functions are directly intended by a user[5].

Def. 3 *External function context* (***Ext-FC***) $=_{\text{def}}$ a function context (*FC*) determining how the whole system is used by an (external) end user. The *Ext-FC* is fixed by the end-user's intention.

Def. 4 *External actual function* (***Ext-AF***) $=_{\text{def}}$ an actual function (*AF*) performed by the whole system under an *external function context (Ext-FC).*

An artifact generally has some capacity functions CF_1.. CF_n for external actual functions. We define them as *external capacity functions* (*Ext-CF*) as follows:

Def. 5 *External capacity function* (***Ext-CF***) $=_{\text{def}}$ a capacity function (*CF*) can realize an *external actual function (Ext-AF).*

Then, among those possible $Ext\text{-}CF_1$..$Ext\text{-}CF_n$, an external actual function $Ext\text{-}AF_x$ is performed according to the user's specific intention. For example, a screwdriver can be used for performing a screwing (rotating a screw) function or a hitting (exerting linear force on something) function using the base of the screwdriver handle. Some of such capacities are intentionally designed by the designer, as discussed in the next section. Note that the distinction between external (*Ext*) and component (*Cmp*) functions is orthogonal to the distinction between actual function (*AF*) and capacity function (*CF*). Thus, we call it just *external function* (*Ext-F*) if the latter distinction is not needed.

Def. 6 *System function context (**Sys-FC**)* $=_{\text{def}}$ a function context determining how a component embedded in a system contributes to the realization of the system's whole actual function collaboratively.

Def. 7 *Component actual function (**Cmp-AF**)* $=_{\text{def}}$ an actual function performed by a component embedded in a system under a *system function context (Sys-FC).*

The functions of the heat exchanger discussed above are examples of this type. When the heat exchanger is embedded in a power plant, which performs the whole function "convert heat energy to electricity", the heat-exchange behavior plays the function-role "to give heat" as a component actual function $Comp\text{-}AF_1$, which contributes to the realization of that whole function collaboratively under the system function context $Sys\text{-}FC_1$. Precisely speaking, such functional contribution to the whole system's function is done through the nested hierarchical structures of sub-systems. So, a component actual function $Cmp\text{-}AF_x$ of a device is dependent directly on the smallest larger sub-system that contains the device. $Cmp\text{-}AF_x$ contributes to the sub-system's function collaboratively with other components. This sub-system's function is determined by further larger sub-system. Such nested contribution structure is so-called a *functional structure*.

[4] The word "use" has at least two meanings in general. One is that an intentional agent directly operates the whole system with a specific intention to make the whole system work and then to make it generate intended changes (output(s)) for his/her own purpose. We mean this sense of the word here and call the agent an "end-user" for easy understanding. Another case is when a designer (or a manufacturer) of a system uses an artifact as a component to integrate in a system.

[5] Note that the success of the actual function and its validation by a user are different problems.

As discussed for the external function, we define component capacity function (*Cmp-CF*) below, and we call this just *component function* (*Cmp-F*) if the distinction between *AF* and *CF* is not needed.

Def. 8 *Component capacity function* (***Cmp-CF***) $=_{def}$ a capacity function (*CF*) can realize a *component actual function (Cmp-AF).*

The functional structure is the hierarchy of functions in the system and is also known as "degree of complexity" (Hubka & Eder, 1988), function decomposition (Pahl & Beitz, 1996), or function achievement relation (Kitamura et al., 2006). Causal-role function analysis (Cummins, 1975) also captures the relationships between the whole function and the component functions as contributions. Furthermore, the constituent function (Johansson, 2006) is similar to the component capacity function.

The external vs. component distinction is related to the issue of what a function depends on. The external function depends primarily on a user's intention, whereas a component function depends directly on the functional structure of the system. For an artifact, the component capacity functions $Cmp\text{-}CF_1..Cmp\text{-}CF_n$ as a standalone device are determined by the designer of a component rather than the designer of the system. When a component is embedded in a system, however, some component capacity functions $Cmp\text{-}CF_1..Cmp\text{-}CF_m$ are selected from $Cmp\text{-}CF_1..Cmp\text{-}CF_n$ (where $m \le n$) according to $Sys\text{-}FC_1$ determined by the designer of the system[6]. The external actual function $Ext\text{-}AF_1$ of the whole artifact system is determined by the user's intention. In this sense, the component actual function $Cmp\text{-}AF_x$ of an artifact *indirectly* depends on the user's intention as well. For a biological organ in an organism, Section 5.1, its component actual function $Cmp\text{-}AF_y$ contributes to the function of the organism as the whole system in the same manner as that of an artificial component.

We thus separate the user's intention and the designer's intention from the system function context $Sys\text{-}FC_x$ of the component function, and thus we regard the component function (*Cmp-F*) as being dependent only on the system. So, the general notion of a component actual function ($Cmp\text{-}AF_x$) is independent of the designer's and user's intentions. In other words, $Cmp\text{-}AF_x$ contributes to a "non-intentional" goal (the NI-goal in (Mizoguchi & Kitamura, 2009)) given by the system's view that all components contribute to the entire system's function.

*2.4. **Essential Function and Accidental Function***

There is another dimension to categorize a function namely, *essential function* vs *accidental function*, according to the designer's intention. This distinction is orthogonal to both the distinction between actual and capacity functions (*AF/CF*) and that between external and component functions (*Ext/Cmp*). So, any instance of these functions can be categorized into essential or accidental.

Def. 9 *Essential actual function (**Ess-AF**)* $=_{def}$ an actual function (*AF*) that is intended by a designer to be realized in the use phase envisioned by the designer.

Def. 10 *Essential capacity function (**Ess-CF**)* $=_{def}$ a capacity function (*CF*) to perform an essential actual function. The physical make-up necessary for realizing the performance is intentionally designed by the designer and is manufactured.

After the design and manufacture of an artifact, the artifact has at least an $Ess\text{-}CF_y$ to perform an $Ess\text{-}AF_x$. In addition to $Ess\text{-}CF_y$, the manufactured artifact might have other $CF_{x'..y'}$ that are not intended by the designer but that potentially inhere in the device, called *accidental capacity functions*.The *Acc-CF* of an artifact are distinct from its *Ess-CF*.

Def. 11 *Accidental actual function (**Acc-AF**)* $=_{def}$ an actual function that is not intended by the designer.

