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FORMALCAD – AN APPROACH FOR SEMANTIC SUPPORT IN ENGINEERING DESIGN PROECESSES

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ABSTRACT

The engineering design process follows a series of standardized stages of development, which have many aspects in common with software engineering. Among these stages, the principle solution can be regarded as an analogue of the design specification, fixing as it does the way the final product works. It is usually constructed as an abstract sketch (hand-drawn or constructed with a CAD system) where the functional parts of the product are identified, and geometric and topological constraints are formulated. Here, a semantic approach is outlined where the principle solution and other engineering documents are annotated with ontological assertions, thus making the intended requirements explicit and available for further machine processing; this includes the automated detection of design errors in the final CAD model, making additional use of a background ontology of engineering knowledge. We embed this approach into a document-oriented engineering design process, in which the background ontology and semantic annotations in the documents are exploited to trace parts and requirements through the design process and across different applications.

1 INTRODUCTION

Every product development process follows a series of standardized development stages, and is formally described as such by a range of product development process models and methodologies. The Systematic approach to Engineering Design of Pahl and Beitz [PBF07], the Münchener Vorgehensmodell of Lindemann [L09], the Systematic Approach to the Design of Technical Systems and Products according to the guideline VDI2221 [VDI95] and the Design Methodology for Mechatronic Systems, also known as the V-model [VDI04] are just a few well-known examples. Within this contribution we mainly refer to VDI2221 with its seven steps and the different outcomes of each phase. Computer based approaches have been developed to support the design engineer in the stages within different product development process models. Well-known examples are Computer-Aided Design (CAD), Computer-Aided Engineering (CAE) or Computer-Aided Manufacturing (CAM). They all have in common that they are based on formal (i.e. machine-interpretable) representations of the outcomes of the specific development stage, such as CAD-models, FEA-models (CAE), or CNC-code. However, other recognized development stages and their associated documents such as requirement lists, function models or the principle solution are left largely informal and in fact are often not laid down in any immediately machine-processable form (being, e.g., just hand drawn sketches). This circumstance leads to gaps regarding the semantic links between stages of the product development process and related documents and objects. These links embody questions such as “Does the geometry X fulfil the requirement Y?” or, as a more specific example, “Does this main frame embodiment still correspond to the predetermined principle solution and function structure?”. Almost no machine-support is currently available for verifying such consistency assertions in the development process.

This paper is the result of a research collaboration between the School of Engineering and Science (Jacobs University Bremen), the Chair of Theoretical Computer Science and the Chair of Engineering Design (both Friedrich-Alexander Universität Erlangen-Nürnberg). We propose a semantic approach where objects are linked across the stages of the product development process using a federated ontology, in which all objects are grounded via annotations with ontological concepts and assertions. The approach is embedded into a document-oriented design work flow, in which the so called federated ontology and semantic annotations in design documents are exploited to trace parts and requirements through the development process and across different applications. Both, requirements and ensuing design decisions are made explicit and, hence, are available for further machine processing. Within a short use case a sample requirement is traced through the development of a spring tester.

2 SEMANTICS AND ONTOLOGIES IN ENGINEERING DESIGN

Many approaches have been proposed to integrate semantics into the engineering design process, whereas the so-called feature technology is one of the most well-known. According to VDI2218 [VDI03], features are an aggregation of geometry items and semantics. Depending strongly on the technical domain and the product life-cycle phase, different types of features are defined (e.g. form features, semantic features, application features, compound features).

Li et al [LMN13] proposed an ontology-based annotation approach to support multiple evaluations of computer-aided designs, especially in later phases of the design process. The annotation data are contained within a consistent three-layered ontology framework that supports the integration of multiple specialist viewpoints by associating annotation content with anchors in a boundary representation model. The ontology also allows checking of data structures and other reasoning.

