TAXONOMY OF COGNITIVE FUNCTIONS

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ABSTRACT

This paper presents a taxonomy of cognitive functions that supports formal functional modeling of cognitive technical systems (CTSs) and cognitive products. To date, there is little support for functional modeling of such systems and products even though their interdisciplinary complexity exceeds that of electro-mechanical products and makes modeling support in conceptual design even more important. The taxonomy of cognitive functions is based on literature research and consists of a set of cognitive capabilities on three hierarchical levels as well as a defined set of flows. Relationships among cognitive capabilities have been identified using WordNet, a lexical database of English. The application of the taxonomy is demonstrated through the example of a coffee robot waiter, which has been designed and prototyped in the research group of the authors. Through defining a common taxonomy of cognitive functions and flows, a common practice for functional modeling of cognitive products is defined thus supporting re-use of functional models. This creates the foundation for creating model-based design repositories for CTSs and cognitive products to support their future development.

Keywords: cognitive products, cognitive capabilities, functional modeling, formal representation, functional languages

1 INTRODUCTION

CTSs and cognitive products have been gaining increasing interest and importance in research and industry due to their potential superior product properties like improved robustness, reliability, flexibility and autonomy. These superior product properties are enabled through flexible control loops and cognitive software algorithms, differentiating CTSs and cognitive products from mechatronic systems that act according to rigid and pre-defined control algorithms. The development process of CTSs and cognitive products is complex and requires the coupling of different domains, e.g. mechanical engineering, electrical engineering, computer science, psychology and cognitive neuroscience. The potential application areas for such products seem endless and are targeted to change and improve everyday life. Nevertheless, up to date, only few immature methods exist to support their development from conceptual design to production. This paper presents an approach to systematically model such systems in conceptual design by creating a new taxonomy of cognitive functions that enables unified functional modeling of CTSs and cognitive products across domains. Functional modeling of CTS and cognitive products is regarded as a key point to enable better communication in multidisciplinary teams, re-use of models, and provide graphical representation of complex relationships. Further, a commonly defined taxonomy is the first step to developing a model-based approach for cognitive products and facilitates providing computational support through modeling tools.

This paper starts with an introduction to functional modeling with a focus on formal representations. Next, CTSs and cognitive products are briefly explained and cognitive capabilities elaborated. The result of literature research on cognitive capabilities is presented in Section 3, providing the foundation for a taxonomy of cognitive functions. In the method section it is further illustrated how the cognitive capabilities found are adjusted in order to extract a generalized set. Beyond that, the relations among different cognitive capabilities are investigated. This allows the compilation of a hierarchy of cognitive functions establishing the first part of the vocabulary. The second part is represented by a set of flows the cognitive functions operate on. In Section 4 the applicability of the taxonomy is demonstrated by modeling a coffee robot waiter. The paper concludes with a discussion of found results and a brief outlook.

2 BACKGROUND

This section introduces functional modeling and points out advantages of formal function representations that e.g. can reduce ambiguity and increase uniformity of functional models for potential re-use. Afterwards, a definition of CTSs and cognitive products is given before it is elaborated on cognitive capabilities.

2.1 Functional Modeling

The process of describing the product function of a system or product in a model through sub-functions is called functional modeling [22, 27]. This usually takes place in conceptual design after identifying the system or product requirements and before searching for solutions. It is a key step in the product design process for original and redesign [2]. Functional modeling is an abstract but direct method for understanding and representing technical systems considering the product function and all sub-functions of the system or product while also representing their connectivity. It can help designers to better understand complex products [26, 27], e.g. cognitive products and CTSs. Design activities are eased through functional modeling by problem decomposition, physical modeling, product architecting, concept generation and team organization [2, 3, 21, 22, 26]. Flow-oriented function models are appropriate to describe systems or products with flows [21, 22, 3, 2]. Therefore, it is essential to define how different functions can be connected. This is usually done using energy, material and signal flows between functions. In contrast, relation-oriented function models sketch the interrelationship of functions in a system or product [22].

It is proven that creating a functional model together in a team assists the common understanding of the modeled object [22]. Especially in interdisciplinary teams, communication and coordination during the development phase is enhanced through high-level abstraction [22, 27]. Therefore, a common design language, understood by all involved persons, is essential and becomes of particular importance in interdisciplinary design processes, such as design teams developing cognitive products. However, there are only few methods supporting the functional modeling of products and systems where different domains are involved [24]. So far, no known method supports the product developer to model cognitive functions and create cognitive function structures. For example, modeling of cognitive products that rely heavily on software using the conventional approach as in [2, 3, 21, 22, 23] can put restrictions on the software development that is usually carried out after creating the physical architecture [24]. This hinders efficient functional modeling of multi-domain projects. Another reason is that the definition of function and flows does not allow an appropriate modeling of the aspired functions because the functions have been defined for a mechanical or electro-mechanical domain [2, 3, 21, 22].