Def. 12 *Accidental capacity function (**Acc-CF**)* $=_{def}$ a capacity function to perform *Acc-AF*.

According to the definitions, *Ess-AF* (or *Ess-CF*) of a device is disjoint with *Acc-AF* (or *Acc-CF*) of the same device. In the case of the external use of artifacts, according to a given external function context $Ext\text{-}FC_1$ and appropriate inputs, either an essential or accidental capacity function ($Ess\text{-}CF_x$ *or* $Acc\text{-}CF_y$) is induced and exhibited as an *essential external actual function* ($Ess\text{-}Ext\text{-}AF_{x'}$) or an *accidental external actual function* ($Acc\text{-}Ext\text{-}AF_{y'}$). In the example of the screwdriver discussed above, the screw rotating function and the hitting function are essential ($Ess\text{-}CF_1$ and $Ess\text{-}Ext\text{-}AF_1$) and accidental ($Acc\text{-}CF_2$ and *Acc-*

[6] As noted above, this action can be regarded as 'use' of a component. However, in this paper the terms 'use' and 'user' are reserved for the end-user's direct operation of an artifact.

$Ext\text{-}AF_2$), respectively. The former function is intended by both the designer and the user. The latter function is intended not by the designer but by the user. This distinction is relative to a device. For example, the screw rotating function could also be performed by a key as an accidental function. The hitting function is an essential function of a hammer.

In the case of an artificial component in the system, if a component in a given system function context $Sys\text{-}FC_1$ performs AF_x that is an instance of the same function type intended by the designer of the component, it is an *essential component actual function* ($Ess\text{-}Cmp\text{-}AF_x$); if not, it is accidental. The latter case is where the designer of the system uses the component in a way that differs from that intended by the component's designer. For example, slurry containing diamond powder is manufactured for improving cutting efficiency. However, in a cutting machine, the slurry is also used for cooling the cutting blade. In such a case, from the viewpoint of the intention of the designer of the slurry as a component, the slurry performs a cooling function as an accidental component actual function ($Acc\text{-}Cmp\text{-}AF_y$).

The essential vs accidental distinction applies also to *non-designed entities*, that is, to physical entities that are not intentionally designed like biological organs and non-biological natural things. All *external* functions (*Ext-F*) of such non-designed entities are regarded as *accidental* (*Acc-F*). If there is no designer of a system (e.g., an organism), its component functions (*Cmp-F*) are *essential* (*Ess-F*), because they are developed in nature (e.g., by natural evolution). If there is a designer of a system and no designer of a component (e.g., an artifact has a natural thing as one of its parts), the component function (*Cmp-F*) of the component is *accidental* (*Acc-F*) in the same manner as the external function (*Ext-F*). So, we can extend **Def. 9** and **Def. 11** to include non-designed entities as follows[7]:

Def. 9' *Essential actual function (**Ess-AF**)* $=_{def}$ For an artifact, an actual function (*AF*) that is intended by the designer to be realized in the use phase envisioned by the designer. For a non-designed entity, if it is a component that does not have a system designer, its component actual function (*Cmp-AF*).

Def. 11' *Accidental actual function (**Acc-AF**)* $=_{def}$ For an artifact, an actual function that is not intended by the designer. For a non-designed entity, its external actual function (*Ex-AF*) and, if a non-designed entity is part of an artifact, its component actual function (*Cmp-AF*).

*2.5. **Actual function and Specification of Function***

In this section, we distinguish a realized function from a required function to be realized. A so-called *required function* in engineering design is a design requirement to realize (embody) an artifact that can perform the specified type of actual function in the proper envisioned use context (in the screwdriver example, to rotate a screw when held in the user's hand). The type of function is discussed in the next sub-section. We call such a function a *required function in the design phase* (*RFd*). It exists in nature as a *specification of function*, defined as follows:

Def. 13 *Specification of function (**SoF**)* $=_{def}$ a proposition that specifies mainly what type (e.g., rotating-type) of actual function (AF_x) is required to be realized in the use phase. It also sometimes specifies values of the qualities related to the performance of a function, called *functional parameters*, e.g., the maximum torque value for the rotating-type function.

Def. 14 *Required function in the design phase (**RFd**)* $=_{def}$ a specification of function (*SoF*) that is given as a part of a design requirement before designing.

The notion of *specification* is treated as a primitive here. By specification, here we mean a *proposition* that specifies an entity in the real world independently of whether or not it is explicitly written. For a detailed discussion of the general sense of specification, please refer to (Mizoguchi, 2003, 2004).

In addition to the *required function in the design phase* (*RFd*) introduced above, there is the *required function in the use phase* (*RFu*), which a user has in mind as a requirement to realize a specific type of function (e.g., to hit a nail) before he/she uses an artifact (say, a hammer). They are defined as follows:

Def. 15 *Required function in the use phase (**RFu**)* $=_{def}$ a specification of function (*SoF*) that is intended by a user before use as an implicit (non-written) specification of function.

More generally, we define required functions as follows:

Def. 16 *Required function (**RF**)* $=_{def}$ a *specification of function* (*SoF*) that subsumes the *required function in the design phase* (*RFd*) and the *required function in the use phase* (*RFu*).

[7] In the same way, we can extend **Def. 10** and **Def. 12.**

We can generally say that a required function RF_x mainly specifies a type of an actual function AF_y required to be realized.

If design, manufacture, and use are successful, the required function as a specification of function SoF_x is realized as an actual function AF_y that satisfies the required specification SoF_x. In this case, we say that there are the following relations between them:

AF_y "*is-realization-of*" SoF_x and AF_y "*satisfies*" SoF_x

If not, it means that some act fails. We discuss such relationships in detail in Section 3. These relations "*is-realization-of*" and "*satisfies*" can be used for any specification as discussed below.

The specifications of function can be categorized into two kinds. One specifies the type(s) of functions to be used externally. In other words, it specifies the external actual function (*Ext-AF*) of an artifact as a whole (we call this type just "specification of function" (*SoF*) hereafter). The required function above is typically of this kind. Another specifies a functional structure and thus specifies types of the component actual functions (*Cmp-AF*) to realize the whole function. We call this type "specification of functional structure" (*SoFS*). The result of the conceptual design includes both kinds of specification of function: *SoF* and *SoFS*.