Several ontologies in the field of CAD have been developed, with interoperability and data interchange between CAD systems being the typical application scenario, rather than verification of qualitative properties of CAD assemblies. E.g., OntoSTEP [BKS12] enriches the semantics of CAD objects represented in the system-independent ISO-standard interchange format STEP. The heterogeneous approach in the present contribution allows integrating OntoSTEP (or any other ontology of features) into the federated engineering ontology and relating it to the ontology of features, without having to modify the verification methodology.

3 SEMANTIC SUPPORT OF A DOCUMENT-ORIENTED ENGINEERNG DESIGN WORKFLOW

Only in the mind of the design engineer the documents generated for the single development stage are initially related. These ties can be made explicit, so that computers can act on them, by annotating parts of these documents with concepts in ontologies. Such annotations (depicted with dashed arrows in Figure 1) can express simple facts e.g. that F_{hand} (from requirements list) is the hand force (from domain ontology) with which a user can interact with a product and constraints like $0N \leq F_{hand} \leq 200N$ for this force (see Section 5 for details). Depending on the complexity of the statement that needs to be made explicit, different logics can be used. This feature is enabled by federated ontologies (the cloud in Figure 1) – a method of combining heterogeneous ontologies by meaning-preserving interpretations [RK13].

3.1 Semantic Annotations in Design Documents

Semantic annotations are also used to relate objects from different design stages e.g. the gear nut from the CAD model in the complete overall layout stage can be annotated as a refinement of the gear nut object from the principle solution. Most software products do not, by default, support the user in creating/updating semantic annotations. However, product dependent extensions may enable users to create/update such annotations.

AktiveMedia [CCL06] is used for annotating images like the principle solution (see Figure 2). As other semantic authoring solutions for word processing documents that fit the needs of this research could not be found, sTEX was used – a semantic extension of the TEX/LATEX format. In order to annotate CAD documents, the ability of the CAD environment (Autodesk Inventor) was used to associate custom information to CAD objects and hence no specialized solution had to be used.

As annotations are assigned to parts of documents (e.g. some character range or assembly part), change management services can approximate how changes made to the document affect. the semantics of these annotations. This allows services to perform impact analysis and management of change.

