Functional Metadata Schema for Engineering Knowledge Management

Yoshinobu Kitamura Naoya Washio Yusuke Koji Riichiro Mizoguchi
The Institute of Scientific and Industrial Research, Osaka University
8-1, Mihogaka, Ibaraki, Osaka 567-0047, Japan
+81-6-6789-8416
{kita, washio, koji, miz}@ei.sanken.osaka-u.ac.jp

ABSTRACT
In the engineering design, engineers have been suffering from a difficulty in sharing conceptual engineering knowledge about functionality representing design rationale because of the lack of rich common vocabulary for functionality. In order to promote sharing of such knowledge, we have developed an ontological framework for its modeling including layered ontologies, which provides rich concepts for describing consistent and reusable knowledge. This article summarizes the framework and the successful deployment in a company. In the context of the semantic web, our framework can be viewed as a metadata schema of documents about engineering devices. This article also discusses metadata from the viewpoint of functionality as a usage of our ontologies in the semantic web.

Categories and Subject Descriptors
I.7.1 [**Computing Methodologies**]: Document and Text Editing – *Document management.*

General Terms
Languages

Keywords
Semantic web, ontology, metadata, functional model, knowledge management

1. INTRODUCTION
In the engineering design community, the importance of knowledge sharing among designers has been widely recognized. Although advancement of computer technologies has enabled easy access to structural information using CAD, such information does not include designer's intention such as so-called design rationale (DR) [13]. A model about functionality of devices (so-called a functional model) describes goals of devices intended by a designer and thus represents a part of DR [2]. However, it is difficult to describe such a conceptual engineering knowledge consistently and share the functional models and generic knowledge about functionality. Although some functional modeling languages have been proposed [2][14][22], there is neither rich common vocabulary for representing functions nor well-established ontological commitment for capturing such knowledge. For example, one might describe "to weld objects" as a function of a manufacturing facility in the similar manner in value analysis [16]. However, "to weld" is not only a function but also implies a certain way to achieve the goal, the objects are fused. In fact, the same goal can be achieved in different ways (e.g., using bolts and nuts) without fusion. To allow freedom in design and to make selection of "bolt & nut" instead of "welding" possible, the achieved function should be the same; "to unify". This example suggests a necessity of carefully designed vocabulary of functions and an ontological framework for functions beyond just lexical vocabulary.

The main goal of this research is to promote sharing of the conceptual engineering knowledge about functionality by providing a conceptual framework enabling systematic description of the functional knowledge and by the Semantic web technology. The framework consists of categorization of the functional knowledge and layered ontologies for capturing functions [7][8]. It gives the knowledge authors a controlled vocabulary and guidelines for consistent and reusable knowledge. The framework has been deployed successfully in a company [9]. In this paper, we first summarize our framework and its deployment.

We view the semantic web as one of the enabling technologies for knowledge sharing in a community. Our framework has been developed intended to create another metadata schema of web documents. Our ontology and generic knowledge can be treated as a metadata schema. This paper also discusses metadata from the viewpoint of functionality as a usage of our ontologies in the semantic web. Such metadata for a web document of an artifact show functionality of the artifact, how to achieve the function and thus designer's intention of the artifact, which tends to be implicit in usual design documents.

2. A FRAMEWORK FOR FUNCTIONAL KNOWLEDGE
Our framework for functional knowledge [7][8] is shown in Figure 1 as layers of ontologies, knowledge and instance models. Basically, knowledge or a model in a certain layer is described in terms of more general (and/or fundamental) concepts in the upper layer.

At the bottom in Figure 1, a function decomposition tree is a functional model of a specific device (In the figure, a washing machine). It represents that a required function (called a macro-function) can be achieved by specific sub(micro)-functions [19]. We introduce the concept of "way of function achievement" as

WWW 2005, May 10--14, 2005, Chiba, Japan.

conceptualization of background knowledge of functional decomposition such as physical principles and theories as the basis of the achievement. The conceptualization of way of achievement helps us detach “how to achieve” (way) from “what is intended to achieve” (function). For example, “to weld something” mentioned in Introduction should be decomposed into the “unifying function” and “fusion way”. This increases generality and capability of a functional model which accepts wide range of ways such as the bolt and nut way as an alternative way of achievement.

At the lower right, there is a general function decomposition tree that includes alternative ways of function achievement in OR relationship. It can be used when designers explore and investigate possible ways to achieve a specific required function.