The capacity function (*CF*) also has the sense of *specification* that specifies what type of actual functions the device can perform in the use phase, though it has the sense of 'possibility' as well. *Capacity function* (*CF*) consists of a capacity and a specification of function (*SoF*), which specifies what type of actual function the device can perform.

In the same manner, we can consider a *specification of a device* (*SoD*), *a specification of behavior* (*SoB*), and *a specification of function context* (*SoFC*). For example, a specification of a device is typically produced as the result of designing and specifies the physical properties of the device to be manufactured. In this case, we can say "the device *is-realization-of SoD* and "the device *satisfies SoD*".

2.6. Types and Instances of Functions

We have discussed instances of function thus far. We can identify generic types of function in *is-a* hierarchies, such as those in (Hubka & Eder, 1988; Pahl & Beitz, 1996; Hirtz et al., 2002). We have also proposed an ontology of generic functional types called a functional concept ontology (Kitamura et al., 2002). In the ontology, a functional type is defined by constraints[8] on both behavior and function context (Sasajima et al., 1995; Kitamura et al., 2002). The constraint on behavior is needed for restricting what behaviors can play an instance of the function type as potential role-players. The constraints on function context specify mainly which parts of behavior are focused on in the function context from a teleological viewpoint. For example, a definition of the "to give heat (to medium A)" function includes behavioral constraints: the existence of two mediums A and B for heat and the existence of a thermal energy flow from B to A. The definition includes also a focus on the transferred thermal energy and a focus on the heat receiver (the medium A) for teleological interpretation, which collectively specify the functional context. Refer to (Sasajima et al., 1995; Kitamura et al., 2002, 2006) for details of how a function type is defined. The important point here is that we can define the generic functional types without reference to a concrete entity (e.g., a heat-exchanger).

2.7. Types and Instances of Artifacts

Function is one of the main aspects of artifacts from an engineering point of view. We intuitively define an artifact as "a physical object created by an intentionally performed production process, which is intentionally performed by one or more agents with the goal of producing the object which is expected to realize intended behavior in some given generic technical situation" (Borgo et al., 2011b)[9]. The goal of the agent is that, under a given situation, the produced object will realize (exhibit) a specific behavior, which in

[8] The function type is defined here by constraints to be satisfied by instances of function that belong to the type. This way of defining a type is a so-called intensional way rather than the extensional way in artificial intelligence research [Sowa, 2000, p.99]. In addition, a functional type specifies its instances. In this sense, a functional type is similar to a specification of function (SoF_x). In fact, the *instance-of* relation is similar to the *realization-of* relationship between SoF_x and an instance of actual function AF_y. A specification of function (SoF_x) is, however, not a type, but is an entity at the instance level.

[9] Defining artifacts is not our main aim here. Our aim is to explain the relationship between artifacts (and artifact-types) and function from our point of view. See (Borgo et al., 2011b).

turn realizes a specific type of its essential actual function (*Ess-AF*$_x$). This view of an artifact is not based on the user's intention in the use phase but on the designer's and manufacturer's intention in the design phase and the manufacturing phase. In short, a designer intends that an artifact will have an essential capacity function (*Ess-CF*$_y$) after manufacturing. Note that an artifact in the use phase might not have actually the essential capacity function *Ess-CF*$_y$ intended in the design phase and in the beginning of the manufacturing phase. A type of an artifact (e.g., the screwdriver type) can be given in terms of a type of essential capacity function that is intended by the designer and/or the manufacturer. We here just assume the existence of conditions for determining whether an instance belongs to a specific type or not.

2.8. ***Summary of kinds of functions***

Figure 1 shows a summary of the kinds of functions which are defined in Sections 2 and 3 with subsumption relations among them. As discussed before, the distinctions shown in the first level in Figure 1 are orthogonal to each other. So, we can specify a kind of function by the conjunct manner as shown in the second and the third levels. The functions at the third level in Figure 1 are not exhaustive. Table 1 summarizes the major relations among them.

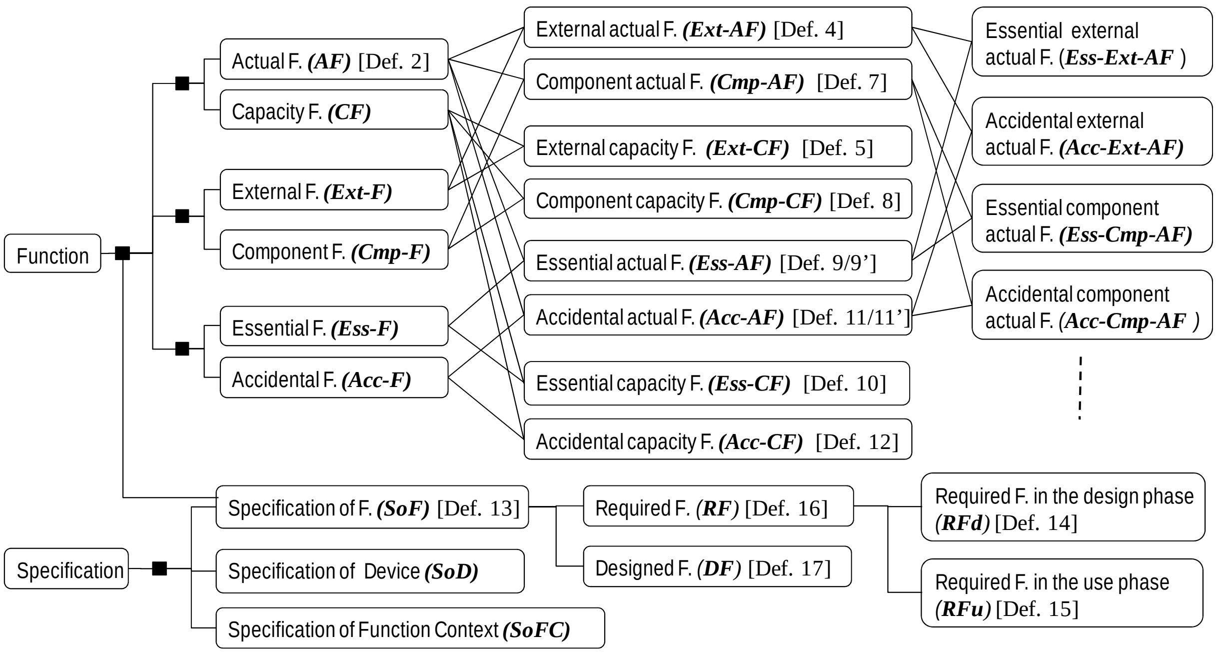

Figure 1. A summary of kinds of functions with subsumption relations

Table 1. A summary of major relations.