2.1.1 Formal Product Representation

Formal representations in functional modeling are important to reduce ambiguity, create a unique product concept model and increase uniformity of functional models for potential re-use. A formal representation defines functions and flows and constraints on how they can be connected. To date, there exist several formal representations of functions and flows [21, 22, 23, 2] as well as function taxonomies. There have also been efforts to establish a common design language resulting in the NIST functional basis for engineering design, focusing primarily on the mechanical and electro-mechanical domains [2, 3].

The NIST functional basis for engineering design evolved through reconciling and integrating two independent research efforts into a significantly evolved functional basis [3]. Former taxonomies like the ones developed by Pahl and Beitz [21], Hundal [28] and Altshuller [29] have been analyzed and reconciled in order to create an exact and systematic formal representation. The result is a common design language for use with functional models, focusing primarily on mechanical and electro-mechanical domains [2]. Initial research issues have been the development of a taxonomy of standardized terminology to help provide consistency in, and across, design repositories. Also the indexing, search and retrieval of information is enabled using a taxonomy [3]. The authors claim that a commonly agreed-on set of functions that is able to be performed by mechanical systems is necessary to create reproducible functional models [3].

Nevertheless, to date, there exists neither a common set of cognitive nor mechatronic functions. Common approaches in formal modeling are mostly limited to specific domains, e.g. the NIST functional basis, and do not support multi-disciplinary functional modeling.

The goal of this paper is to create and establish a common, formal modeling language for cognitive products and CTSs, comprehensively describing the modeling of cognitive functions. Initially, only system level functions are considered but as research advances component level functions will be investigated as well. It is expected that component level functions can be modeled with state-of-art modeling approaches but, for system level functions and direct sub-functions a new modeling approach is required. To date, there exist several approaches for product- and software development. For the interdisciplinary development of systems, e.g. mechatronic systems there exists a very generic process model [31] but only few and immature methods and tools to support conceptual design, e.g. [32].

As for the mechanical and electro-mechanical domain, a consistent language or coding system is required that is both human and machine readable, according [2]. This is inevitable if computational support is aspired, e.g. using the “Systems Modeling Language” (SysML) [32] as a language for functional modeling. A consistent language will greatly enhance the re-use of previous modeled systems and has the potential to expand design repositories [3]. The proposed formal representation, or taxonomy of cognitive functions, in this paper is presented in Section 3.

2.2 Cognitive Technical Systems and Cognitive Products

CTSs and cognitive products build on mechatronic systems. However, instead of obeying rigid and pre-defined control algorithms perceived data, i.e. through sensors, is always processed according to the perceived situation. Therefore, CTSs need adaptable and flexible control loops [8]. Systems are considered CTSs if they possess similar cognitive capabilities as humans [34]. Cognitive products, which are based on CTSs, have either all or a subset of capabilities of CTSs, based on the required functions to meet user needs and desires. Cognitive products are tangible and durable things with cognitive capabilities that consist of a physical carrier system with embodied mechanics, electronics, microprocessors and software. Customer needs are satisfied through the intelligent, flexible and robust behavior of cognitive products that meet and exceed customer expectations [1].

The benefits of CTSs and cognitive products are generated through high-level capabilities, for example, to robustly adapt to a dynamic environment. They do not only act autonomously but in an increasingly intelligent and human-like manner. They can be integrated into human living environments and show a high level of interaction and cooperation with humans. Moreover, they are able to maintain multiple goals and make appropriate decisions. By doing so, CTSs and cognitive products exhibit higher reliability, flexibility, adaptivity, interaction and an improved performance compared with mechatronic products.

2.3 Cognitive Capabilities

What makes systems and products cognitive are their high-level capabilities, in literature often described as cognitive capabilities [8, 1, 10], cognitive abilities [13] or cognitive functions [12]. In the following, the term “cognitive capabilities” is used consistently to describe the basic functions enabling cognition as a whole. According to the literature, CTSs require all human cognitive capabilities in order to reach human-like cognition [34]. Whereas, the authors state that cognitive products are characterized through a subset of these cognitive capabilities [1]. However, in literature, there is no common list of cognitive capabilities that are required for a cognitive system, neither human nor artificial. Typically, researchers in the area each compile their own list of cognitive capabilities. Moreover, there is no definition about the degree of each cognitive capability, e.g. type and depth of learning, a system needs to be characterized as a CTS.

A missing set of common cognitive capabilities and flows hinders functional modeling up to date. Further, it would be difficult to model a system or product that, for example, is able to simply “*perceive*” because it needs to be specified what has to be perceived and to what degree.

3 TAXONOMY OF COGNITIVE FUNCTIONS

Functional modeling requires the use of natural language to define functions, or how a product fulfills tasks and requirements. In order to formalize the way this is done for potential model re-use, an agreed on, or controlled, design vocabulary must be defined. This vocabulary must be systematic and exhaustive with a consistent level of detail. Each set of terms at a certain hierarchical level should provide complete coverage of all concepts within a category [3]. The aspired goal is a comprehensive set of cognitive functions that can be used to model any cognitive product or technical system. This

will also enable the implementation of software tools supporting consistent functional modeling in conceptual design through a standardized representation. Using a fixed vocabulary for cognitive functions and flows, they can be grouped into a hierarchy that creates a taxonomy [3] describing the design space for cognitive products and CTS.
Therefore, in this section common vocabularies of cognitive capabilities and flows are proposed. These vocabularies are based on the literature research presented in Section 3.1, and together form the taxonomy of cognitive functions, with functions that are represented by verb-object pairs, e.g. "*perceive signal*" and "*learn data*".
The challenge according to [3] is to choose a minimalist approach regarding the vocabularies and keep them as atomic as possible but generic enough to allow functional modeling of a broad variety of cognitive products and CTS. Section 3.1 describes how the original list of cognitive capabilities was compiled in order to extract the proposed vocabulary of cognitive functions that is presented in Section 3.2. In Section 3.3 the vocabulary of flows among cognitive functions is shown.

