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# Deep Semantic Mapping between Functional Taxonomies for Interoperable Semantic Search

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**Abstract.** This paper discusses ontology mapping between two taxonomies of functions of artifacts for the engineering knowledge management. The mapping is of two ways and has been manually established with deep semantic analysis based on a reference ontology of function for bridging the ontological gaps between the taxonomies. We report on the successful results thanks to such deep analysis not at the lexical level but at the ontological level. Using the mapping knowledge, we developed a semantic search system which can provide engineers with interoperable access to technical documents by searching for functional metadata based on either of functional taxonomies.

**Keywords:** Knowledge management, ontology, ontology mapping, metadata

## 1 Introduction

Functionality is one of the key aspects of knowledge about artifacts [1,2]. The goal of this research is to manage engineering documents using semantic annotation about functionality of artifacts. Such function-oriented knowledge management is very useful in engineering design by finding previous design cases for the same required function or by finding related patents [2]. The semantic annotation about function is expected to solve the difficulty of the current document-based engineering knowledge management based on lexical expressions, that is, many terms (verbs) are used in documents for the same function (and vise versa) without clear semantics.

For this, we have proposed a framework of an ontology-based semantic annotation about functionality (we call *Funnotation* (abbreviation of FUNctional anNOTATION) hereafter) [3]. It includes a metadata schema in OWL for functional annotation. The schema is based on our functional ontologies [4,5,6] (we call FOCUS (abbreviation of Functional Ontology for Categorization, Utilization and Systematization)), which have been deployed successfully in industry [6]. Metadata in RDF based on the schema shows the function of the artifact mentioned in documents. Then, a document search system using the functional metadata as an engineering knowledge management system is designed to help engineers access technical documents in a web system on an intranet within a company by specifying “what they want to realize”, i.e., function, independently of lexical terms in the documents.

Our aim in this paper is to realize interoperability between functional taxonomies in the functional annotation. Some taxonomies of verbs for generic functions have been proposed in the literature, e.g., [1,4,7,8]. Among others, we concentrate on (Reconciled) Functional Basis in the NIST Design Repository Project (hereafter FB) [8] and our functional concept ontology (hereafter FOCUS/Tx) [4]. Thus, our goal here is to search for documents using metadata based on either of these taxonomies.

The research issue here is to establish the two-way *mappings* (by which we here mean directed correspondence relations) between similar functional terms in those taxonomies. This is a problem so-called the *semantic integration* [9] or *ontology matching* [10]. General techniques for this problem can be categorized into 'automatic mapping discovery' [9] and 'manual mapping analysis'. The current majority of research efforts aim at 'automatic mapping discovery' which is to automatically determine which concepts in two ontologies represent similar notions [9]. Such techniques mainly use lexical information based on natural language processing techniques, the structural features of ontologies, and/or shared instances [9,10]. Although the automatic mapping discovery can be applicable to large-scale ontologies, it is difficult to get precise mappings reflecting the deep semantics[1] of the target concepts. Moreover, the automatic mapping discovery hardly contributes to revealing the underlying differences and in-depth investigation on the target concepts.

On the other hand, the manual mapping analysis can establish precise mappings based on deep analysis of the taxonomies and account for the ontological differences of taxonomies and the concepts. Of course, the manual analysis is a time-consuming task and then it is difficult to establish mappings between large-scale ontologies.

The crucial issue here is that the differences between those functional taxonomies are *not only* terminological *but also* ontological, because some functions are based on different conceptualizations. For example, "link" in FB implies not only "to couple flows together" [8] as the change at input and output but also "by means of an intermediary flow" [8] as how to realize it. Thus, it cannot be fully mapped onto "combine" in FOCUS/Tx which implies "to bring two operands into an operand" as the change at input and output, which corresponds to only the former part of the meaning of "link". This is not a terminological but an ontological difference, because "the change in the target object" and "how to realize the change" are ontologically different. One of the deep causes of such a confusion is the lack of clear understanding of the notion of function, though much research has been conducted on functionality in engineering design (e.g., [1,2]), in artificial intelligence (e.g., [12]) and in philosophy [13]. Our aims here include contribution to accounting for the notion of function by comparing those taxonomies as well.

On the basis of the above observation, this research adopts *not* the automatic mapping discovery *but* the manual mapping analysis based on a reference ontology of function. Its main reasons are the deep ontological gaps between taxonomies and our aim of investigating function ontologically discussed above. The small numbers of terms of the taxonomies (52 terms [8] and 89 terms [4]) enable us to analyze mappings manually. Although the numbers are small, FB is founded on a great number of empirical studies [7,8] and FOCUS/Tx has been successfully deployed in

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[1] Some matching methods use 'logical semantics' of axioms (e.g., [11]). The 'deep semantics' we would like to capture here is, however, not identical to those formal semantics.

industry [6]. These facts strongly suggest that these taxonomies cover wide-range of artifacts. So, it is worth to perform the labor-intensive and time-consuming manual process for precise mappings. The reference ontology of function [14] defines upper-categories of several kinds of function. It is utilized here for clarifying ontological differences between the taxonomies and for bridging the gaps for mappings between them. The mapping framework has been reported in [15,16]. This paper reports the concrete two-way mappings (only one-way has been reported in [16]), their analysis, and their use in interoperable semantic search for knowledge management.