Relation	Domain	Range
is-realization-of (general)	Any realizable entity	Specification
is-realization-of (subtype 1)	Actual F. (*AF*)	Specification of F. (*SoF*)
is-realization-of (subtype 2)	Device (*D*)	Specification of Device (*SoD*)
is-realization-of (subtype 3)	Function Context (*FC*)	Specification of *FC* (*SoFC*)
satisfy (general)	Any realizable entity or specification	Specification
satisfy (subtype 1)	Actual F. (*AF*)	Specification of F. (*SoF*)
satisfy (subtype 2)	Capacity F. (*CF*)	Specification of F. (*SoF*)
satisfy (subtype 3)	Specification of F. (*SoF*)	Specification of F. (*SoF*)
induced	Actual F. (*AF*)	Capacity F. (*CF*)

3. A Phase-oriented Model of Function

In this section, we discuss temporal changes in the existence of function in the phases in a product life-cycle using the distinctions and the kinds of function introduced in Section 2. The transitions between phases are made by acts such as designing, manufacturing, and use. The aim of this section is to investigate the ontological issues, such as what kinds of function exist in these phases and when a function comes into existence and disappears. We propose a model of macroscopic temporal changes of function based on the product-life-cycle phases, which we call a *phase-oriented model* of function or an *ecological model* of function. Figure 2 shows a part of the model of a screwdriver as an example. It shows macroscopic temporal changes of the instances of function, where time flows from left to right. Each entity is denoted by a symbol name plus a suffix number in the same way as above. For example, AF_1 indicates an instance of the actual function (*AF*), which is a different instance from AF_2. Each (a),(b) etc. in Figure 2 gray box represents a phase in a time interval or at a time point. For example, Figure 2(a) represents the phase at the starting time point of the designing activity. The transition from one phase to the next phase is made by an act depicted as a dark-gray arrow in Figure 2. For example, the design act causes the transition from the phase (a) to the design result phase shown in (b). In the following sections, we discuss what kinds of function exist in what phase and the relations among them.

3.1. *Designing Activity*

For a designing process, as discussed in Section 2.5, a function context (FC_x) of anticipated use and a required function in the design phase (RFd_y), which mainly specifies a type of an actual function to be realized, are usually given as a design requirement. In Figure 2(a), they are represented as specifications. The former anticipated function context is represented as a specification of a function context ($SoFC_1$: "to drive a screw", in the screwdriver example). The latter required function (RFd_1: "rotating a screw" (screwing)-type) is represented as a specification of function, which specifies that an instance of the screwing-type function should be performed by a device to be designed. Precisely speaking, based on the device ontology, the function of screwdriver is "to increase torque". Its functional input and output are the torque given by the hand and that on the slot(s) in the head of the screw, respectively. It is simplified here for easy understanding. It is regarded also as a function-level specification of the device. Note that these specifications of the functional context and the function are incomplete in many cases.

After the designing process, more detailed specifications of the device and of the function are determined as a result of the designing act for satisfying the design requirements. In Figure 2(b), as the design result, a *designed function* (DF_1), a specification of functional structure ($SoFS_1$), and a specification of a device (SoD_1) are shown.

Def. 17 *Designed function (DF)* $=_{\text{def}}$ a specification of function (*SoF*) that is a result of the designing act and specifies the designer's intended actual function (AF_x) to be existent in the real world. Typically, it

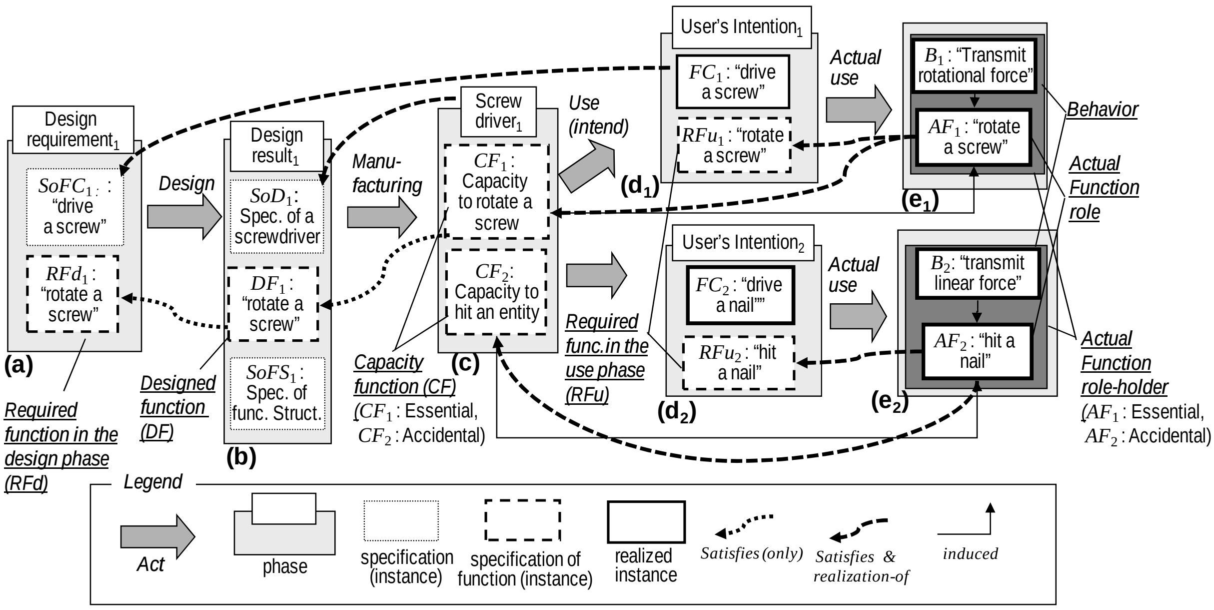

Figure 2. A phase-oriented model of function.

specifies the type of AF_x and the values of some functional parameters (see Def. 13).

The distinction between *RF* and *DF* is based on their occurrence in the product-life cycle. *DF* and *RF* are better understood when seen as roles in the context of the product life-cycle.