3.1 Method

To form the basis for creating a common set of cognitive capabilities, 15 publications from computer science, engineering and cognitive science dealing with cognition have been searched for cognitive capabilities and synonyms in order to compile a common set of terms. So far, 37 terms and phrases describing cognitive capabilities have been found. Nevertheless, it is difficult to work with these initial terms and phrases since some terms are used synonymously, some terms overlap in their meaning and some describe cognitive capabilities in phrases instead of using one significant term. Further, some terms characterize what arises through the combination of different cognitive capabilities, e.g. intention recognition [12] requires at least perception and interpretation of the perceived data. The revised set of terms is shown in Table 1.
In this paper cognitive capabilities are considered the basic abilities of a cognitive system and can be described through a set of networked cognitive functions. According [4], verbs are words indicating an action, occurrence or state of existence. Because a capability expresses the ability to perform an action, the appropriate representation for each cognitive function is an active verb. This aligns well with functional modeling according to [1, 2, 3, 21, 22, 27] where the verb-object format is predominant and verbs are generally used as operators. Therefore, the verb-object format is maintained by the authors and all cognitive capabilities that were found in literature have been translated to a verb, if not already expressed through a verb, expressing the intended action by the initial term or phrase. The result of the literature research, condensed to 27 verbs representing cognitive capabilities, is shown in Table 1. In the first column the 27 cognitive capabilities are listed and in the first row the investigated publications are presented. Each "X" indicates a statement related to a cognitive capability. A first indicator of the commonality of terms is the sum of how many times each cognitive capability has been stated, shown in the second column. Some, e.g. "*to perceive*", "*to learn*" and "*to act*" have been explicitly mentioned by almost every publication. Others, like "*to schedule*", "*to judge*" and "*to create*" have been mentioned only by a single publication.
While compiling the list of cognitive capabilities in Table 1 it became obvious that many verbs are somehow related. One example is "*use of language*" that is a specification of "*to communicate*" that relates to "*to interact*". To create a common list of cognitive capabilities, the terms found and shown in Table 1 must be related and combined, e.g. to eliminate functions that are specializations of more generic ones.
In order to find synonyms and the relations among all the different verbs in Table 1, WordNet was used. WordNet is a large online lexical database of English [4] and the most commonly used computational lexicon of English for "Word Sense Disambiguation" [5]. It is organized according to current psycholinguistic theories on how people use and remember language, not alphabetically like dictionaries [20]. It allows arranging all verbs in a hierarchy, identifying which terms belong together and how.

Table 1: List of Cognitive Capabilities Found in Literature.

Cognitive Capability \ Reference	Sum	Beetz et al. [8]	Brachmann [9]	Borst et al. [10]	Haikonen [11]	Burghart et al. [12]	Evaluation Burghart et al. [12]	Paetzold [13]	Kinsner [14]	Earl [15]	Morris [16]	Nadel [17]	Anderson [7]	McClelland [6]	Strube [18]	Vernon et al. [19]	Metzler et al. [1]
to perceive	16	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
to learn	14	x	x	x	x	x	x	x		x	x	x	x	x	x		x
to memorize	7				x	x		x					x	x	x	x	
to know	6	x				x	x			x			x				x
to think	2							x							x		
to reflect	2	x	x														
to focus	4				x				x				x		x		
to reason	9	x	x	x			x				x	x	x	x			x
to compute	4		x					x		x		x					
to deduce	2				x										x		
to find, to feel	4				x		x		x						x		
to plan	7	x		x		x				x			x		x		x
to schedule	1			x													
to solve (problems)	6					x	x	x					x	x	x		
to interpret	2							x						x			
to appreciate	6	x	x		x		x		x						x		
to decide	3			x							x		x				
to judge	1				x												
goal orientation	4			x			x			x					x		
to act	15	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
to coact	2		x												x		
to create	1								x								
to interact	5	x							x						x	x	x
to communicate	12			x	x	x	x	x	x		x	x	x		x	x	x
to explain	2	x	x														
use of language	4							x					x	x	x		
to react	4	x	x	x	x												

Among others, verbs are grouped into sets of cognitive synonyms called synsets with every synset expressing a distinct concept. Synsets can be a synonym set or a set of words that are interchangeable in some context without changing the truth value of the preposition in which they are embedded. Verbs are generally organized in hierarchies based on the hypernym relation between synsets. Additional pointers indicate semantic relations. For verbs only semantic relations that hold between word meanings are relevant [4]. A hypernym is the generic term used to designate a whole class of specific instances, for example "*to act*" is a hypernym of "*to interact*" because "*to interact*" is a kind-of "*to act*". In comparison to hypernyms, troponyms are verbs expressing a specific manner of another verb, for example "to communicate" is a troponym of "to interact" because "to communicate" is "to interact" in some manner. The term for troponym verbs sharing a common hypernym is "coordinate terms" [25]. The relations among verbs according WordNet are illustrated in Figure 1.

