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An Ontology-Based Concept to Support Information Exchange for Virtual Reality Design Reviews

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Abstract. The current change of traditional products towards intelligent, connected cyber-physical systems (CPS) increases the amount of heterogenous data and models generated throughout the products' life cycle stages, starting from their development and reaching as far as reconfigurations in the product use phase. As CPS are highly modular and often customizable by the user, the management and decision support regarding product variants is critical. Mastering the vast complexity of these product-type and product-instance-related information has become one of the main challenges in modern engineering.

In previous works, the authors presented different mixed reality (MR) approaches as suitable tools to integrate product-related information and facilitate the interaction with digital contents such as product manufacturing information (PMI) and inspection characteristics for design reviews or real-time sensor values to support maintenance tasks.

This contribution proposes an ontology-based concept to facilitate the information exchange from distributed data sources for mixed reality usage and vice versa. The goal of this paper is to improve the information provision and interaction within a collaborative Virtual Reality-driven design review process for CPS. The ability of ontologies for querying and reasoning of linked information supports the comparison of design variants and feedback integration from design reviews of previous or existing product generations as well as allocating relevant design review metrics such as requirements, simulation results, costs or product use data. The capability of CPS to call upon services from other Industrie 4.0 components opens up a way to implement said ontology to meet today's engineering challenges.

Keywords: Ontology, Interoperability, Virtual Reality, Design Review, RAMI 4.0.

1 Introduction

Throughout a product's life cycle, several validation and assessment tasks are performed on the product and its related processes and artifacts. Design reviews are essential for the quality assessment and troubleshooting in product engineering in this context, especially those using collaborative software approaches. According to IEC 61160 [1], design reviews are performed at different stages of the development process, mostly

at project critical milestones to verify compliance with the previously defined requirements and aim to reveal potential deviations for correction at an early stage. The review usually involves an interdisciplinary team to address issues of all related departments in a collaborative process. Evaluated characteristics can be the product's overall impression, functionality, design and ergonomics, safety aspects, legal requirements, project timing, budgeting or production requirements and so on. In the end, a final status report documents the evaluation results along with possible countermeasures.

The radical change from traditional products towards "smart" products or more precisely cyber-physical systems (CPS) emphasizes the need for a unified data acquisition and traceability approach, which supports the fusion of real and virtual systems [2]. These cyber-physical systems have the ability to communicate and interact with their environment and other products by using Internet of Things (IoT) technologies and web-based services [3], [4], with the consequence of an increased amount and heterogeneity of product related information. This significantly complicates the information exchange and provision for later usage. Another relevant aspect in this context is the user interaction with the provided information. Virtual Reality (VR) is generally suitable to visualize digital contents (models or data) for multiple users at the same time and allows for intuitive interactions within a completely immersive virtual environment. Therefore, VR contributes to information transparency and facilitates collaborative interactions with this information. A core challenge in review processes, not only for VR utilization, is the provision or availability of relevant information. Regarding VR-supported design reviews, information on the characteristics to be evaluated must be available. However, this information is usually created in different engineering authoring systems and therefore often lies distributed in different models, documents or databases, which is further amplified in the case of CPS.

The persistent storage of performed user interactions within the immersive VR environment is another typical weak point of VR applications that needs to be addressed in the context of design reviews. As mandated by [1], observed errors during a design review and their countermeasures must be documented according to legal responsibility. Moreover, the general traceability of results and performed actions is compulsory when companies are certified following DIN ISO 9001 [5].

As a result, the goal of this paper is to propose a concept that accommodates the aspects of information and knowledge exchange, context-specific provisioning for VR usage from heterogeneous data sources with a specific focus on characteristics of CPS (i.e. use data from products in the field), a CPS-compliant data model and an overarching ontology to connect the entities in this context semantically. Based on this concept, user interactions in a VR-based design review can be recorded and their entities linked to allow a persistent record and therefore a consistent process documentation and traceability of actions, results or decisions made during the design review.