This paper is organized as follows. Firstly, we overview the interoperable semantic search to be realized in this paper. Then, the taxonomies to be dealt with are introduced in Section 3. Section 4 discusses the reference ontology of function and the mapping process based on it. Section 5 reports the mappings obtained. Section 6 demonstrates the functional annotation and the interoperable search based on the mappings. Section 7 discusses related work followed by the conclusion.

## 2 Framework of Interoperable Semantic Search based on Functional Annotation

Figure 1 shows an overview of the *Funnotation* framework. Its F-Core schema defines fundamental classes such as *device*, *stuff*, *energy*, *function* and *way* (of function achievement) together with properties such as *has-function* and *selected-way*. The *way* (of function achievement) represents how to achieve a function as discussed in Section 3.2. The F-Vocab schema defines generic functions based on the functional concept ontology; FOCUS/Tx [4]. Such schemata implemented in OWL enable us to describe metadata in RDF representing functionality of engineering devices in documents. For example, the metadata $m_a$ in Fig. 1 shows that the device in annotated document $d_a$ (a filter) can perform an instance of the *separating* function class defined in the schema. This is annotated to the term “extract” in $d_a$. The metadata $m_b$ shows that the distiller in the document $d_b$ has the same *separating* function, which is, however, annotated to the term “refine” in $d_b$. In this manner, functional metadata shows device’s functions independently of the terms in documents and indicates URI to the original documents and/or terms. Moreover, the metadata show how to achieve a function, i.e., in this case, two different *ways* (i.e., the filtering way and the different-boiling-points (distilling) way) to achieve the *separating* function.

Moreover, the document $d_c$ is annotated in terms of another functional taxonomy; Functional Basis (FB). The word “grinding” of a coffee grinder is annotated as the *branching* function in FB. As discussed in this paper, the authors prepare the mapping knowledge between FOCUS/Tx and FB based on the reference ontology of function. As discussed later, in this simple example, the *branching* function of FB has a direct mapping to the *separating* function of FOCUS/Tx.

Given a query in terms of functions of FOCUS/Tx, a semantic search system provides access to the annotated documents by searching for the functional metadata. In Fig. 1, if an engineer specifies the *separating* function as a goal-function (function to be achieved) as a query, the system provides links to the both documents $d_a$ and $d_b$. Moreover, according to the mapping knowledge, the document $d_c$ is also retrieved.

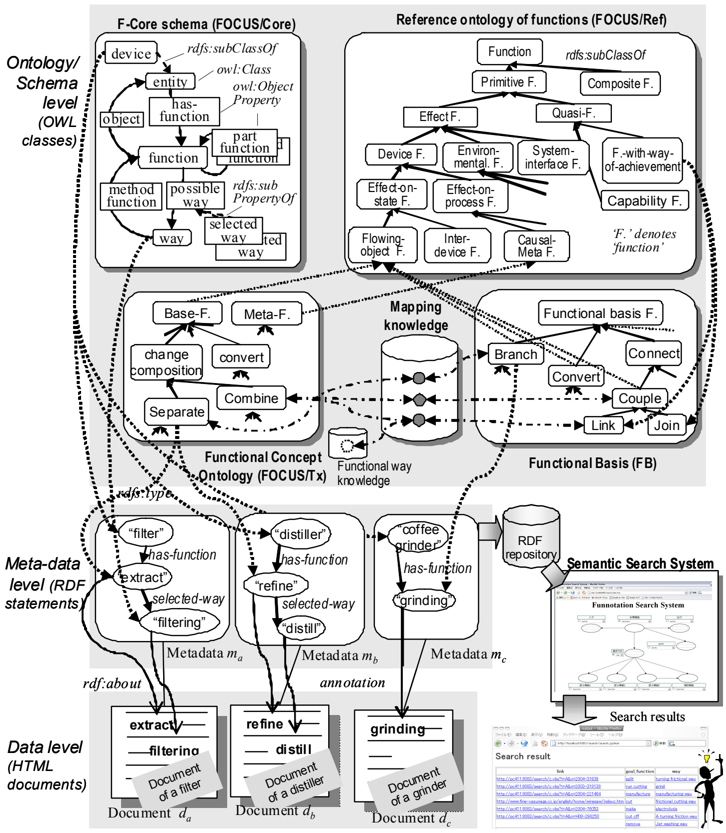

**Fig. 1.** Overview of *Funnotation*: A Framework for Semantic Annotation about Functionality for Engineering Documents.