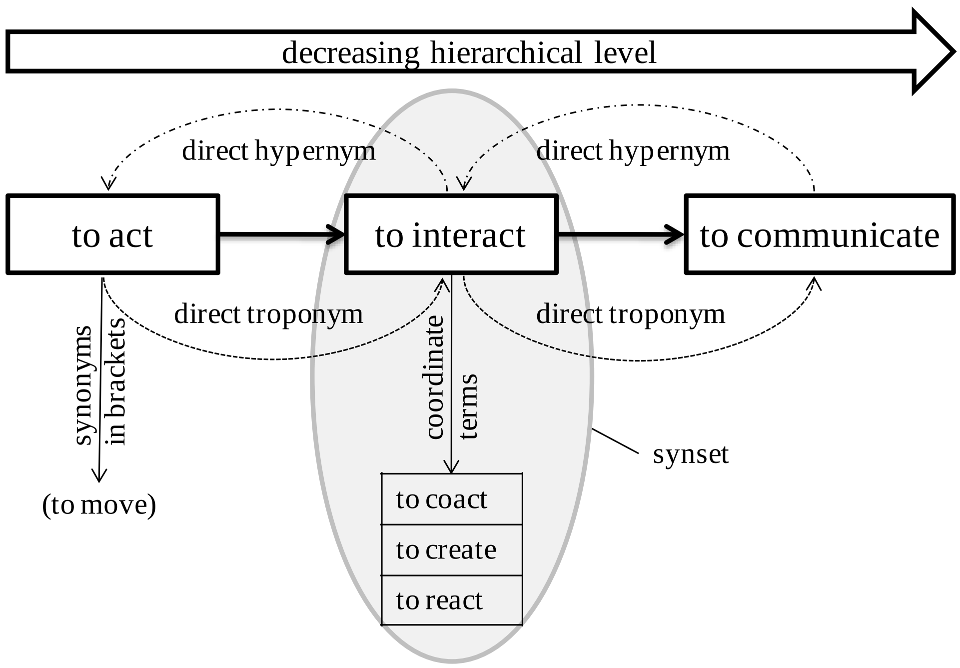

Figure 1: Relations among verbs according WordNet.

In Table 1 synonym terms have already been removed and are represented through the most stated term. In addition, the relations of the stated cognitive capabilities are illustrated using different grey shades and different indentation lengths. In total, cognitive capabilities on four hierarchical levels have been identified through WordNet and are presented starting with the highest hierarchical level in dark grey and white letters to the lowest level with a white background and black letters. This allows one to intuitively understand the relations of the stated cognitive capabilities. It also becomes obvious that for some cognitive capabilities only a superordinate verb at the highest hierarchical level has been mentioned, e.g. "*to perceive*", while for others the stated capabilities are spread over four hierarchical levels, e.g. "to act". Looking at the sum of how many times each cognitive capability has been stated, it can be identified that cognitive capabilities at the highest hierarchical level are used most often. In addition, if a subordinate verb has been stated, in most cases, the hypernym is stated as well. An exception is the cognitive capability "to think" that only has been stated in two publications whereas subordinate verbs of "to think" have been mentioned in 15 publications.
The reasons why cognitive capabilities are mentioned at different hierarchical levels are not clear. One might assume that some terms are naturally more understandable than others. For example, most people would have similar interpretations of "*to perceive*" which makes an additional description needless. In contrast, "*to think*", "*to understand*" or "*to act*" are multidimensional; meaning that a subordinate verb might better express what the author specifically intended to say. Another explanation could be due to the different research domains of the publications, e.g. robotics, computer science, psychology, and different commonly accepted terms. Both possibilities will be investigated in future research.

3.2 Vocabulary of Cognitive Functions

Considering the relations between cognitive functions that have been identified using WordNet (see Section 3.1) and are stated in Table 1, the cognitive functions have now been arranged in a hierarchy. Since taxonomies are classifications typically arranged in a hierarchical structure, similar to the result of the WordNet analysis, they are an appropriate classification for the vocabulary of cognitive functions. As mentioned in Section 3.1, cognitive functions on four hierarchical levels have been identified but since only two terms are on the fourth hierarchical level and have been mentioned only in two and four publications respectively, the taxonomy is established with three hierarchical instances (Table 2). If future work identifies that more specific cognitive functions are required to model cognitive products, the taxonomy can be extended by additional hierarchical levels. In case it is found that a taxonomy with a hierarchical structure is not appropriate to represent the structure of cognitive functions because additional relations among them are discovered, the representation will be changed to an ontology that is capable of more flexibility representing relationships.