2 Related Work

2.1 CPS in the Reference Architecture Model Industrie 4.0

Initiatives such as Reference Architecture Model Industrie 4.0 (RAMI 4.0) [6] of the National Platform Industrie 4.0, the Industrial Internet Reference Architecture (IIRA) of the Industrial Internet Consortium (IIC), among other things, are intended to solve the problems of model fragmentation and their lack of semantic descriptions in engineering [7]. Since 2016, these initiatives have been cooperating with each other, resulting in a functional mapping that ensures compatibility between the approaches and their implementations [8]. A prerequisite for the desired degree of interoperability in the context of VR design reviews using Industrie 4.0 methods is the introduction of a uniform digital representation for each product involved in the value creation process. The model of the asset administration shell (AAS) from RAMI 4.0 [6] can be used to achieve this functionality. Each so-called asset is subject to a life cycle in RAMI 4.0 according to the usual understanding but differentiated by the life cycles of the product type and the individual product instances. An asset is a tangible or intangible object with value for the organization, regardless of whether it is a tangible product, a software component or a service. The information about an asset is stored digitally in the associated asset administration shell and made available for human-machine and machine-machine communication, so that a so-called Industrie 4.0 (I4.0) component is created as a combination between an asset and its administration shell (cf. Fig. 1). The AAS comprises a “Header” with identifying details about the asset and its associated AAS as well as a “Body” with a large number of sub-models, representing different aspects of the asset. Depending on the kind of asset, these aspects could describe manufacturing capabilities (e.g. drilling, assembling), the lifecycle status, condition states or similar type- or instance-based information. As part of the particular sub-model, proprietary data models (CAD data, source code etc.) are managed by a component manager, which can also provide interfaces to other I4.0 components [9]. In this way, information can be interlinked between assets via the sub-models of their related AAS.

The combination of I4.0 components creates new I4.0 components, i.e. a new asset with its own administration shell. This results in a recursive asset description that is able to map any granularity level [9], from simple semi-finished products and individual parts to modules and components to complete systems and end products themselves, and to link them together by stored references. Recently, the National Platform Industrie 4.0 released a comprehensive guide on how to implement the asset administration shell in detail and with schema examples regarding (industrial) standards like XML, JSON, RDF, OPC-UA and AutomationML [10].

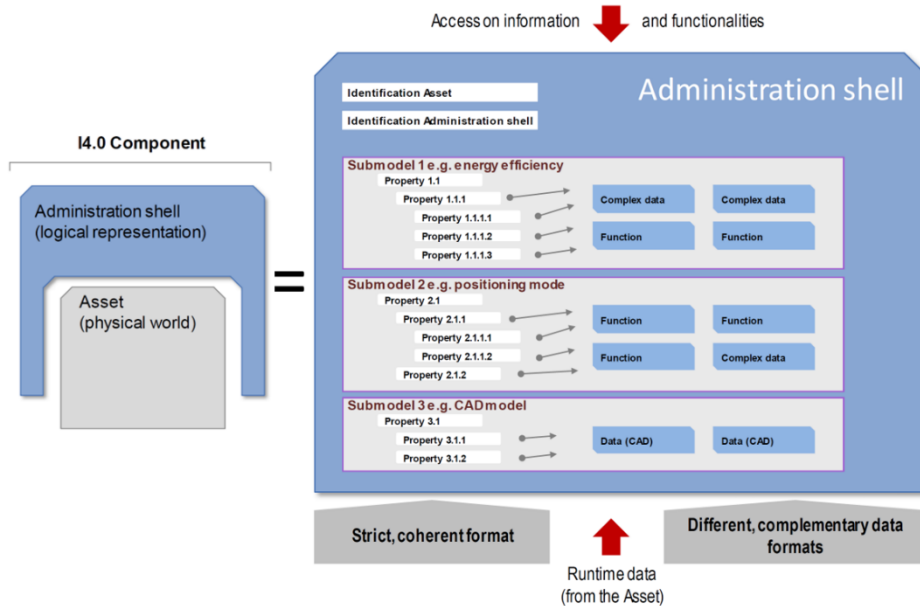


Fig. 1. Basic structure of the asset administration shell and I4.0 component - based on [10]

2.2 Knowledge Representation and Sharing

Several methods can be found in academic literature to represent and structure domain- or organization-specific knowledge. For example, Taxonomies are used to classify and categorize terms, whereas Thesauri additionally describe their relationship through synonyms, hypernyms or hyponyms [11]. Semantic networks map concepts, terms and their relations into a graph that consists of vertices (concepts and terms) and edges (relationships) that link vertices to each other [12]. Another common concept to represent knowledge are ontologies, which rest upon semantic networks, but are much stricter and more formal due to their axiomatic structure. Originally coined by Gruber [13], Studer et al. [14] define ontologies as “a formal, explicit specification of a shared conceptualisation”. Therefore, ontologies are capable of modelling knowledge domains with complex, linked information structures as well as sharing and integrating heterogeneous information originating from other domains. Due to axiomatic rules, ontologies allow for inferencing, i.e. new facts can be derived based on existing knowledge. In this context, the resource description framework (RDF) facilitates standardized data interchange through a textual formalization of resources and their properties expressed by statements in a triple structure (subject, predicate or property, object) [15].

Using ontologies or RDF stores for CPS data is encouraged by the fact that the asset administration shell schemata are now available in [10] and [16], so that a “common language” can be used between sub-models of different categories.