In the example of Figure 2, the designed function DF_1 specifies the rotating-type of an external actual function ($Ext\text{-}AF_x$) and its functional parameters (e.g., the maximum torque) in the anticipated use context $SoFC_1$. If the designing task is successful, DF_1 as a specification of function *satisfies* the required function RFd_1. This relationship "*satisfies*" holds when DF_1 satisfies all the constraints specified by RFd_1 and is a more detailed specification than RFd_1 typically with respect to constraints on functional parameters. Note that this relationship "*satisfies*" is different from that discussed in Section 2.5 between AF_y and SoF_x. On the other hand, $SoFS_1$ restricts component actual functions (*Cmp-AF*) in the whole system under their system function contexts (*Sys-FC*).

A specification of a device SoD_1 specifies the physical make-up, such as the shape (e.g., the shape of the head of a screwdriver for fitting in the slot(s) in the head of a screw), the material, and so on to be realized by manufacturing[10].

3.2. *Manufacturing Activity*

The manufacturing activity involves making a device in the real world which satisfies the given specification of the device. In the example of the screwdriver in Figure 2, the manufacturing activity makes an instance of the screwdriver type of device C_1 that satisfies the conditions of the specification of a device SoD_1 as shown in Figure 2(c). The screwdriver instance C_1 has an *instance-of* relation with the screwdriver-type and has a *realization-of* relation with the specification of a device SoD_1. As discussed in footnote 8, these relations have the same role, that is, to restrict the screwdriver instance C_1.

In Figure 2(c), the screwdriver instance C_1 has a capacity function CF_1, which is the capacity to perform an instance of the "rotate a screw"-type actual function. The existence of CF_1 is based on the designed function DF_1 as a result of the designing. Thus, CF_1 is an *essential capacity function* (*Ess-CF*). The content of CF_1 is realized by the manufacturing process. If the manufacturing is successful, CF_1 *satisfies* DF_1. In addition, C_1 could have *accidental capacity function*s (*Acc-CF*). Those *Acc-CF*s are based on the physical properties of C_1 as the derived (and unintended) results of the designing and the manufacturing for realizing the designed function DF_1. In Figure 2(c), C_1 has $Acc\text{-}CF_2$, which is a capacity to perform an instance of the "to hit an entity"-type *AF*. In general, CF_x is based on physical makeup of a device C_y as the result of the manufacturing. If the physical makeup can realize AF_z that satisfies the given $DF_{z'}$ for C_y, then CF_x is essential. If not, CF_x is accidental.

3.3. *Use Activity: Intending to Use*

Figure 2(d_1) shows a situation where a user intends to realize a specific function in a specific *external function context* (*Ext-FC*). There is an external function context (FC_1: "to drive a specific screw (screw$_1$)") and a *required function in the use phase* (RFu_1: "to rotate the screw$_1$"). The RFu_1 represents the user's intention to realize an instance of the specified-type of actual function as a specification of function. The required function in the design phase RFd_1 specifies only looser restrictions on actual functions in a generic context, whereas the required function in the use phase RFu_1 specifies tight restrictions on the instance of the actual function in the function context that is fully determined according to the specific context of use. However, the function context FC_1 and the required function in the use phase RFu_1 specify neither the instance of the device to perform the function nor type of devices. Thus, the user does not determine what device he/she wants to use in this phase yet.

Vermaas and Houkes (2006) emphasize that functions are features that are ascribed by agents to artifacts relative to use plans and human beliefs regarding capacity. Our external function context depends on such a "use plan," though such agent's beliefs regarding capacity are implicit.

[10] Although someone could regard the specification of a screwdriver SoD_1 as a sub-type of the screwdriver type, we do not adopt this view because this view implies that each designing process generates a new type of device.

3.4. *Use Activity: Actual Use*

As shown in Figure 2(e_1), if a device C_1 is used in the function context FC_1 intended by a user and the device C_1 has the capacity to perform a function satisfying the required function in the use phase RFu_1, the device performs a behavior instance B_1 and the behavior B_1 plays an actual function AF_1 as a role in the intended function context FC_1. This is a result of a user's activity of selecting such a device C_1 that has a capacity to perform the actual function AF_1 that can satisfy the required function in the use phase RFu_1. Thus, AF_1 *satisfies* RFu_1 and AF_1 *is-realization-of* RFu_1 (See Section 2.5).

In Figure 2(e_1), because the actual function AF_1 satisfies the capacity function CF_1 (that is, the essential capacity function (*Ess-CF*) of the device C_1) associated with the designed function DF_1 as a result of the designing process, we can say that an essential function of the device C_1 is actually performed, and that AF_1 is an essential external actual function (*Ess-Ext-AF*). As a result, AF_1 is a *realization-of* DF_1, CF_1, and RFu_1.

On the other hand, as shown in Figure 2(d_2) and 2(e_2), an actual use of an accidental capacity function (*Acc-CF*) of the device C_1 can be represented as a situation where the actual function instance AF_2 *satisfies* a different required function in the use phase RFu_2 under a different functional context FC_2 based on the accidental capacity function CF_2 ("to hit an entity"). The capacity that implicitly inheres in the device is induced by the use, and then an accidental external actual function (*Acc-Ext-AF*) AF_2 is performed.

Thus, the performance of an actual function (AF_1 or AF_2) can be regarded as successful if it *satisfies* both the required function in the use phase (RFu_1 or RFu_2) and the capacity function of a device (CF_1 or CF_2). If not, it represents the case of failure to perform an actual function for given required function.

In Figure 2(e_1), AF_1 is an instance of the rotating function-role type. The existence of this role-instance primarily depends on the intended function context FC_1. Then, the actual function-role instance AF_1 and the behavior B_1 as its player compose a role-holder as a complete actual function. From a temporal point of view, these occurrences are at the same time point. From the viewpoint of causality, however, we can consider that the causal order of these occurrences is the existence of the function-role and then the role-playing by the behavior. In this sense, the existence of the actual function as a role-holder also depends primarily on the function context FC_1 as the user's intention, while also depending on the device's capacity function (for the existence of the behavior) as well.

3.5. *Use Activity: Non-Use and Malfunction*

In a situation where the screwdriver C_1 is not used, we can describe this situation as a model in which the capacity functions CF_1 and CF_2 exist as properties of the screwdriver C_1 and there is neither functional context nor actual function.