We have developed an ontology of functions of components (called a functional concept ontology at the third layer from the top in Figure 1) [7] which are detached from ways of function achievement. It defines about 220 generic concepts for representation of functions in 4 is-a hierarchies. Only a few (4-16) generic functions have been proposed to date [19]. Tejima et al. proposed a set of 158 verbs representing function only for human comprehension in Value Engineering area [21]. The recent efforts toward a standard taxonomy for engineering functions by the NIST Design Repository Project [6] are well established; however, they lack an operational relationship with behaviors and ontological specifications. In the functional concept ontology, each generic functional concept has clear operational relationship with objective behavior of a device. In order to capture functions consistently, it is based on an extended device ontology. Using these functional concepts as vocabulary, the function decomposition trees at the bottom in Figure 1 are described.

The concept of “way of function achievement” also helps us generalize concrete ways into generic ways and organize generic ways in is-a relations according to their principles (called functional way knowledge). Although the feature of function decomposition is also captured in [15], he focuses strictly on the function decomposition tree of a specific product and little attention on general knowledge is paid.

A similar hierarchy of ontologies in engineering domain is proposed in [1]. However, it does not include an ontology of functionality that is our main issue.

3. USE AND DEPLOYMENT

Our framework contributes to making it easier to author consistent and reusable functional knowledge of a device. Because functionality can partially represent DR, the functional model of a device can be representation of DR. The functional knowledge can be used for redesign of artifacts by changing a way of function achievement in the original design into an alternative way.

Our framework has been deployed since May, 2001 into the plant and production systems engineering division of Sumitomo Electric Industries, Ltd. (hereinafter referred to as SEI) [9]. A knowledge management software named SOFAST has been developed based on part of the methodology and then deployed since December, 2002. The targets are manufacturing equipment mainly used in semiconductor manufacturing processes including the wire-saw, a wafer polisher, an optical fiber connector adjusting machine, and inspection machines. SOFAST has been used by 13 other companies since April, 2003 some of which use it in actual work. The following summarizes some of usages and effects in the deployment.

One of the uses of the function decomposition tree is to clarify functional knowledge, which is implicitly possessed by each engineer, and share it with other engineers. The experiential evaluation by Sumitomo’s engineers was unanimously positive. Writing a function decomposition tree according to the methodology gives designers the chance to reflect on good stimuli, which leads them to an in-depth understanding of the equipment. This is because such a function decomposition tree shows the designer’s intentions on how to achieve the goal function and justify design decisions, which are not included in the structural or behavioral models.