Disregarding that a design vocabulary should be exhaustive at each instance, Table 2 includes just the cognitive functions found in the literature review and, in addition, the most relevant synonyms of these functions selected from WordNet in parentheses. Only two exceptions have been made because subordinate terms, e.g. "*to memorize*" and "*to solve*", are mentioned but the superordinate term has not been mentioned. The two exceptions that have been added, "*to study*" and "*to understand*", are indicated by grey shaded cells. "*To understand*" is a direct hypernym of "*to solve*", "*to interpret*", "*to perceive*", and "*to appreciate*" at the highest hierarchical level. "*To study*" is a direct hypernym of "*to memorize*" and at the same time a troponym of "*to learn*" residing on the second instance of the hierarchy.
The reason to include these two verbs that have not been mentioned in one of the publications is to avoid inconsistency and to allow the reconstruction of the hierarchy.

Table 2: Hierarchy of Cognitive Functions.

Primary	**Secondary**	**Tertiary**
to perceive (to comprehend)		
to learn (to aquire)	to study (to hit the books)	to memorize (to learn)
to understand	to interpret (to construe, to see)	
	to solve (to work out, to figure out)	
	to perceive (to become concious of)	
	to appreciate (to take account)	
to know (to cognize)		
to think (to cogitate, to cerebrate)	to reflect (to think over, to meditate, to ponder, to contemplate, to speculate)	
	to reason	to calculate (to cypher, to compute, to work out, to figure)
	to reason (to conclude)	to deduce (to infer, to deduct, to derive)
		to find (to feel)
		to deduce (to infer)
	to plan	to schedule
	to focus (to concentrate, to center)	
to decide (to determine)	to judge (to adjucate, to try)	
to act (to move)	to react (to respond)	
	to create	
	to interact	to communicate
	to coact	
	to move	

Even though the proposed method is appropriate to find cognitive capabilities of the primary instance, it is not sure if the method can be applied to find subordinate terms efficiently. It is now investigated if the blank fields of Table 2 can be completed in order to guarantee a consistent level for functional modeling of cognitive capabilities. An example is given in Table 3 where all direct troponyms of "*to perceive*" are listed in the second column. In order to compile an exhaustive but redundancy-free set of secondary instances all coordinate terms have to be analyzed. Inappropriate terms for technical products and systems are then removed. In Table 3, these terms are designated with a black background. Secondary cognitive capabilities like "*to divine*", "*to hallucinate*", "*to dream*" or "*to hurt/ache/suffer*" are not considered relevant for CTS and cognitive products.

Table 3: Direct Troponyms for "*to perceive*" according WordNet [4].

Primary	Secondary
to perceive (to comprehend)	to sense, to feel
	to apperceive
	to pick up, to receive
	to divine
	to hallucinate
	to misperceive
	to catch, to pick up
	to dream
	to hurt, to ache, to suffer
	to smell
	to touch
	to see
	to spy, to sight
	to hear
	to listen
	to taste
	to find
	to see through

3.3 Vocabulary of Flows among Cognitive Functions

To date, the common taxonomies for functional modeling typically use three different flows on the primary level: "*material*", "*energy*" and "*signal*" [2, 3, 21, 22]. To create a taxonomy of cognitive functions it is now investigated if these flows are appropriate objects for the previously defined cognitive capabilities. Since CTS and cognitive products rely on mechatronic hardware platforms [8, 12, 13, 18], it is assumed that these flows can be adopted from the established functional modeling approaches since they are already used for modeling electro-mechanical systems. However, additional flows may be required.

In [26, 13] "*energy*", "*material*" and "*information*" are stated as elementary flows, varying from the common set of flows by substituting "*information*" for "*signal*". However, considering the definition from [30], "*signal*" and "*information*" can not be considered equal. The relations among "*signal*", "*data*" and "*information*" are illustrated in Figure 2. At the bottom level of Figure 2 there are a large amount of signals that are technically represented by pulse sequences that can be sensed (not perceived) by a CTS or cognitive product. These signals can be electrical, mechanical, acoustic, visual, etc. Signals that have been sensed by the system without any instruction about what to do with them are declared as data. It is noteworthy that by the transformation from signal to data, the system border of CTSs or cognitive products is passed. Through context, data becomes information that is then useful to make decisions [30]. This differentiation has to be taken into account while modeling CTSs and cognitive products because, as initially stated, they process data always according to the perceived situation [1, 8].

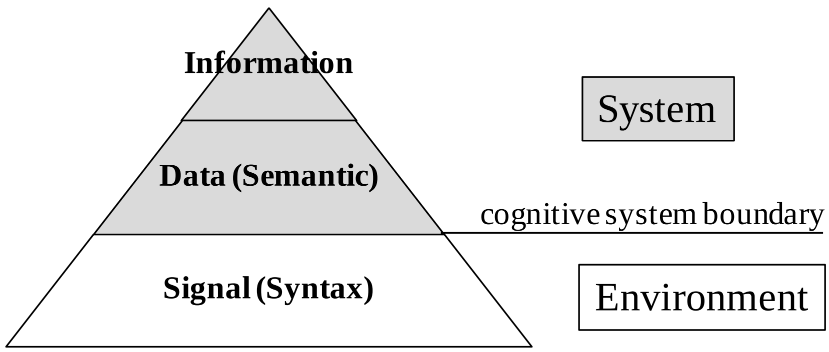

Figure 2: Hierarchy of Signal, Data and Information according [30, 33].