In our view, malfunction of an artifact is defined with respect to its designed function (*DF*) determined by a designer. Its main part is the type of function F_T[11] to be realized as an instance of actual function. In addition, it includes the level of performance of the functioning. So, an artifact instance $\boldsymbol{x}$ is said to be malfunctioning with respect to the designed function DF_x, which is an instance of F_T, *iff*: (0) it is explained that the designer intended that $\boldsymbol{x}$ has a capacity function CF_y satisfying DF_x; (1) the appropriate function context (e.g., based on the user's intention) for the required function in the use phase RFu_z, which is an instance of F_T, is given to $\boldsymbol{x}$; (2) the appropriate behavioral inputs for realizing RFu_z are given to $\boldsymbol{x}$; and (3) an actual function instance realized by $\boldsymbol{x}$ does not satisfy DF_x. The condition (0) specifies the presumption that artifact $\boldsymbol{x}$ is designed for DF_x. The condition (1) excludes cases where $\boldsymbol{x}$ is not used and $\boldsymbol{x}$ is improperly selected for RFu_z. The condition (2) excludes cases where sufficient conditions are not given for use of $\boldsymbol{x}$ for F_T.

There are two cases of dissatisfaction of DF_x: (a) the artifact $\boldsymbol{x}$ has a capacity function instance CF_y of F_T but it is insufficient, so that the level of performance of an actual function (e.g., the output temperature of a heating function) is insufficient with respect to DF_x, and (b) $\boldsymbol{x}$'s capacity function instance CF_y of F_T is lost, so that $\boldsymbol{x}$ cannot perform an actual function of F_T.

For example, let us consider a situation where there is a crack in the shaft of the screwdriver C_1, and, when a user uses it for rotating a screw in the right way, the shaft breaks and thus the user fails to rotate the screw (the case (b) above). In this case, it is explained that the designer intended that C_1 has the rotating capacity function CF_1 (the condition (0) above), the user uses C_1 with the intention of rotating RFu_1 (the

[11] As an exception to the usual nomenclature in this paper, F_T represents not an instance but a type of function.

condition (1)), appropriate behavioral conditions are given (the condition (2)), then an actual function AF_1 exists for a moment then immediately disappears due to the breakage of the shaft. This situation is recognized as malfunctioning of the screwdriver C_1 according to the definition above.

The explanation above is mainly of malfunction of the external function (*Ext-F*) of the whole artifact. For a component function (*Cmp-F*), its malfunction is defined with respect to a specification of functional structure (*SoFS*) determined by the designer. Note that the functional context and behavioral inputs for a component are given by the connected components and the upper-level system (i.e., the functional structure with the system structure).

3.6. ***Summary of Existence of Function***

The following shows a short summary of the existence of instances of function discussed thus far.

- Start of designing (shown in Figure 2(a)): A required function in the design phase (RFd_x) (as a specification of function (SoF_y)) exists as given inputs for designing.
- Result of designing (Figure 2(b)): A designed function DF_z (as a specification of function) exists as a design result.
- Result of manufacturing (Figure 2(c)): Capacity functions $CF_{n..m}$ (as specifications of function) inhere in the device as its properties.
- The time when a specific use is intended (Figure 2(d)): A required function in the use phase ($RFu_{x'}$) (as a specification of function) exists in an external function context ($Ext\text{-}FC_{y'}$) representing the user's intention.
- During actual use (Figure 2(e)): An actual function ($AF_{z'}$) role exists and is played by a behavior performed by a device. The actual function-role and the behavior compose an actual function role-holder as a complete existence of the actual function.

Thus, the answers to the ontological issues noted in the Introduction, such as "when a function exists" and "on what the existence of a function depends", are different according to the kinds of function to be considered. For the actual function (*AF*), an instance of that function $AF_{z'}$ (1) comes into existence when a device is actually performing the function, (2) exists dependently on a function context ($Ext\text{-}FC_{y'}$) for the function as the user's intention, (3) exists dependently on the device's capacity function ($CF_{z''}$), where $CF_{z''}$ is one of $CF_{n..m}$, (4) exists dependently on the existence of a behavior as a player and of the performing device, and (5) exists as a role-holder.

On the other hand, for the essential capacity function (*Ess-CF*), an instance of that function $CF_{z''}$ (1) comes into existence when a manufacturing process of a device finishes, (2) depends on the designer's intention for the device (i.e., DF_z), (3) exists dependently on the device, and (4) inheres essentially in the device. The main contribution of this paper is that the ontological distinctions introduced here enable us to clearly describe such propositions based on different perceptions of function.

4. Justification of "Function" from an Engineering Point of View

In this section, we justify our definition of function (Kitamura et al., 2006; Kitamura & Mizoguchi, 2009a; Mizoguchi & Kitamura, 2009) using the distinctions proposed in Section 2 from an engineering point of view. First, recall that we take the actual function (*AF*) as the primary notion. The first justification for this is the importance of *actual effects* and value for users from an engineering viewpoint. What is important in engineering is what type of actual effects are realized in the use phase. This is represented as an instance of a specific type (e.g., "giving-heat") of the actual function in the use phase. In philosophy, much work treats capacity function (in our terminology) as just a capacity and pays little attention to the type of realized effects. As a consequence, some classify the act of walking as a function, which realizes no effect on others.

The second justification of actual function as our primary definition is the definition of those specific types of function. Such a definition (e.g., the "giving-heat function" type) refers to a behavior as a role-player (heat-flow between two entities) and a function context as a role context (the teleological focus on the heat-receiving entity), as discussed in Section 2.6. Thus, these specific types of function are defined as sub-types of the actual function. Each capacity function cannot be defined without referring to those types of actual functions. For example, the heat-exchanger has two capacity functions, which are the capacities to perform the giving-heat actual function and the removing-heat actual function. In addition, the required function (*RF*) in engineering design refers to those types of actual function in the same manner. In the design phase, there is no *instance* of the actual function to be realized, but its *type* exists before almost all designs start[12].

The third justification is from the realization-independence of function. A specific required function RF_x can be realized by different artifacts with different physical features. This engineering requirement justifies our definition of function not as the capacity function, which is a property of an artifact, but as an actual function *detached* from artifacts, which is a role played by the behavior of a device.