Such a deep understanding contributes to redesigning and solving

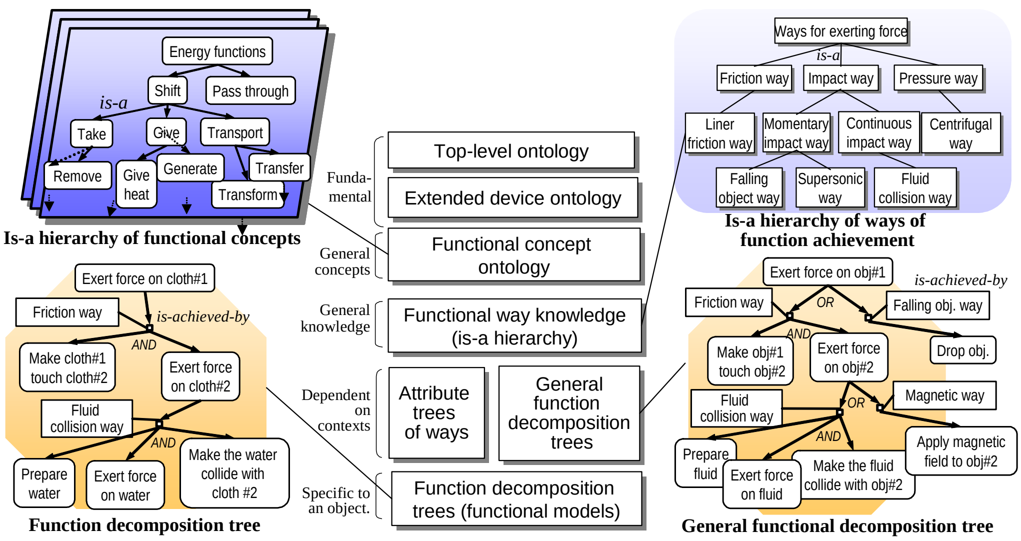


Figure 1. A layered framework of ontologies, knowledge, and models of functions

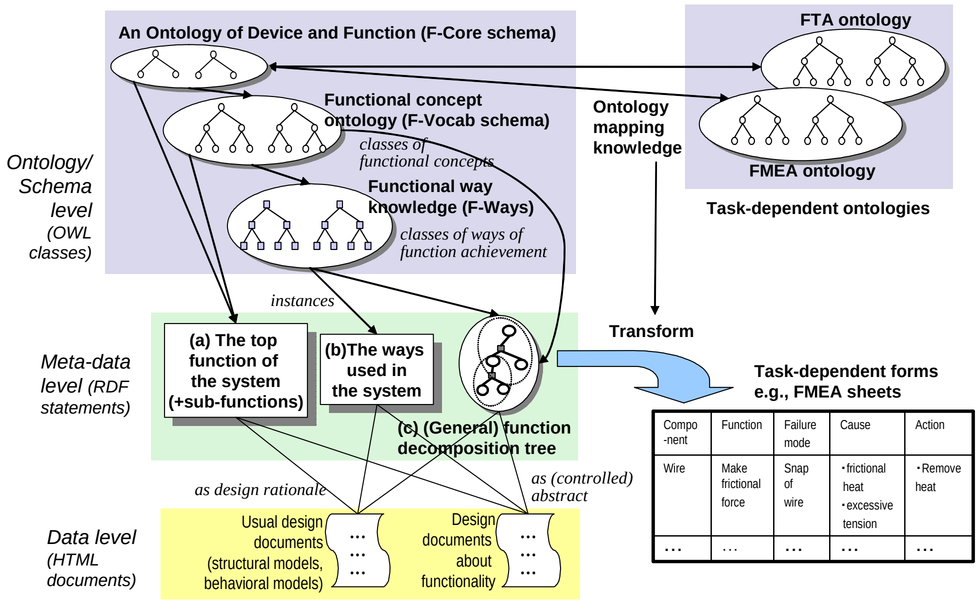


Figure 2. *Funnotation* Framework

problems concerning the equipment. For example, an engineer was not able to reduce the time a machine requires to polish semiconductor wafers after four months of investigation by adjusting the known working parameters. He consequently described its function decomposition tree, by referring to that of the wire saw. Although these two devices have the different main functions, he found the shared function "to maintain a large friction coefficient" and its sub-function "to place diamond powder between wafers and the table". As a result, he became aware of an implicit function and its parameters for placing more diamond powder to obtain a high friction coefficient. Eventually, he reduced the necessary time to 76%, which was better than the initial goal. This improvement was achieved within three weeks.

4. METADATA ABOUT FUNCTIONALITY

4.1 *Funnotation* Framework

In the semantic web context, our ontology can be used as a metadata schema for engineering documents as shown in Figure 2. It enables us to describe metadata representing functionality of engineering devices mentioned in the target engineering documents. Such metadata can be regarded as "content descriptors" like keywords or "logical structure" of "content representation" like a summary or an abstract in terms of categorization in [4]. By the logical structure, we here mean the relationship among functions such as functional decomposition. Functional metadata explicates the design rationale underlying design documents such as design drawing.

The functional concept ontology in our framework provides hierarchies of classes (types) as a metadata schema in OWL (Web Ontology Language) [23]. The metadata about functionality as RDF (Resource Description Framework) statements [24] in XML syntax are described as instances of those classes. The functional way knowledge also provides hierarchies of classes for representing types of "how to achieve a function" of a devices.

Furthermore, the system can provide users(designers) with the metadata in the form their task requires by automatic transformation according to the ontology mapping. The current implementation has realized a function which generates FMEA (Failure Mode and Effects Analysis) sheets for reliability analysis [3][17] by transforming a functional meta-model in the extended functional model [10][11]. The transformation is done by referring to the ontology mapping between ontologies of the both knowledge models: the extended function model and FMEA model.

4.2 *Funnotation* Schema

The proposed metadata schema, called *Funnotation* Schema hereafter, has been built intended to annotate web resources about artifacts from the functional aspects. The schema consists of layers (sub-schemata) such as F-Core, B-Unintended, F-Vocab and F-Ways schemata as shown in Figure 2. In F-Core schema, core concepts such as *entity*, *function* and *way* are defined together with properties such as *agent* which represents that an *entity* can perform *function* as an agent and *part_function* which represents functional decomposition (whole-part) relations between functions. Table 1 shows some examples.