## 3 The Functional Taxonomies

### 3.1 Reconciled Functional Basis (FB)

Reconciled Functional Basis has been proposed by Hirtz et al. [8], which is a result of reconciliation of some previous taxonomies and empirical generalization based on a great number of empirical studies. A function of a device is expressed as a pair of an active verb and its (grammatical) object (called 'flow'). We call the taxonomy of function (verb) FB in this paper. FB consists of 52 terms in three levels of categorization. Table 1 shows its small portion [8]. Each of functional terms is defined in natural language with examples and correspondents (synonyms). For example, the *separating* function is defined as "to isolate a flow (material, energy or signal) into distinct components. The separated components are distinct from the original flow, as well as each other" [8].

**Table 1.** A Portion of Reconciled Functional Basis [8]

| Class (Primary) | Secondary | Tertiary | Correspondents |
|---|---|---|---|
| Branch | | | |
| | Separate | | Isolate, sever, disjoin |
| | | Divide | Detach, isolate, release, |
| | | Extract | Refine, filter, purify .... |
| | | Remove | Cut, drill, lathe, polish, |
| | Distribute | | Diffuse, dispel, |
| Connect | | | |
| | Couple | | Associate, connect |
| | | Join | Assemble, fasten |
| | | Link | Attach |
| | Mix | | Add, blend, coalesce, |

Such definitions in natural language are sometimes ambiguous and it is difficult to distinguish similar terms. Garbacz points out some problems of the classification of FB such as lack of principle of categorization and non-exhaustiveness from logical and ontological viewpoints [17]. Moreover, the concept of function is defined as "a description of an operation to be performed by a device or artifact" [7]. In this definition, the intention of a designer or a user is implicit, which is a crucial characteristic of function in comparison with objective *behavior* [1,2,4,6,12,13].

### 3.2 The Functional Concept Ontology (FOCUS/Tx)

In comparison with FB, the functional concept ontology (FOCUS/Tx) has an ontological foundation. It is based on a device-centered ontology; FOCUS/Core [6], which enables us to distinguish function from *behavior.* The behavior of a device is defined as temporal changes of things (called operands) as input-output relation in a black box. A (base-) function is defined as "a *role* played by such behavior in a specific *context of use*" [6]. The context of use depends on intentions of users or designers, or the system that the component embedded in. This definition is based on the notion of "role concept" in [18]. Much research has been conducted on "role" in Ontology Engineering [e.g., 19]. The concept of function satisfies fundamental characteristics in [19] as discussed in our paper [6].

FOCUS/Tx defines generic types of the base-functions (called functional concepts). Figure 2 shows its portion[2]. A functional concept (a class of function) is defined ontologically using constraints on the cardinality of operands, relationships among them and/or designer's intention to change (focus of intention). For example, a function, "to divide an operand", is defined by the following semantic constraints; (1) the cardinality of the input focused operand must be 1, (2) the cardinality of the output focused operands must be greater than 1, (3) there must be *material-product* relationship between the input operand and the output operands and (4) all the output operands are equally focused. The first three are inherited from the super-concepts such as 'separate'. The fourth one is the criterion of categorization at this level and enables us to distinguish the 'divide' function from the sibling function 'take_out'.

[2] The initial version of the ontology was organized in four *is-a* hierarchies [4]. It has been restructured into single *is-a* hierarchy based on the common definitions in the hierarchies.

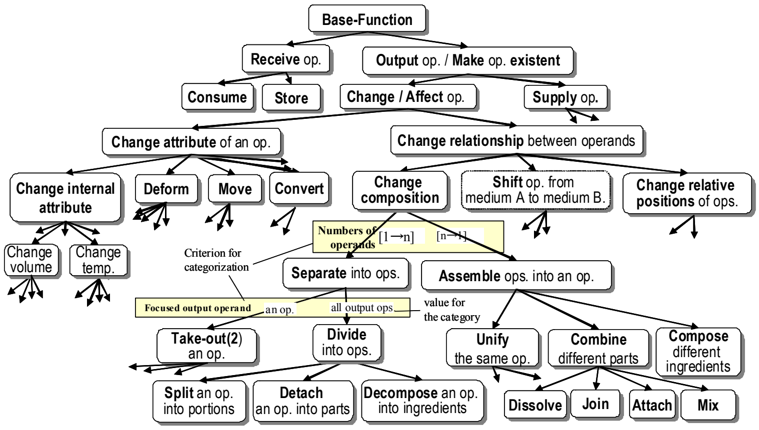


**Fig. 2.** A portion of FOCUS/Tx

We distinguish a function from a *way of function achievement* [5,6], which represents background knowledge such as physical principle in functional decomposition [1], in which part-functions achieve a whole-function. It enables us to distinguish "what to achieve"(function) from "how to achieve" (way of achievement).

FOCUS ontologies have been implemented in our role-centric ontology editor Hozo [18] (http://www.hozo.jp). Some portions of the implementation have been reported in [3,6]. Currently, we are rebuilding them and are implementing in OWL.