As a consequence, the existence of an instance of actual function AF_x is *dynamic.* It exists dependently on a specific function context, such as a user's intention, and its existence is supported by a realized behavior of a device and the device's capacity to perform AF_x. This dynamism fits in well with the function's properties, which are dependence on contexts and realization-independence. On the other hand, an instance of essential capacity function $Ess\text{-}CF_y$ exists during the whole period of the device's existence, except during (a kind of) malfunctioning as discussed in Section 3.5. Thus, its existence is *stable*. This difference is the result of the detachment of function from a device.

Our definition of function includes accidental actual functions (*Acc-AF*), as well as essential actual functions (*Ess-AF*). An accidental use is distinguished from a (proper) function in many philosophical writings (e.g., (Perlman, 2004; Wouters, 2005)). Such accidental use is called "function-as." We regard an accidental effect as a function if it is recognized in a specific function context. If not, it is a behavior. The first justification for our use of the term 'function' here is the effect-oriented definition from the engineering viewpoint. As actual effects, $Ess\text{-}AF_x$ and $Acc\text{-}AF_y$, which are instances of the same type of function, can have the same intended effect for users[13]. The second justification is that our primary definition of function is an actual function, which is different from the capacity function inhering in a device, which is mainly discussed in philosophy.

5. Characterizing Functions along the Evolution of Creatures

In this section, we try to explain the differences among the notions of functions of artifacts, biological organs, non-biological natural things, and the artifact function using our terminology. The differences between biological functions and artificial functions are extensively discussed in (Vermaas, 2009). Our approach is to characterize those differences based on an ontological model along the evolution of creatures using the ontological distinctions discussed in Section 2. We call this model an evolution-oriented model of function, which is depicted in Figure 3.

5.1. ***Pre-human era: Bio-function***

In the pre-human[14] era, there was no external use of biological organs. So, in our terminology, there was no *external function* (*Ext-F*) of a biological system based on the user's intention, but only *component functions* ($Cmp\text{-}F_x$) under *system function contexts* ($Sys\text{-}FC_y$). For example, the function of the heart, "to increase the pressure of the blood", is regarded as a component actual function ($Cmp\text{-}AF_1$) that is performed (realized) in the system function context ($Sys\text{-}FC_2$), which is associated with the blood circulation system. This is the same as that of a pump embedded in a fluid circulation system. In this sense, as discussed in Section 2.3, the functions of biological organs and those of artificial components are the same. There is, however, no designer's intention for biological organs, which are developed in nature (e.g., by natural evolution). Thus, as defined in Section 2.4 (see **Def. 9'**), the component function ($Cmp\text{-}F_x$) of biological organs is *essential.* In addition, for a biological organ, the system function context is fixed to the organ and does not change. Thus, the relationship between the organ's capacity function (CF_z) and the

[12] One might think that so-called innovative design invents a new type of function. We think that many such designs invent not a new type of function but a new way of function achievement ("how to achieve a function") (Kitamura et al., 2006) for an existing type of function or new application of an existing function to a different operand. This is a benefit of our detachment of function from the way of function achievement (Kitamura et al., 2006).

[13] By the "same effect", we here mean the same type of the function. The level of optimization of a function's performance measures, which are values of so-called functional parameters such as efficiency, accuracy and reliability, is different between that of $Ess\text{-}AF_x$ and that of $Acc\text{-}AF_y$.

[14] By 'human', we here mean an agent which has abilities to use, design and manufacturing with its intention. So, it includes not only human being but also some of animals and sentient beings.

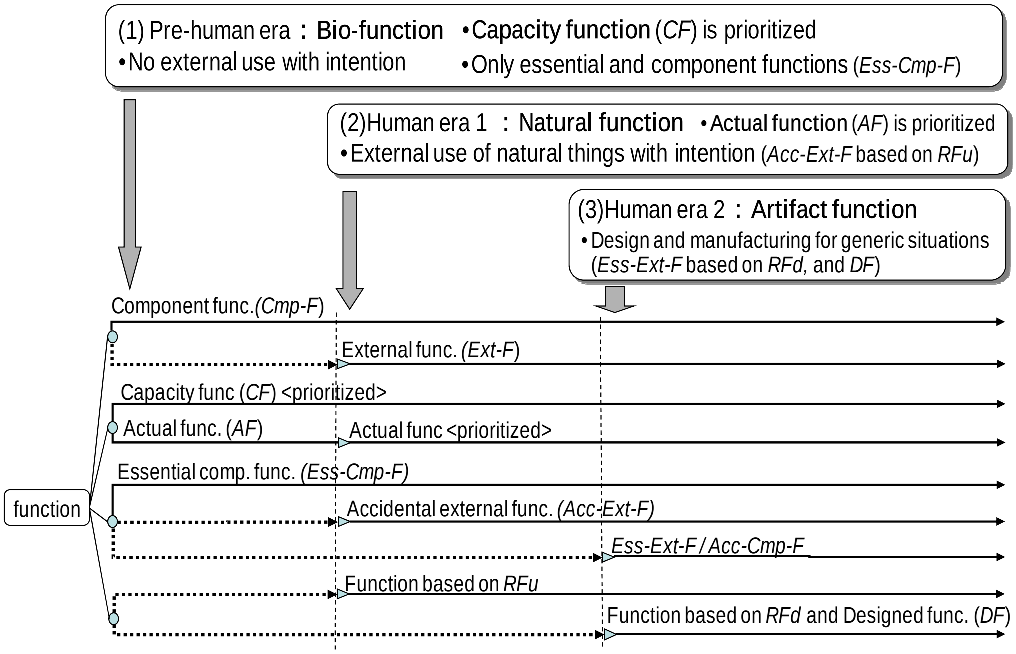

Figure 3. An evolution-oriented model of function.

actual function ($AF_{x'}$) performed by the organ as $Cmp\text{-}F_x$ is *constant*, unlike the component functions of engineering artifacts. This seems to be one of the reasons that the capacity function (*CF*) is prioritized for biological organs. So, in our terminology, the function of biological organs is the *essential and component capacity-function* (*Ess-Cmp-CF*)[15]. Thus, we can regard these notions applicable to this era, as shown in Figure 3. This notion of function can be regarded as the core notion of function.