Verbs such as *convey* and *separate* are defined in F-Vocab schema as subclasses of *function*. Those terms come from the functional concept ontology. In F-Ways schema, generic function-achievement ways such as *frictional_way* are defined as subclass of *way* class. The definition of each way of function-achievement is composed of the principle on which the achievement is based, the goal function (achieved function) and sub-functions which collectively constitute the way.

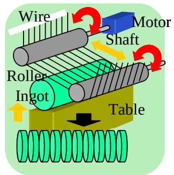
The layered architecture of metadata schema provides users with a few levels of ontological commitments. Concerning the functional terms, the system will be able to allow users to use

Table 1. Classes and properties of F-Core (portion)

Class			
entity	Physical entity		
function	Interpretation of behavior under a goal		
way	Way of function achievement: conceptualization of the principle essential to the achievement of the parent (goal) function by the sub(part)-functions		
Property			
Name	Domain	Range	
agent	*function*	*entity*	*Function* is achieved (performed) by the *entity*
part_function	*function*	*function*	*Function* in the Domain (Subject) is decomposed into that in Range (Object)
possible_way	*function*	*way*	*Function* can be achieved by the *way*
method_function	*way*	*function*	*Way* contains *function* as sub(part)-functions to achieve the goal (whole) function

Document (adapted from http://www.fine-yasunaga.co.jp/english/home/wiresaw/index.htm)

What is Wire Saw?...... A wire (a piano wire of ϕ0.08 to 0.16mm) is wound around several hundred times along the groove of guide roller. Free abrasive grains (a mixture of grains and cutting oils) are applied to the wire while it keeps running. The abrasive grains rolled on the wire work to enable cutting of a processing object into several hundred slices at one time. It is mostly used to cut electronic materials.



Functional metadata

```
<funnotation:device rdf:about="http://ex.org/ex1.html#wire-saw">
  <funnotation:has_function>
    <funnotation:split_entity rdf:about="http://ex.org/ex1.html#cut">
     <funnotation:selected_way rdf:about="http://ex.org/ex1.html#grains">
      <funnotation:fricitional_way/>
     </funnotation:selected_way>
    </funnotation:split_entity>
  </funnotation:has_function>
</funnotation:device>
```

The wire-saw has a splitting function with a frictional way of achievement

Figure 3. Examples of metadata for a document of a wire-saw

Generally-Valid Functions [19] defined by Paul & Beitz or Functional basis proposed by NIST [6].

4.3 *Funnotation* Meta-data

The *Funnotation* schema enables users to represent functional metadata (called *Funnotation* metadata) with RDF which include (1)Functions of the device/component/part of interest, (2)Function-achievement ways used, (3)Function decomposition trees representing the functional structure of the device, and (4)Generic function decomposition trees. While (3) and (4) correspond to a full model of the functional structure, (1) and (2) to “indexing” information(content descriptors) representing some portion of the full model.

Fig. 3 shows functional metadata about the explanation of a wire saw in which two metadata that the wire saw is an instance of the device (*Funnotation:device*) and that it has a function *Separate (Funnotation:split_entity)* which is an instance of *Function* class are represented using *Funnotation:has_function* property.

Such metadata enable us to search documents of engineering devices using their functions using a common vocabulary and *is-a* hierarchies of functional concepts. Such usage of ontologies has been extensively discussed to date in the semantic web community.

Here, the discrimination between functions and ways plays an important role. As mentioned in the introduction, usually both concepts are confused and thus it causes failure of search by functions. As well as the metadata by functions, secondly, one can describe ways of function achievement used in the device. In fact, Figure 3 shows that the instance of *funnotation:frictional_way* is linked to the *split_entity function* instance via *selected_way* property to demonstrate the wire saw achieves its main function using *frictional_way*. Thanks to our functional ontologies, a user can search functions and ways separately.