The vocabulary of flows among cognitive functions consists then of five objects according to the previous elaboration: "*material*", "*energy*", "*signal*", "*data*" and "*information*". According to [3] these flows can be further specified.

4. APPLICATION – A COFFEE ROBOT WAITER

How the taxonomy of cognitive functions is used to model a cognitive product is demonstrated in this section using an example: a coffee robot waiter that has been developed at our institute [1]. In the operational mode the robot is able to serve coffee on demand within an office environment autonomously. For this use case several cognitive capabilities are required due to the constantly changing environment and frequently changing tasks.

According to section 2.3 CTSs require all primary cognitive capabilities. This implies that from the primary cognitive capabilities only a single function structure can be compiled that is valid for all CTSs. This is slightly different for cognitive products, e.g. the coffee robot waiter, where the functional model can vary according the required cognitive capabilities. To make the example tangible the coffee robot waiter is modeled using cognitive functions on the secondary level according Table 2. If a cognitive capability is not available at the secondary level the term of the primary hierarchical level is applied instead. Due to the complexity of the whole system the coffee robot waiter is modeled only partially, taking into account functions that are related to the planning part of serving coffee. The result is a clearly arranged function structure, shown in Figure 3.

During service hours of the robot there is "*interaction*" between the users and the robot, more precisely the users can place orders on their computers that are transferred through electronic "*user signals*" to the robot. The robot "*perceives user states*" including who placed an order, expressed as "*user data*", and where to deliver coffee to, expressed as "*location data*". Because the robot has an internal map of its environment it "*knows locations in the environment*" and can transform the "*location data*" into "*location information*", meaning that it knows of where to deliver the coffee in its environment. This is the first information necessary to "*plan a route*" for delivering coffee. Additionally, the robot is able to allocate certain user profiles to "*user data*" and assign user habits to the "*user data*". This is possible because every user has to register prior to use the service. The robot "*knows user habits*" of every user from past events. The result is "user information". Together, "*coffee pot data*" that comes from "*perceiving coffee state*" and "*user information*" enable the robot "*to reason about coffee range*" according previous coffee consumption of the users in the queue waiting for coffee and current filling level of the coffee pot. As a result "c*offee information*" is generated and integrated in the route planning. Since the start location for the route is necessary and given by the actual location of the robot, it needs "*to perceive the environment*", e.g. with a laser range scanner, and compare the "*perceived environmental data*" with an internal model of the environment. The robot "*knows locations in the environment*" and compiles "*location information*" about the current position. "*Location information*" of the robot itself and users is essential "*to plan an optimal route*" considering distance and "*take account*" of all waypoints. In our application example the cognitive function "*plan route*" is accomplished by applying an online traveling salesman algorithm. The result is "*route information*".

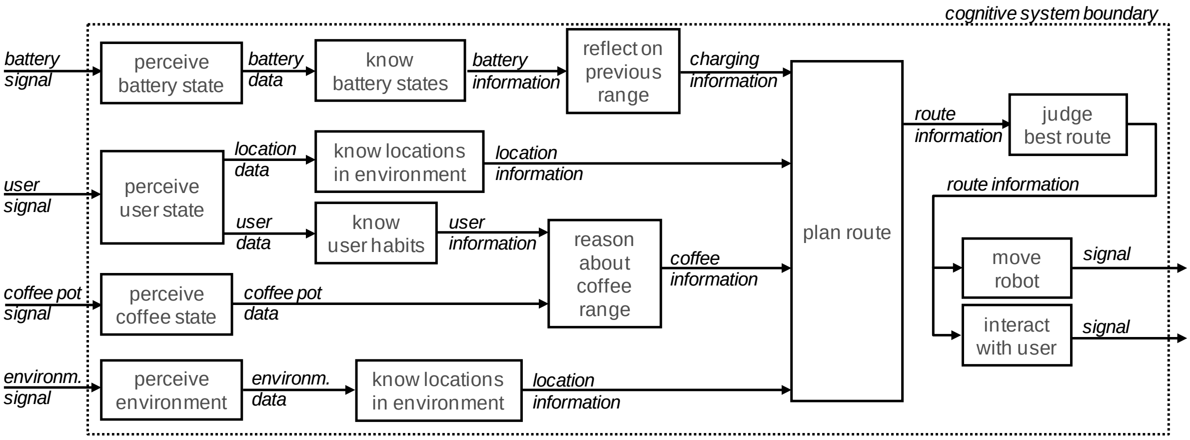

Figure 3: Partial Function Structure of the Coffee Robot Waiter.

To further improve the route planning, the robot could "*perceive the battery state*" that allows it to get "*battery information*" by comparing "*battery data*" with "*known battery states*". This allows "*reflecting on the previous range*" according to the "*battery information*", generating "*charging information*" about when and how long to charge batteries to avoid breaking down during the route.