In fact, in philosophy, a function of a biological organ, typically, inheres in the organ and is an *objective non-relational property*, as pointed out in (Vermaas, 2009). For example, Johansson et al. (2005) define a function of a biological organ as "a disposition to act in a certain way to contribute to the realization of [a ...] larger function on the part of that whole organism which is its host". The function in this definition roughly corresponds to the *component capacity function* (*Cmp-CF*) in our terminology. The notion of "functioning" in (Johansson at al., 2005) roughly corresponds to the *actual function* (*AF*). Arp and Smith (2008) recently proposed a sophisticated definition of biological function under that generic definition[16] of functions, including artifact function as well. That definition includes the component function only in the same manner as the above.

5.2. ***Human era 1: Natural-function***

In the human era, humans *use* a physical thing externally with an intentional goal. In the first phase of this era, physical things were neither intentionally designed nor manufactured. We call such an object a *natural thing* here[17,18]. When a physical thing is regarded as a natural thing and it is used under a teleological intention, it is regarded as performing an *accidental external actual function* ($Acc\text{-}Ext\text{-}AF_x$) for *a required function in the use phase* (RFu_y). For example, let us consider a situation where a pebble, as a natural thing, is used by a user as a paperweight. In our view, the pebble performs the "to exert vertical

[15] The malfunctioning of component functions of biological organs cannot be accounted for based on the definition in Section 3.5, because that definition refers to the designer's intention. This issue remains the topic of future work. We think, however, that the functional structure can be explained based on the domain knowledge, and thus the malfunctioning can be defined with respect to this explained functional structure commonly for biological organs and artifacts.

[16] In (Arp & Smith, 2008), a (generic) function is a *realizable entity* ("realizable dependent continuant"), which has a *realization*(s) as a process in which its bearer is a participant. The realization occurs by virtue of the bearer's physical makeup, which that bearer possesses because of how it came into being. This definition of function is also similar to the *capacity function (CF)*, whereas its realization corresponds to the *actual function (AF)*.

[17] We exclude biological things, organic things, and living things from the natural things discussed here.

[18] Our goal here is neither to define notions of artifacts and natural things nor to define the designing and manufacturing activities that change a natural thing to an artifact. Instead, we discuss their functions, when a physical thing is regarded as a (non-biological) natural thing. Borgo and Vieu (2009) extensively investigated an ontological definition of 'artifact'. We are currently engaged in collaborative research on the comparison of some definitions of artifacts with Borgo et al. (2011b).

force on a piece of paper" function as an accidental external actual-function (*Acc-Ext-AF*$_1$). The pebble potentially has the capacity to perform that function as an accidental capacity function (*Acc-CF*$_2$) based on its weight and the shape of its bottom. It is induced by the use as a paperweight[19]. It is regarded as *accidental*, because there is no designer's intention for external use of a natural thing (see **Def. 11'**). It is impossible to enumerate all the capacity functions ($CF_{n..}$ CF_m) of a natural thing like the accidental capacity functions (*Acc-CF*) of an artifact. The concepts of the *external function* (*Ext-F*) based on the external use, *the required function in the use phase* (*RFu*), and the *accidental function* (*Acc-F*) are applicable to this era, while these concepts are not applicable to the pre-human era, as shown in Figure 3.

In the definition of artifacts by Borgo and Vieu (2009), an artifact is the result of "intentional acts" of an agent, which are selection of a physical object and attribution of some capacities to it. According to this definition, even if a user only selects an object and attributes a capacity to it without any manufacturing activity[20], the object can be regarded as an artifact. The function in this case roughly corresponds to the notion of function in this era.

The function context of a component function (i.e., system function context (*Sys-FC*$_z$)) of a sub-part of a non-biological natural thing is a functional structure equivalent to that of the biological system. The whole goal of the functional structure of the biological system, however, inheres in itself, whereas that of the non-biological natural thing in the external use depends on the intention of an external user. Therefore, although definition of biological function as a kind of *essential and component capacity-function* (*Ess-Cmp-CF*) makes sense in the pre-human era, it is not successful in explaining the *accidental and external function* (*Acc-Ext-F*) that is applicable to the human era.

5.3. ***Human era 2: Artifact-function***

In the second phase of the human era, in order to improve the quality of the performance of functions, humans started to carry out the designing activity and the manufacturing activity under their intentions of generic use. In this phase, the notion of the *required function in the design phase* (*RFd*) and the *designed function* (*DF*) are applicable, as shown in Figure 3. In our view, the notion of an *artifact* is applicable based on such a designer's intention. Our functional model presented in Section 3 includes all of these notions.

In this model shown in Figure 3, we understand that the notion of function has evolved along with the evolutional history of creatures. In the evolutional process, we can characterize the functions of biological organs and of non-biological natural things in external use at the initial and intermediate eras. Then, the artifact function is applicable to the last era.

6. Concluding Remarks

In this paper, aiming at a clearer understanding of the notion of function, we presented two ontological models of function based on proposed fundamental kinds of functions. The phase-oriented model showed the differences and changes of the notion of function of artifacts along the product-life cycle. The evolution-oriented model showed ontological differences of the functions of artifacts, biological organs, and non-biological natural things. This line of research has been further investigated for a unified definition of function for artifacts and biological organs, as discussed in (Mizoguchi et al., 2012), based on the observation of Footnote 15.

Our aim here is not standardization of the definition of function, but to ensure interoperability of different definitions of function. To do so, we previously proposed some upper-level types of function as a reference ontology of function (Kitamura et al., 2007). The kinds of functions in this paper are more fundamental and will be integrated into the reference ontology.

Of course, we do not claim that the ontological distinctions in this paper are sufficient for explaining all the differences among the functions of artifacts, biological organs, and non-biological natural things. The contribution of this paper is to point out some important distinctions from an engineering point of view.

[19] In the case where a pebble with a flat bottom is selected from many natural pebbles in a dry riverbed, this act is regarded as a selection activity to select an appropriate function-performer based on the required function in the use phase. This is the same as the act performed in the transition from the phase (d) to the phase (e) in the model for artifacts shown in Figure 2. For example, a user can select either a screwdriver or a key for the rotating function.

[20] Their definition includes the case where a designer/manufacturer is the *creator* of artifacts as well. See (Borgo & Vieu, 2009, Borgo et al., 2011b).

There are other important aspects for the difference (Wouters, 2005), such as the social aspect in artifact function (Borgo & Vieu, 2006) and the evolutional aspect for biological organs (e.g., reproduction). Finally, a formal account of the distinctions like that in (Borgo et al., 2009) is expected.

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