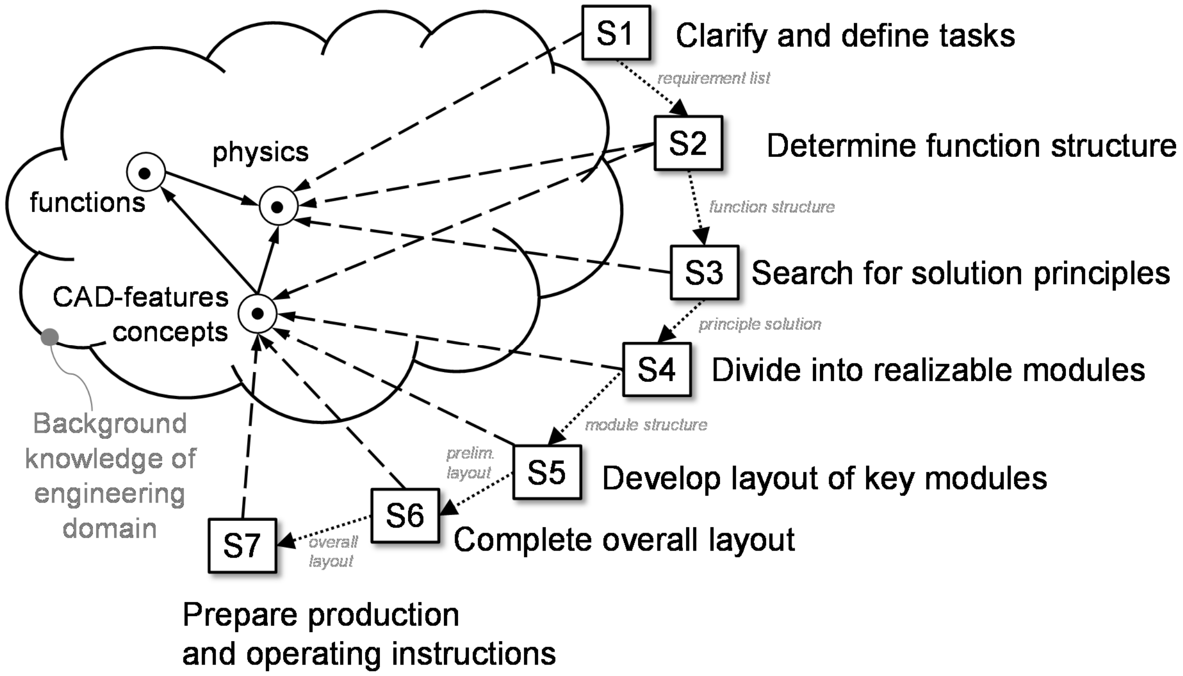


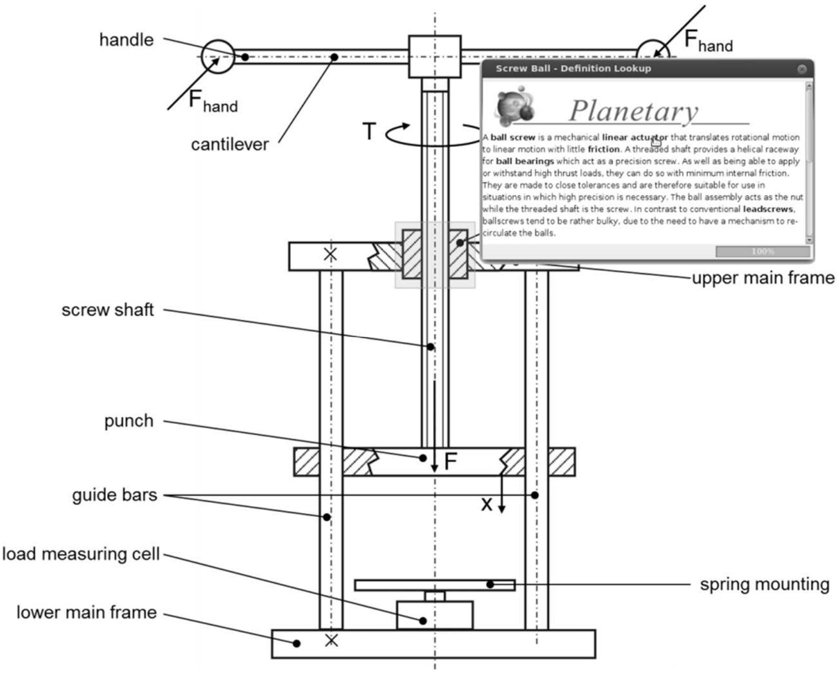
Figure 1: An ontology-supported document-oriented design process, in accordance to [Breitsprecher 2013]

3.2 Semantic Services via the MASally System

The Multi-Application Semantic Alliance Framework (MASally) is a semantic middleware that allows embedding semantic interactions into (semantically preloaded) documents. The aim of the system is to support the ever more complex work flows of knowledge workers with tasks that so far only other humans have been able to perform without forcing them to leave their accustomed tool chain. The MASally system is realized as:

- a set of semiformal knowledge management web services (comprised together with their knowledge sources under the heading Planetary on the right of Figure 3);
- a central interaction manager (Sally, the semantic ally) that coordinates the provisioning and choreographing of semantic services with the user actions in the various applications of her workflow;
- and per application involved (see CAD system and document viewer for S4/S5 in Figure 3)
    - a thin API handler Alex that invades the application and relates its internal data model to the abstract, application-independent, content-oriented document model in Sally;
    - an application-independent display manager Theo, which super-imposes interaction and notification windows from Sally over the application window, creating the impression the semantic services they contain come from the application itself.

This software and information architecture is engineered to share semantic technologies across as many applications as possible, minimizing the application-specific parts. The latter are encapsulated in the Alexes, which only have to relate user events to Sally, highlight fragments of semantic objects, handle the storage of semantic annotations in the documents, and export semantically relevant object properties to Sally. In particular, the Theos are completely system-independent. In the author's experience developing an Alex for an open-API application is a matter of less than a month for an experienced programmer; see [DJK+12] for details on the MASally architecture.