# 4 Mapping Process based on a Reference Ontology

As discussed in Introduction and Section 2, the mappings are based on the reference ontology of function (FOCUS/Ref hereafter) [3], which defines *function categories,* that are, the upper types of functional terms defined functional taxonomies. By a reference ontology, we here mean that the ontology referred to for categorizing existing definitions of function and for defining the mappings between them (in comparison with "reference for system design" such as the ISO's OSI network reference model). Note that the set of the functional categories of FOCUS/Ref is *neither* a super-set *nor* a merged-set of those of functional taxonomies.

The upper-right part of Fig. 1 shows a portion of FOCUS/Ref. For example, an *effect function* implies changes of a target object (*operand*). It is categorized into a *device function*, an *environmental function*, and a *system-interface function*. These sub-categories imply changes of an operand *within* the system boundary, that *outside* of the boundary and that *on* the boundary, respectively. The *flowing-object function* as a sub-type of the *device function* represents input-output changes of an operand that flows through a device from the device-oriented viewpoint. The *function-with-way-of-achievement* category implies a specific *way of function achievement* (discussed above) as well as a function. Its examples include welding, washing, shearing and adhering. For example, the welding implies not only the *joining* function but also the *fusion way*. Because meaning of this type of function is impure, we regard this functional category as a subtype of the *quasi-function*. See [3] for the detail.

In the mapping process, the authors firstly analyzed the definitions of FB terms and gave them ontological definitions using Hozo. Then, the authors classified each functional term in the taxonomies into a *function category* of FOCUS/Ref. Because both FB and FOCUS/Tx adopt the device-centered viewpoint, all base-functions of FOCUS/Tx and many functional terms of FB are categorized into the *flowing-object function* category. The definition of *function* in FOCUS/Core also is based on the *flowing-object function*. Some functions of FB are, however, categorized into other categories of FOCUS/Ref. Then, according to such classification of functional terms, the mapping knowledge is described for each pair of two functional terms. If functions are categorized into the different categories, the mapping becomes complex for bridging the ontological gaps as discussed in the following section.

## 5 Mappings between Taxonomies

We have established two-way mappings (directed correspondence relations) between FB (52 terms) and FOCUS/Tx (89 terms) according to the mapping process discussed above. The statistics of the mappings is shown in Table 2. Figure 3 shows the types of the mappings. Table 2.1 shows statistics on the mappings from FB to FOCUS/Tx. If both functional terms are categorized into the same functional category of FOCUS/Ref, they are mapped onto each other directly. For example, 'couple' of FB and 'combine' of FOCUS/Tx are categorized onto the same *flowing-object function* category of FOCUS/Ref, and they are mapped onto each other (Table 2.1. (A)). In addition, we allow such mapping that several terms are mapped onto one term. For example, both 'extract' and 'remove' of FB are mapped onto 'take out' of

**Table 2.** Statistics of the ontology mappings.

**Table 2.1.** From FB to FOCUS/Tx.

| Mapping Type | Number of terms in FB | Ratio in FB terms |
|---|---|---|
| Mappings within the same category of function | 31 | 60% |
| 1 to 1 | 17 | 33% |
| (A) 1 to 1 | 15 | 29% |
| (B) N (OR) to 1 | 2 | 4% |
| (C) 1 to N (OR, selection) | 8 | 15% |
| ($E_1$) ◌ is a func. type | 6 | 12% |
| Mappings between different categories of function | 21 | 40% |
| (D) 1 to N (AND) | 10 | 19% |
| ($E_2$) ◌ is a meta func. | 5 | 9% |
| ($E_3$) ◌ is a way of function achievement. | 4 | 8% |
| (F) ◌ is an operand. | 2 | 4% |

**Table 2.2**. From FOCUS/Tx to FB.

| Mapping Type | Number of terms in FOCUS/Tx | Ratio in FOCUS/Tx terms |
|---|---|---|
| Mappings with terms in the same grain-size | 36 | 40% |
| Mappings within the same category of func. | 32 | 36% |
| 1 to 1 | 23 | 26% |
| (A) 1 to 1 | 15 | 17% |
| (B) N (OR) to 1 | 8 | 9% |
| (C) 1 to N (OR, selection) | 4 | 4% |
| ($H_1$) Mappings to a super-concept | 5 | 6% |
| Mappings between different categories of function | 4 | 4% |
| (G) Partial mapping | 4 | 4% |
| Mappings with terms in different grain-sizes | 53 | 60% |
| ($H_2$) Mappings to a super-concept | 49 | 56% |
| (I) Mappings to a sub-concept | 4 | 4% |

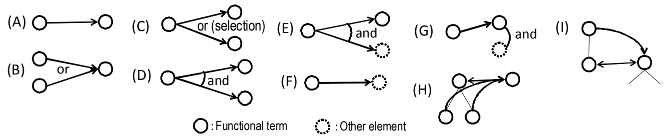


**Fig. 3.** Mapping types

FOCUS/Tx (Table 2.1. (B)). Next example is ‘mix’ in FB which is mapped onto ‘unify’ or ‘compose’ in FOCUS/Tx (Table 2.1. (C)). By “or” in (C), we here mean that the concrete corresponding term is selected according to the *context of use* (e.g., the whole system) in which the *mixing* function is used.