Furthermore, by adding metadata about sub-functions to the metadata shown in Figure 3, one can describe a function decomposition tree of a device as metadata of a document about the device. Many design documents describe only results of design activities without design rationale. The functional decomposition tree as metadata gives a part of the design rationale of devices described in the document. For the rare documents describing functional structures, the functional

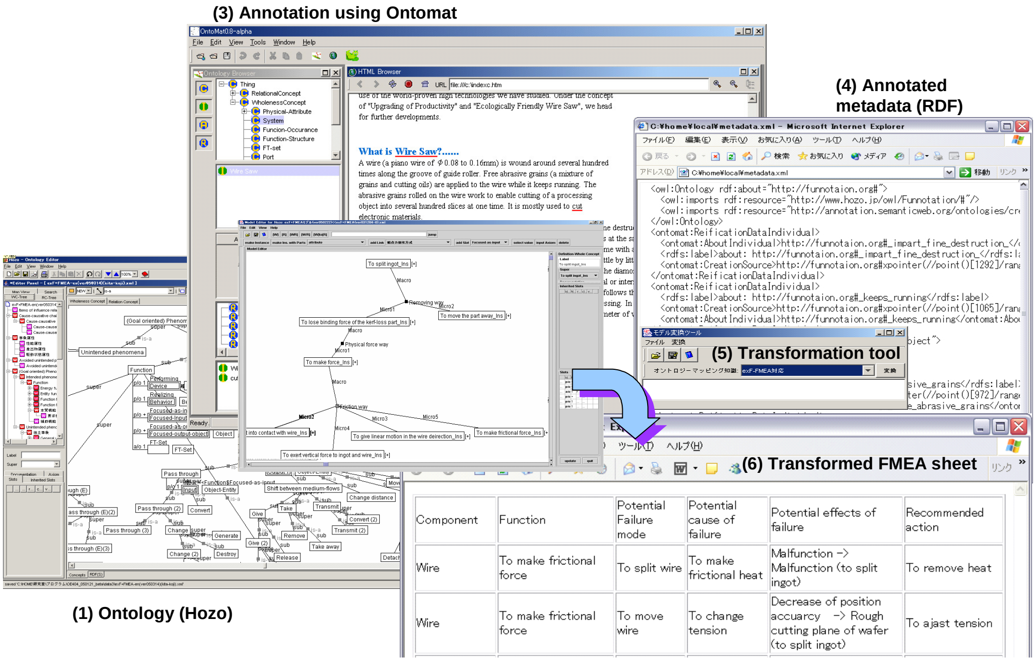


Figure 4. Screen snapshots of the systems used in the *Funnotation* Framework

decomposition tree gives a kind of a summary or an abstract of the document.

Furthermore, the general function decomposition tree can be regards as another kind of metadata. It can consist of several ways of function achievement used in different devices in OR relationship. Thus, it can give a combined summary of some documents from the viewpoint of functionality.

4.4 Knowledge Transformation

Funnotation schema has a layer named B-Unintended (Unintended behavior layer) whose role is to represent phenomena/behavior unintended by designers rather than function intended by them. The former is usually considered as tightly connected to anomaly. Therefore such description provides useful information for redesign task and is sometimes written in design documents as the background knowledge. Annotation about anomaly and related background phenomena thus enables redesign more successful.

B-Unintended layer is an extension of the functional model and the whole model is called Extended functional model which includes both intended and unintended models, in other words, functional and anomalous models [10]. Preparing both ontologies of function and anomaly together with the mapping between the two ontologies enables automatic form translation to generate, say, FMEA sheet(See Figure 4) [11].

4.5 Implementation

We implemented our ontological framework using our ontology development environment named Hozo [12] as shown in Figure 4. The ontologies are described in Hozo as shown in Figure 4(1). Hozo can exports ontologies and instance models in OWL. The extended device ontology, the functional concept ontology, and the functional way knowledge are exported as classes in OWL. A specific way knowledge is represented as a sub-class of the "way" class in hierarchies by restricting (specializing) its range of the property to a specific function class in the functional concept ontology.

There are two methods for annotation: One is to represent an instance model in Hozo (as shown in Figure 4(2)) and the other is to use OntoMat-Annotizer [18] with the schema in OWL exported by Hozo (Figure 4(3)). Then, functional metadata in RDF is gotten (Figure 4(4)). For generating FMEA sheet, we implemented a module for model translation embedded in Hozo (Figure 4(5)) [11]. The XML file generated by the module is transformed into HTML format using XSLT as shown in Figure 4(6).

5. CONCLUSION

We have developed a modeling framework including ontologies for functional design knowledge. It has been deployed in a company successfully. It can be used as a metadata schema from a viewpoint of functionality of engineering devices. The functional metadata can include design rationale behind usual design documents such as design plans.

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