A **ball screw** is a mechanical **linear actuator** that translates rotational motion to linear motion with little **friction**. A threaded shaft provides a helical raceway for **ball bearings** which act as a precision screw. As well as being able to apply or withstand high thrust loads, they can do so with minimum internal friction. They are made to close tolerances and are therefore suitable for use in situations in which high precision is necessary. The ball assembly acts as the nut while the threaded shaft is the screw. In contrast to conventional **leadscrews**, ballscrews tend to be rather bulky, due to the need to have a mechanism to re-circulate the balls.

Figure 2: Principle Solution of a spring tester with definition Loockup

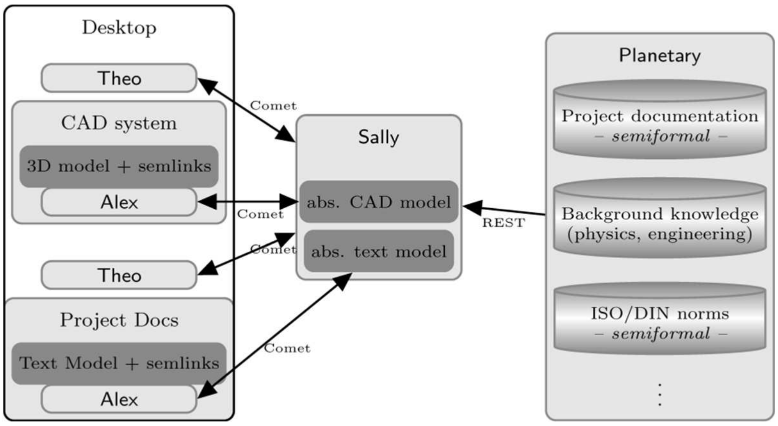


Figure 3: The MASally Architecture, in accordance to [BCJ+13]

To fortify the intuition about semantic services, the following situation is considered: The design engineer is working on the principle solution from Figure 2 – a sketch realized as a vector image, displayed in an (in this case browser-based) image viewer. The user clicked on a detail of the sketch and received a (Theo-provided) menu that:

1. identifies the object as "ScrBall4" (the image is extended with an image map, which allows linking the region "ScrBall4" with the concept of a "screw-ball" in the ontology); further information about the object can be obtained by clicking on this menu item;
2. gives access to the design refinement relation between the project documents: here, the object "ScrBall4" is construed as a design refinement of the requirement "ScrBall2" from the project requirements and has been further refined into object "ScrBall6" in the CAD assembly and the plans generated from that;
3. gives access to the project configuration that identifies the other documents in the current design;
4. allows direct interaction with the ontology (e.g. by definition lookup; see Figure 2, here triggered from the CAD system for variety);

5. gives shortcuts for navigation to the other screw balls in the current project.

Generally, the MASally system supports generic help system functionalities (definition lookup, exploration of the concept space, or semantic navigation: lookup of concrete CAD objects from explanations) and allows focus-preserving task switching (see [KKJ+13] for a discussion). All that is needed for this are annotations of the VDI2221 relations, ontology links and of course the ontology itself, which is discussed next.

4 THE FEDERATED ENGINEERING ONTOLOGY (FEO)

The design of the ontology that acts as the central representation of the background knowledge and the common ground of all actors in the design process is discussed. It serves as a synchronization point for semantic services, as a store for the properties of and relations between domain objects, and as a repository of help texts for the MASally system. The backbone of the federated ontology is provided by flexiformal documents consisting of concept definitions and statements of properties of the objects described using these objects. The statements are given in natural language and are interspersed with formulas. Furthermore, the federated ontology contains formal ontologies that enable verification of properties between different stages of design.