On the other hand, if two similar functional terms are classified into different categories of FOCUS/Ref, they are mapped in a complex manner. For example, ‘guide’ in FB is categorized into the *composite function* which consists of two primitive functional concepts. Thus, it is mapped onto ‘supply motion’ plus ‘change direction of motion’ functions (Table 2.1 (D)). The ‘link’ function of FB is categorized into the *function-with-way-of-achievement* category, because its definition implies “by means of an intermediary flow” [8] which represents *a way of achievement* as discussed in Introduction and Sections 3 and 4. Then ‘link’ of FB is mapped onto the ‘combine’ function of FOCUS/Tx plus the *intermediate-object way* for achieving the combining function (Table 2.1 ($E_3$)). The ‘import’ and ‘export’ of FB are categorized into the *system-interface* category of FOCUS/Ref. Because FOCUS/Tx is defined strictly based on the device-centered ontology, there is no corresponding functional concept in FOCUS/Tx. Thus, ‘import’ and ‘export’ of FB are mapped onto an operand from the outside of the system and an operand to the outside in a functional model of the FOCUS framework, respectively (Table 2.1 (F)).

Table 2.2 shows the statistics of the mappings from FOCUS/Tx to FB. Since the grain-sizes (granularity) of the functional concepts in FOCUS/Tx are finer than those of the FB terms, we took care of the difference of grain-sizes between two taxonomies in the mapping process. If the grain-size of each functional term is the same (the upper half of Table 2.2), the mappings have been established in the same manner of the mappings from FB to FOCUS/Tx[3]. If the grain sizes of functional terms are different (the lower part of Table 2.2), they are mapped to an upper-concept ($H_2$) or to a sub-concept (I). For example, the ‘deform’ (i.e., ‘change shape') in FOCUS/Tx has subclasses such as ‘change length’ and ‘change area’, while ‘shape’ in FB has no subclass. In this case, ‘deform’ itself is mapped onto ‘shape’ in FB (Table 2.2 (A)), while those sub-concepts with finer granularity (e.g., ‘change length’) are mapped onto the coarser one; ‘shape’. Table 2.2 ($H_2$) shows the numbers of such the mappings. The mapping type (I) indicates the reverse case of the type ($H_2$) for some highly abstracted concepts such as ‘change an operand’ in FOCUS/Tx. In both cases, those concepts are categorized into the same *flowing-object function* category.

We here compare the ratios of covering functional terms in the mappings. In the mappings from FB to FOCUS/Tx, the terms in FB cover (have mappings to) 33 terms in FOCUS/Tx out of the total of 89 (37%). In the mappings from FOCUS/Tx to FB, the terms in FOCUS/Tx cover 43 terms in FB out of the total of 52 (83%). Among the 9 terms of FB which are not covered, 6 terms are categorized into the *function-way-of-achievement* or the *system-interface* functions in FOCUS/Ref, both of which are not functional concepts from the device-oriented viewpoint, strictly speaking. The rest of 3 terms of FB are classified according to the quantitative difference (e.g., ‘inhibit’ from ‘prevent’), which is, we think, unnecessary classification of functional concepts.

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[3] In Tables 2.1 and 2.2, the numbers of the case (A) (the 1 to 1 mapping) are the same. The numbers of the case (B) are different, because they show the numbers of the source-side terms.

In other words, these 9 terms in FB are not target terms in the mapping from FOCUS/Tx to FB. Thus, we can say that FOCUS/Tx covers FB sufficiently.

Next, we discuss the ratios of successful mappings. There are, however, difficulties in accurate evaluation of their successfulness. Firstly, because the terms of FB are defined in natural language, it is difficult to calculate the similarity (or equality) between the meanings of the mapped terms. Secondly, we allow ambiguous mappings ('or'). Lastly, it is essentially difficult to determine criteria for evaluating differences between concepts in different categorizations. Considering these difficulties, in this article, we regard a mapping as successful if and only if that mapping is established only between the functional concepts with neither addition of extra information at either side nor heavy loss of information. For example, because the case ($E_3$) in Table 2.1 shows mappings to the way of function achievement (i.e., an element other than the functional concepts in FOCUS/Tx), those mappings in ($E_3$) are regarded as failure.