After all input "*information*" is available the optimal route can be planned. Therefore the algorithm has to "judge the best route" according to some goal function. Finally the robot "interacts" with the users by generating an output "*signal*" and starts the delivering process by "*moving the robot*".

5. DISCUSSION

In this paper a taxonomy of cognitive functions is presented, enabling formal functional modeling of CTSs and cognitive products. The taxonomy consists of two vocabularies: the vocabulary of cognitive functions and the vocabulary of flows. Especially the vocabulary of cognitive functions is based on literature research of 16 publications and is not an exhaustive overview. Further work is needed to fill the blank fields in Table 2 to an adequate level of abstraction with terms that have no or minimal overlap in their meaning. A method according to the above illustrated approach where troponyms of "*to perceive*" have been analyzed and highlighted in Table 3 is aspired and could help to create an exhaustive vocabulary of cognitive functions. The application of the taxonomy was inconsistent due to missing functions on the second hierarchical level, shown in Figure 3. However, the presented method made it possible to group cognitive capabilities into a hierarchy that allows adding cognitive functions according to their level of abstraction considering the hypernym-troponym relationship of WordNet.

More research is necessary to investigate how the definitions of cognitive functions vary among different domains, e.g. psychology, computer science and engineering disciplines, to identify a common set of cognitive functions that can be used by all disciplines to model CTSs and cognitive products. The majority of publications used in the literature review to build the taxonomy come from the engineering and computer science domain. Future work will investigate cognitive science and psychology to a similar extent, especially investigating existing cognitive architectures and taxonomies of human cognitive functions. Further, this would establish a vocabulary that is agreed on in all research fields related to CTSs and help to reach a common understanding of cognitive capabilities in technical systems. So far, no distinction between different domains has been made.

In the future, relationships can be added to the taxonomy of cognitive functions to describe which function requires which other function(s), or relationships between functions that constrain their connectivity. Further, these relationships can be expressed as formal constraints among functions. For example, the cognitive function "*to learn*" may require "*to perceive*" and "*to know*" as prerequisites.

In the vocabulary of flows among cognitive capabilities, an inconsistency was found between the presented argumentation and WordNet. According to WordNet, "*data*" and "*information*" are considered synonym terms. This is a contradiction to the proposed differentiation between "*signal*", "*data*" and "*information*" flows following information theory [30, 33]. "*Data*" with the intended meaning in information theory and this paper is described as "*raw data*" in WordNet. Raw data is unanalyzed data or data that has not yet been subjected to analysis. For simplicity reasons the simple term "data" is used and the domain-specific view to differentiate these three terms.

6. CONCLUSION AND OUTLOOK

This paper presents a taxonomy of cognitive functions derived from analyzing research literature on CTSs from computer science, psychology, mechanical engineering and electrical engineering. A taxonomy of cognitive functions is important for formal functional modeling of CTSs and cognitive products to create reproducible and re-usable models. Further, it will provide for a common understanding of cognitive capability terms among disciplines. Cognitive capabilities and functions that have been found in literature have been analyzed and relations among them were identified using WordNet. These relations allowed ordering the cognitive functions in a hierarchy with three instances forming the first part of the design vocabulary. The second part is the vocabulary of flows among the cognitive functions. The main difference to common functional modeling is the introduction of "*data*" and "*information*" as flows, in addition to "*signal*". The approach was demonstrated through an example of a coffee robot waiter. After expanding the current taxonomy, future work also includes validating it through creating functional models in SysML for a range of cognitive products in different areas developed by students in the research group. It will further serve as the basis for a library of functions in SysML to enable the consistent, formal modeling of CTSs and cognitive products. This will also include defining and modeling constraints on the connectivity of functions.

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REFERENCES

[1] Metzler, T., Shea, K.: Cognitive Products: Definition and Framework. In: *11th International Design Conference – DESIGN 2010*, Zagreb, 2010, pp. 865-874.

[2] Stone, R.B., Wood, K.L.: Development of a Functional Basis for Design. In: *Journal of Mechanical Design*, Vol. 122, December 2000, pp. 359-370.

[3] Hirtz, J., Stone, R.B., McAdams, D.A., Szykman, S., Wood, K.L.: A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts. *NIST Technical Note 1447,* Washington, February 2002.

[4] Princeton University "About WordNet." WordNet. Princeton University. 2010. http://wordnet.princeton.edu.

[5] Navigli, R.: Word Sense Disambiguation: A Survey. In: *ACM Computing Surveys*, Vol. 41, No. 2, Article 10, February 2009.

[6] McClelland, J.L.: Connectionist Cognitive Modeling. In*: The MIT Encyclopedia of the Cognitive Sciences,* edited by Wilson, R.A.; Keil, F.C., The MIT Press, 2001.

[7] Anderson, J.R.: Kognitive Psychologie, 6th Edition, Springer, Berlin, Heidelberg, 2007.