For further information on the design or content of the FEO, the reader can refer to [BCJ+13]. However, it is noted that a document is called flexiformal, if it contains material at different levels of formality [KKJ+13], ranging from fully informal – and thus foreign to machine support – text via text annotated with explicit semantic relations – i.e. open to semantic services – to fully formal – i.e. expressed in a logical system, which supports machine inference and thus verification of constraints – content. As the FEO has to cover quite disparate aspects of the respective engineering domain at different levels of formality, it is unrealistic to expect a homogeneous ontology in a single representation regime. Instead, the heterogeneous OMDoc/MMT framework [K06, RK13] that allows representing and interrelating ontology modules via meaning-preserving interpretations (i.e. theory morphisms) is utilized.

As an example of formal ontologies, as detailed in [BCJ+13], OWL ontologies are built for stating qualitative properties (e.g. abstract geometrical properties, but also function and behaviour or parts could be included) and for representing a CAD model as an assembly of parts built using features, according to its history of construction. A further OWL ontology of rules regarding geometrical properties of objects is built by repeated applications of features and thus enables verification of these properties for actual designs. The formal ontologies are related to the backbone flexiformal ontology by theory morphisms. A similar approach can be pursued to obtain tool support for checking that other steps of the design process are correct, e.g. that the principle solution fulfils the functions specified in the function structure.

5 CASE STUDY

This study is based on a simple spring tester which is used to measure the spring force of cylindrical compression spring for a given deflection. It was previously used in practical design assignments for engineering students. They were given the sketch of a principle solution (see Figure 2) for the spring tester (stage S3 of the design process in Figure 1) along with some requirement specifications and a function structure (stages S1 and S2), and were asked to design an embodiment, i.e. to complete stages S4 to S7 of the design process.

The requirement specification (S1) states the goal of creating a spring tester to determine the spring rate of cylindrical compression springs according to a specific norm. The device has to be hand-driven, where it is assumed that a normal person can act with a hand force of approximately 200 N per hand. During the measurement, the spring is to be compressed by 5mm. The resulting force is detected via a suitable load cell. In order to avoid distorting the force measurement, the spring tester must not exceed a critical elastic deformation of half of the load cell's accuracy class.

In this case study, documents from stages S1-S3 were annotated, which were produced by faculty members, and two sets of documents from stages S4-S7 produced by students – the intension is to study supporting design alternatives. As these documents come from an ongoing educational process, the annotation was necessarily post-mortem; experiments with integrating the described methods in a live development process are the subject of future research. In particular, a focus is put on the following services: i) definition lookup for document elements (see Figure 2), ii) topical navigation among documents in different development stages along the refinement relations (see Figure 4), and iii) propagation of change impacts by highlighting document elements in other documents that would need to be revised (see Figure 6).

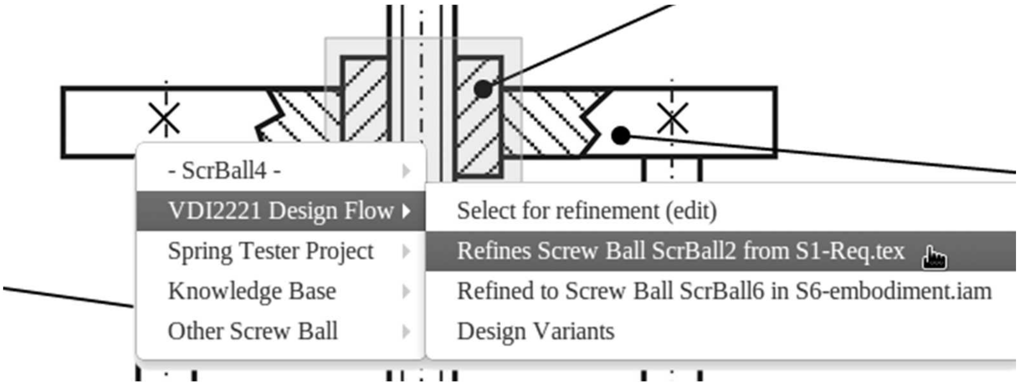


Figure 4: Navigating the Refinement Relation

Note that these services can only work if explicit semantic annotations in the documents exist. For instance, for definition lookup, documents with concepts in the ontology had to be annotated. For text documents, that meant using the sTEX macros that link text fragments with ontological concepts. From these a pdf/html document can be generated where a piece of text, e.g. “screw nut”, is annotated with a suitable ontology term such as screw-nut (internally represented as a URI). The use of sTEX serves to provide a proof-of-concept; current work focuses on the integration of semantic annotation functionalities into more widely used document preparation systems. It is also noted that many of these annotations could be semi-automatically detected using the NNexus [G13] framework in the future; the integration of this framework with the current approach is ongoing.