According to this criterion, in the mappings from FB to FOCUS/Tx, about 80% of the FB terms have been successfully mapped to the functional concepts of FOCUS/Tx (note that the covering ratio of those mappings is 37% as discussed above). On the other hand, in the mappings from FOCUS/Tx to FB, about 30% of the functional concepts of FOCUS/Tx have been successfully mapped to the terms in FB (the covering ratio is 83%). This low ratio is mainly due to the difference of granularity of the taxonomies, because we regard all the mappings between different grain-sizes (i.e., Table 2.2 ($H_2$) and (I)) as failure with the heavy information loss. The granularity of a taxonomy, however, heavily depends on an arbitrary decision made by its author and thus it is not essential to compare the core contents of different taxonomies. Thus, we can say that about 70% of the functional concepts of FOCUS/Tx successfully correspond to the terms in FB excluding the terms in the different grain-sizes. More accurate evaluation of the mappings remains as future work.

Even if we consider mappings only between terms in the same grain-size, their successful ratios in the two mapping directions (about 80% and 70%) are significantly different. One of its reasons is that FOCUS/Tx can represent the meanings of the terms of FB as combinations of the finely-categorized concepts such as the functional concepts and the meta-functions [4] as a system of the function-related concepts in the mappings from FB to FOCUS/Tx, while FB is single taxonomy of functional terms.

The mapping result discussed above can be regarded as very successful and interesting, considering the following backgrounds of the taxonomies. Firstly, they have been developed independently from each other. Secondly, the natural languages for terms are different. FOCUS/Tx is designed firstly in Japanese, while FB is designed for (and defined by) English. Thirdly, the terms for describing functional knowledge have high diversity. The successful result has been gotten from the concentration *not* on lexical terms *but* on deep semantics of the functional concepts.

Consequently, the result strongly suggests the validity of the content of both FOCUS/Tx and FB from their commonality. The suggested validity is supported by their following applications as well. FOCUS/Tx has been deployed for modeling a real plant and knowledge management in manufacturing companies in Japan [6]. FB is widely used by researchers mainly in the United States. Furthermore the result suggests the adequacy of the mapping methodology in this paper.

# 6 Interoperable Semantic Search

## 6.1 Functional metadata

The *Funnotation* schema [3] overviewed in Section 2 enables users to describe functional metadata with RDF which include (1) functions of the device/component (what is intended to achieve), (2) the used ways of function achievement (how to achieve a function), (3) a functional structure of the device (how to achieve the whole function), and (4) candidates (alternative) of ways of achievement. In the terminology in [20], (1) and (2) are "content descriptors" like keywords, while (3) and (4) are "logical structure" of "content representation" like a summary or an abstract.

Figure 4 shows an example of the metadata added to the document about a wire saw, which is a manufacturing machine to slice semiconductor ingots using moving wires. In Fig. 4, the wire-saw's function is described as an instance of the *splitting* function class (*Funnotation:split*) defined in FOCUS/Tx shown in Fig. 2. It is annotated to the term "cut" in the document. The wire-saw is annotated as the agent (performer) of the function using the *agent* property. The fact that the splitting function is achieved using frictional force is described using the *frictional_way* and the *selected_way* properties.

Much research has been conducted on automatically annotating web-documents with metadata elsewhere. Currently, we use two tools for functional annotation: one is to describe an instance model in Hozo and export it as a RDF file. The other is to use OntoMat-Annotizer with the schema in OWL exported from Hozo. Moreover, the authors and colleagues are currently investigating on automatic annotation of patent documents. It includes automatic identification of functional terms, semi-automatic mapping discovery from those terms to the functional concepts, and semi-automatic identification (mining) of functional structures as functional annotation.

## 6.2 Semantic Search System

In this section, firstly, we overview the basic usages and benefits of the *Funnotation* Semantic Search System [3]. Then, we will discuss interoperability with FB based on the mapping knowledge discussed thus far. This system consists of a

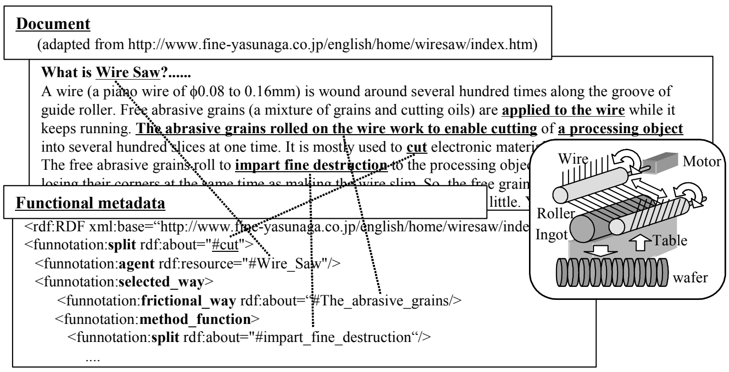


**Fig. 4.** An example of metadata for a document of a wire-saw (portion).

user interface on a web browser using JavaScript and a server module on a web server, which is implemented by Java and uses Tomcat with a HTTP server, Jena to operate the RDF repository, and SPARQL as a RDF query language.