[8] Beetz, M.; Buss, M.; Wollherr, D.: Cognitive Technical Systems – What ist he Role of Artificial Intelligence? In*: KI 2007: Advances in Artificial Intelligence*, Vol. 4667, Berlin, 2007, pp. 19- 42.

[9] Brachmann, R.J.: Systems That Know What They're Doing. In: Intelligent Systems, Vol. 17, No. 6, 2002, pp. 67-71.

[10] Borst, C.; Deml, B.; Felder, M.; Friesdorf, F.; Giuliani, M.; Glasauer, S.; Halbrügge, M.; Lenz, C.; Neumann, H.: White Paper CoTeSys Task Force: Cognitive Architectures. Internal White Paper of the CoTeSys Task Force Cognitive Architectures.

[11] Haikonen, P. O.: The Cognitive Approach To Conscious Machines, Exeter, 2003.

[12] Burghart, C.; Mikut, R.; Stiefelhagen, R.; Asfour, T.; Holzapfel, H.; Steinhaus, P.; Dillmann, R.: A Cognitive Architecture for a Humanoid Robot: A First Approach. In: *Proceedings of 2005 5th IEEE-RAS International Conference on Humanoid Robots, Tsukuba, 2005, pp. 357-362.*

[13] Paetzold, K.: On the Integration of Aspects of Motivation in Cognitive Technical Systems. In: *Proceedings of the International Conference on Engineering Design, ICED'07,* Paris, 2007.

[14] Kinsner, W.: Towards Cognitive Machines: Multiscale Measures and Analysis. In: *Proceedings 5th IEEE Int. Conf. on Cognitive Informatics (ICCI'06)*. Beijing, 2006, pp. 8-14.

[15] Earl, C.: Designing Intelligent Machines Volume 1: Perception, Cognition and Execution. Oxford, 1995.

[16] Morris, R.: The Foresight challenge. In: Newsletter of the Foresight Cognitive Systems Project: Cognitive Systems. Is. 1, 2003. http://www.foresight.gov.uk.

[17] Nadel, L.: Cognitive Systems: Information Processing Meets Brain Science. California, 2006.

[18] Strube, G.: Modelling Motivation and Action Control in Cognitive Systems. In*: Schmid, U.; Krems, J.; Wysocki, F.: Mind Modelling.* Berlin, Pabst, 1998, pp. 89-108.

[19] Vernon, D.; Metta, G.; Sandini, G.: A Survey of Artificial Cognitive Systems: Implications for the Autonomous Development of Mental Capabilities in Computational Agents. In: *IEEE Transactions on Evolutionary Computation*, Vol. 11 No. 2, 2007.

[20] Chiu, I.; Shu, L.H.: Biomimetic design through natural language analysis to facilitate across-domain information retrieval. In: *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 21, 2007, pp. 45-59.

[21] Pahl, G.; Beitz, W,; Feldhusen, J.; Grote, K.-H.: Konstruktionslehre. 7th Edition, Berlin, 2007.

[22] Ponn, J.; Lindemann, U.: Konzeptentwicklung und Gestaltung technischer Produkte. Berlin 2008.

[23] Ehrlenspiel, K.: Integrierte Produktentwicklung – Denkabläufe, Methodeneinsätze, Zusammenarbeit. 3rd Edition, München, 2007.

[24] Wu, J.-C.; Leu, M. C.; Liu, X. F.: A Hierarchical Object-oriented Functional Modeling Framework for Co-Design of Mechatronic Products. In: *Concurrent Engineering,* Vol. 17, No. 4, Decmber 2009, pp. 245-256.

[25] Fellbaum, C.: WordNet: An Electronic Lexical Database. MIT Press, 1998.
[26] Komoto, H.; Tomiyama, T.: Computational Support for systems Architecting. In: *Proceedings of the ASME 2010 International Design Engineering Technical Conference & Computers and Information in Engineering Conference IDETC/CIE 2010*, Montreal, 2010.
[27] Erden, M.S.; Komoto, H.; van Beek, T.J.; D'Amelio, V.; Echavarria, E.; Tomiyama, T.: A review of functional modeling: Approaches and applications. In: *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 22, 2008, pp.147-169.
[28] Hundal, M.: A Systematic Method for Developing Function Structures, Solutions and Concept Variants. In: Mechanism and Machine Theory, Vol. 25, Is. 3, 1990, pp. 243-256.
[29] Altshuller, G.: Creativity as an Exact Science. Gordon and Breach Science Publishers, New York, 1984.
[30] Krecmar, H.: Informationsmanagement. 4th Edition, Berlin, 2005.
[31] VDI 2206: Design Methodology for Mechatronic Systems. Berlin, 2004.
[32] Weilkiens, T.: Systems Engineering mit SysML/UML. 2nd Edition, Heidelberg, 2008.
[33] Ackoff, R. L.: From Data to Wisdom. In: *Journal of Applied Systems Analysis*. Vol. 16, 1989, pp. 3-9.
[34] Paetzold, K.; Schmid, U.: To the Development of a System Architecture of Cognitive Technical Systems. In: *Proceedings of the 10th International Design Conference – DESIGN 2008*. Zagreb, 2008, pp. 1311-1317.

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