Annotating relations among different document was done using the MASally frames. The same document parts that were annotated for definition lookup were used and enriched with additional relations such as “X refines Y”, meaning that a document element Y (usually from a previous development stage) was refined at a later stage of development by document element X (see Figure 4).

For impact analysis, the documents were enriched with more domain specific annotations. Consider the requirement:

“Max hand force F_{hand} = 200 N” (*)

from S1. In the following design steps the user annotates all artifacts in S2-S7 that is influenced by this requirement with a refinement link to (*). For the function structure (S2; see Figure 5) these include the sub-functions “Induce Fhand” (**) or “Amplify F_{hand}” (***). In the principle solution S3 the handle of the spring tester (“Induce Fhand”) and the cantilever between the handle and the spindle (“Amplify Fhand”) are annotated as refinements for (**) and (***).

S4 concerns the modular structure of the design, it identifies the main design-affecting requirements and creates a first CAD-file which represents the main dimensions by limiting reference elements (points, lines, planes). The exemplary requirement influences, for example, the length of the cantilever, because the hand force has to be transformed into a torque (according to the law of the lever) to deflect a spring via the screw spindle. This (canti-)lever length can be represented within the CAD-file by a reference line.

Step S5 is quite extensive because preliminary designs have to be created and assessed. As shown in Table 1 these assessments include the dimensioning calculation of key modules. These calculations can either be done manually on paper or digitally via text/table files. In this case study created MathCAD® files were created and the formulas within were annotated. Here, Fhand was used to calculate dimensions of key modules. An example is the cantilever diameter, which must be sufficient to withstand the bending moment that is caused at the fixing point to the spindle.

At the end of stage S6, the CAD-model of the spring tester, consisting of parts, subassemblies and the main assembly, was finalized and annotated. Annotations were assigned both to parts and assemblies, depending on the purpose of the annotation. The part model cantilever.prt was annotated and linked with the requirement F_{hand} = 200N and thus the cantilever diameter in the CAD-model was linked with the initial requirement.

The utility of an impact management service is at hand: assume the spring tester is to be changed so that it can be used by people with a decreased hand force of F'_{hand}=150N (e.g. for a different market). The change impact service shown in Figure 6 highlights the handle of the spring tester – as it is (annotated to be) a refinement of the changed requirement in S1 – clicking it results in a popup that details the root changes and their influences. The “next/previous [conflict]” buttons are another instance of a semantic interaction (navigation to the next affected part in this document, later even across documents) which supports the change management work flow of the engineer.

Even in the final step S7 (product documentation) semantic annotations are helpful. For instance, a service that justifies the spindle pitch for the trapezoid spindle embedded in the manufacturing drawing helps avoid questions in the manufacturing process, since a change of the spindle pitch affects the torque that is to be provided via hand force.