As shown in Fig. 5, the users input the search condition such as a goal-function (i.e., function to be achieved). For example, let us consider a situation in which an engineer wants to know the possible ways to separate a semiconductor ingot. Firstly, the user selects '*separate'* from the functional terms defined in FOCUS/Tx as a goal-function. Giving such search conditions shown in Fig. 5, he/she gets the search results shown in Fig. 6. The center column indicated as "goal-function" shows the words in documents which are annotated both as the *separating* function class and as a subject of a *selected_way* (or *possible_way*) property. The rightmost column shows the terms annotated as a way.

This example shows that users can search for documents with a generic type of function independently of the lexical words in the documents (e.g., 'split' in the document (a) and 'cut off' in (b)). Using the *is-a* relations in FOCUS/Tx, the search result includes not only 'separate' but also its subclasses such as 'split'. Moreover, this search is based on semantic relations. If a 'separate' function is not a goal-function of a way in the metadata of a document, such documents are not retrieved.

Users can also search for possible *ways* for avoiding problems based on semantic relationships between functions. For example, in order to search for the ways to avoid problems caused by scrapings in a slicing machine, a user checks the "*supplementary* function" box in Fig. 5 (by a supplementary function, we here mean a non-mandatory function that contributes to prevention of faults etc.) and sets the 'separate' function

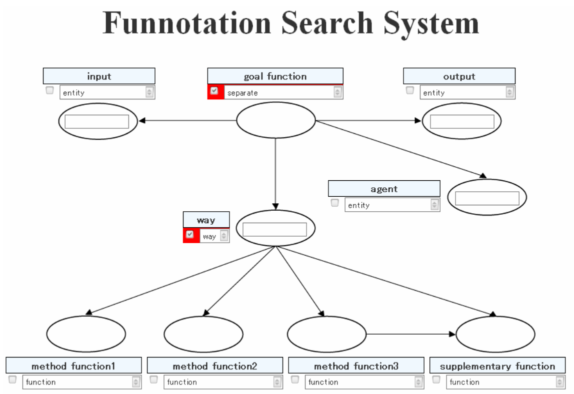


**Fig. 5.** The interface of *Funnotation search system.*

| | link | goal_function | way |
|---|---|---|---|
| *(a)* | http://pc411:8083/search/c.vbs?t=A&n=2004-31639 | split | rotatiing frictional way |
| | http://pc411:8083/search/c.vbs?t=A&n=2003-318138 | cutting | grind |
| | http://www.fine-yasunaga.co.jp/english/home/wiresaw/indexc.htm | cut | frictional cutting way |
| | http://pc411:8083/search/c.vbs?t=A&n=2004-221464 | manufacture | manufacturing way |
| | http://pc411:8083/search/c.vbs?t=A&n=2004-76053 | make | electrolysis |
| *(b)* | http://pc411:8083/search/c.vbs?t=A&n=H08-298250 | cut off | A rotatiing friction way |
| | | remove | Jet washing way |
| | http://pc411:8083/search/c.vbs?t=A&n=2005-153035 | comb out | rubbed up |
| | | cut | cut |

**Fig. 6**. Example of search result (1).

| | link | goal_function | way | supplementary function |
|---|---|---|---|---|
| *(a)* | http://pc411:8083/search/c.vbs?t=A&n=2004-31639 | split | rotatiing frictional way | harden |
| | http://www.fine-yasunaga.co.jp/english/home/wiresaw/indexc.htm | cut | frictional cutting way | applied to the wire |
| | http://pc411:8083/search/c.vbs?t=A&n=2004-221464 | manufacture | manufacturing way | was aligned |
| | http://pc411:8083/search/c.vbs?t=A&n=2004-76053 | make | electrolysis | are along with |
| *(b)* | http://pc411:8083/search/c.vbs?t=A&n=H08-298250 | cut off | A rotatiing friction way | remove |

**Fig. 7.** Example of search result (2) for supplementary functions

| Link | Function | Taxonomy | Functional term |
|---|---|---|---|
| http://pc411:8083/search/c.vbs?t=A&n=2004-31639 | split | FBRL | split |
| http://pc411:8083/search/c.vbs?t=A&n=2003-127058 | manufacture | FBRL | split |
| http://pc411:8083/search/c.vbs?t=A&n=H11-58365 | cut | FBRL | split |
| http://pc411:8083/search/c.vbs?t=A&n=2004-221464 | split | FBRL | split |
| | making | | split |

| Link | Function | Taxonomy | Function term |
|---|---|---|---|
| http://www.gti-usa.com/pages/semi_takatori_wiresaw_MWS_610SD.aspx | cuts | Functional basis | distribute |
| http://www.ctiattachments.com/overview_cutter.htm | cutting | Functional basis | distribute |
| | | | distribute |
| http://www.king-tool.com/drills.htm | cut | Functional basis | distribute |

**Fig. 8.** Search result (3) for FOCUS/Tx (denoted as FBRL) and Functional Basis.

to cause the side-effect (e.g., scrapings). Figure 7 shows a result for this query which includes some possible solutions. The document (a) explains a way that hardens the target objects with ultraviolet rays before slicing to reduce the scrapings. In the document (b), to remove the scrapings by a fluid flow is a supplementary function.