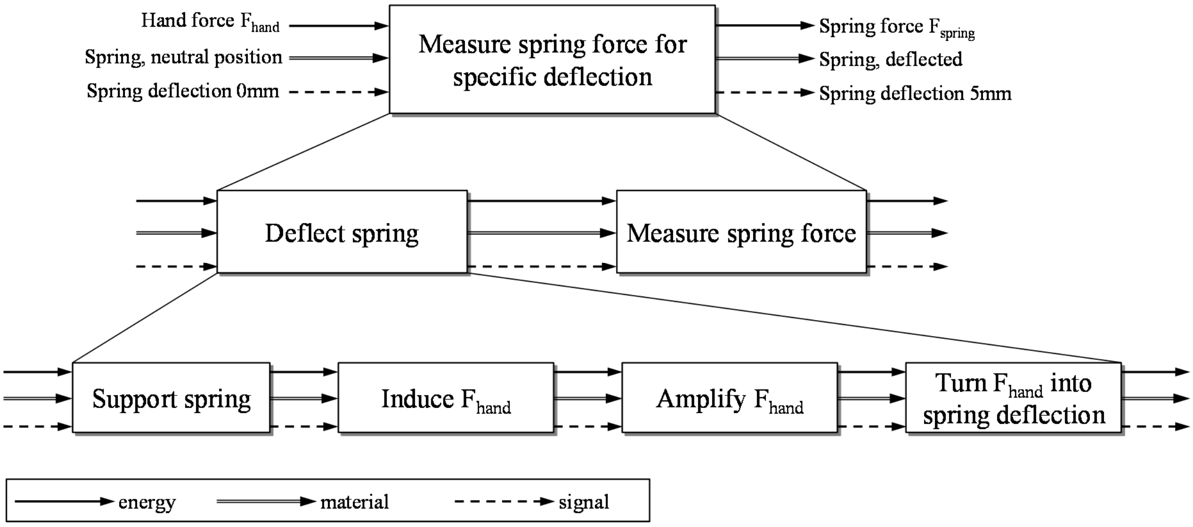


Figure 5: Function structure of the spring tester

6 SUMMARY AND OUTLOOK

While the final stages of the engineering design process have well-established information-technological support in the shape of modern CAD/CAE/CAM systems, tool support for earlier stages of the process (e.g. requirements, function structure, principle solution) is less well-developed, regarding the use of semantic services. Above, a framework for pervasive semantic support in engineering design processes is described, as part of a program to unify the underlying tool chain and enhance tool support in all stages of the design process. The framework is based on a flexiformal background ontology that combines informal and semiformal parts serving informational purposes with fully formalized qualitative engineering knowledge and support for the annotation of design documents (e.g. specifications, principle sketches, embodiments, documentation) with formal qualitative constraints. In the current work, a focus was put on a document-oriented work flow that relies on the background ontology for tracking the identity of parts through the design process and across different applications, which are accessed in a unified manner within the MASally framework. In complementary work it was shown how the approach can be augmented to enable automated requirements tracing and verification of the CAD model against aspects of the principle solution (see [BCJ+13] for details).

Source: S1-Req.tex

old requirement: max-hand-force(hand-force, 200N)

new requirement: max-hand-force(hand-force, 150N)

Figure 6: Impact propagation/resolution for changes to the hand force requirement

The approach was exemplified on the development process of a spring tester, illustrating MASally support for semantic navigation between the various design documents and for tracing and testing requirements. The flexiformal nature of the federated engineering ontology governing the annotation of the design documents makes the integration of formal and informal approaches feasible.

The federated engineering ontology is under continuous development. It will be further integrated with established domain ontologies including geometric ontologies (whose development is an active research field in its own right, see, e.g., the Shapes workshop series [KBB+13]), CAD feature ontologies (e.g. [BG05, AGS+07]), ontologies of function (e.g. [CMS07]), and repositories of standard parts, using modularity mechanisms enabled by modern logical frameworks such as Distributed Ontology, Modeling and Specification Language DOL [MKC+13, MLK13]. Moreover, its base of formalized engineering knowledge will be broadened; the associated knowledge acquisition process is an important aspect of further investigation. In future works the efficiency of the FEO will be proven, for example by different groups of engineering design master students, whereas a control group will be able to use the presented approach including the FEO. In proportion to the degree of formalization of the underlying engineering knowledge, the potential for automated verification of later stages in the design process against requirements formulated in earlier stages increases, as illustrated in [BCJ13].

One major impediment to employing the semantically enhanced work flow described here in industrial applications is the fact that currently the only annotation system for the documents is a variant of TEX/LATEX, which is not commonly used by engineers. The choice of sTEX for this purpose is based purely on availability, and currently the authors are working on Alexes for various word processors (primarily MS Word and OO Writer).

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