The interoperability of the *Funnotation* framework with FB is enabled by the mapping knowledge discussed in Section 5. By translating the functional terms in the query and the metadata, the search system can access both documents that are annotated based on either of FB or FOCUS/Tx. Figure 8 shows a search result for a given goal-function 'split' of FOCUS/Tx. It includes not only documents annotated as 'split' of FOCUS/Tx but also those documents annotated as 'distribute' of FB which has a mapping to 'split' of FOCUS/Tx. In this manner, users can search for documents independently of the natural language of the documents and of the functional taxonomies used in the metadata. For example, an engineer can get ideas how to realize a function from both English documents annotated in FB from a US-based repository and Japanese documents annotated in FOCUS/Tx from a Japan-based repository. Even if he or she cannot read Japanese, the obtained metadata of the type 2, 3 or 4 (in Section 6.1) explain the possible way(s) for achieving the function.

## 7 Related Work and Discussion

As pointed out in [9], a "shared ontology" can facilitate semantic integration. The top-level generic ontologies such as DOLCE [21], SUMO [22] and PSL [23] can be used as the shared ontology [9]. Our FOCUS/Ref also can be regarded as a kind of such a shared ontology for matching concepts in ontologies, though a concept of the ontology is *not defined* as a subtype of a category of FOCUS/Ref in the ontology building process *but is classified* into a category in the mapping process. FOCUS/Ref is at the intermediate-level lower than those top-level ontologies. It is specific to the engineering domain, but it is applicable to wide-range of artifacts (see the discussion on limitation in [6]). It covers also several definitions of function that have been proposed in the literature [6]. We cannot claim its completeness in nature.

ONIONS methodology [24] is pioneering work to integrate terminologies based on formal and generic ontologies. It includes the "conceptual analysis" phase, in which the entities of a source terminology are represented in a formal way. Although our approach is *not* based on formal and generic (top-level) ontologies for integration, we described ontological descriptions of FB terms as a kind of the conceptual analysis and classified them into a category of FOCUS/Ref as an "intermediate ontology" [24].

A matching method based on an ontology that holds 'background knowledge' is proposed in [25]. A concept in source/target ontologies is connected to a concept in the background ontology ('anchoring matches' [25]) similar to the common ontology. Those anchoring matches are, however, produced automatically based on a simple lexical heuristic and the background knowledge (e.g., its semantic structure) is used to find semantic match between the source and target ontologies having few semantics.

Many methods for annotation-based semantic search have been proposed to date (e.g., [26]). Currently, our method simply shows the documents selected by the given query without ranking. More sophisticated search method remains as future work.

As mentioned in Introduction, there are many definitions of function (see [2,12,13]) and functional taxonomies [1,4,7,8]. Reconciled Functional Basis is a result of merging two existing taxonomies aiming at a 'standardized taxonomy' [8]. We aim at establishing mappings ('ontology matching' in the terminology of [10]) rather than merging ('ontology merging'), in order to allow the diversity of conceptualization of functions. Thus, FOCUS/Ref provides not a super-set (logical sum) of the existing taxonomies but generic upper categories of functions.

A functional modeling framework for the Semantic Web has been proposed in [27]. It is based on Functional Basis [8] and is used for reasoning tasks. It lacks an ontological foundation and interoperability with different taxonomies. For example, because it lacks the notion of "way of function achievement", the functional model in [27] is directly associated with components as a part of realization. Such direct association reduces flexibility in realization of functions.

The ontology-based integration and interoperability among engineering knowledge have been investigated from early 1990's such as PACT [28] and KIEF [29]. They mainly focus on generic mechanism for interoperability among engineering tools. The information integration of product data in the automobile industry is realized by ontology mapping [30]. Product data exchange based on a generic ontology has been proposed in [31]. The target knowledge in these papers is mainly the data level such as geometry rather than the conceptual knowledge level discussed in this paper. PhysSys ontology [32] is well-established ontology about physical objects. It, however, has no ontology for functions from the teleological viewpoint.

Our functional ontology is a domain knowledge and is different from "task" knowledge of designing or diagnosing, which has been discussed in the task ontology research (e.g., [33]).

## 8 Conclusion

In this paper, we have established two-way ontology mappings between two functional taxonomies by deep manual analysis based on the reference ontology of function for bridging the ontological gaps. Such ontological-level analysis has brought us the successful mappings, which suggest the validity of the taxonomies. Using the mapping knowledge, the semantic search system can provide users interoperable access to the technical documents by searching for functional metadata based on either of functional taxonomies.

In summary, the contributions of this paper includes (1) to show a successful application of ontological matching for interoperable annotation-based document management, (2) to demonstrate a successful case study of 'deep semantic mapping' based on an intermediate-level reference ontology rather than 'shallow matching', (3) to provide an interoperable engineering document management system and (4) to investigate ontological types of function by comparing the functional taxonomies.

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