2.3 Virtual Reality Design Reviews

The motivation of the approaches described in the previous sections is to bridge the gap between physical and digital world by either bringing “intelligence” into products or linking information to products. Since VR is a suitable technology to visualize and interact with geometric 3D models in a virtual environment [17], it can contribute to this endeavor.

Virtual Reality not only supports immersion in design reviews but also for other engineering tasks it may lead to cost savings and improved and/or accelerated related processes. As concluded by Coburn et al. [18], due to low costs and the high quality of modern VR devices, VR could become ubiquitous for several engineering processes and support everyday engineering tasks. In this context, many examples can be found in academic literature with the aim to support various engineering applications by incorporating VR. Referring to design reviews, Lawson et al. [19] summarize that VR facilitates design verifications and the review process especially for physical prototypes and mock-ups can be replaced by its virtual counterpart, which in turn could lead to cost reductions for manufacturers.

Other contributions focus on improving user interactions within VR environments, such as Martini et al. [20], who developed a hardware and software-based user interface to simplify interactions in VR review processes. Freeman et al. [21] investigate tools and methods for CAD-software-like interaction and manipulation functionalities for 3D models in VR. The fact that interaction in VR environments is generally simple and intuitive is confirmed by Wolfartsberger [22]. Their study on VR-supported design reviews indicates that the participants are more likely to detect errors in a 3D model within an immersive VR scene compared to a traditional CAD software approach on a PC screen. Additionally, performing the design review and interacting with the 3D models is described to be more intuitive and “natural” for non-CAD experts due to the high degree of immersion using VR head mounted displays (HMD).

In our previous works, we presented different mixed reality (MR) approaches as suitable tools to integrate product-related information and facilitate the interaction with digital contents such as product manufacturing information (PMI) and inspection characteristics for design reviews [23] or real-time sensor values to support maintenance tasks [24]. Our most recent contribution [25] proposes a concept for a VR-supported design review process for CPS, taking their characteristics (e.g. use data of previous product instances) into account. This concept was prototypically implemented utilizing modern VR devices, with a clear focus on the collaborative review process, the visualization in VR and the intuitive user interaction.

In contrast to the approaches presented above, the paper at hand focusses on the aspects of information exchange and context-specific provisioning for VR-based design reviews in the light of CPS.

3 Approach

The main goal of this paper is to contribute to interoperability in the context of collaborative VR-based design reviews using the AAS of the relevant (virtual) components.

Another focus is the persistent storage of the user operations within the immersive VR environment in order to comply with documentation and traceability requirements demanded by IEC 61160 [1] or ISO 9001 [5]. To accommodate this, this section presents a conceptual framework based on Industrie 4.0 methods, starting with potential use cases addressed by the concept.

3.1 Considered Design Review Use Cases

Design reviews serve as an instrument for quality inspection and assessment at different stages of a product's life cycle. The main intention is to evaluate product or process related characteristics, usually in a collaborative manner to address issues from all related stakeholders. In a generic design review process according to [1] the operative tasks are accompanied by several administrative processes such as planning, preparation, execution and follow-up. Depending on the pursued objectives of the design review various kinds of information are a prerequisite for discussion and decision making.

Based on the authors previous works [25], the considered use cases in this paper address VR-supported design reviews with a particular focus on cyber-physical systems, also known as smart products. As described above, CPS are characterized by the ability to communicate and interact with their environment and other products. Compared to traditional products, CPS therefore offer additional feedback information and services provided by the product instances and their "smart" components, as well as field reports from physical parts from a previous generation. This enhances evaluation possibilities for the product type under review especially for the development of an advanced product generation or when adapting existing designs.

In this context, the application of mobile VR technology with head mounted displays offers additional benefit. Firstly, it promotes the intuitive user interaction with the displayed information (textual or graphical) in virtual environments even across multiple sites and secondly, it allows for context-sensitive visualizations. As design reviews normally involve an interdisciplinary team, whose participants possess an individual role and function, specific content can and should be visualized for each individual user, for example mechanical simulations or cost overviews. The integrated visualization of relevant information can be used to simultaneously compare two design variants or to access real-time data from the product instances of a previous generation currently in the field.

Furthermore, individual user permissions can be derived, which restrict or allow user interactions during the design review. The same applies to a potential integration of external partners (customer or supplier), for example to clarify requirements or to take their feedback into account during agile review sessions. These participants should have only limited access for editing or viewing functionalities during the review process.

According to the standards ISO 9001 [5] and specifically IEC 61160 [1] regarding design reviews the documentation of organizational process is essential to maintain knowledge, make decisions reasonable and by this errors traceable. Therefore, the considered use cases also have to cover recording of user operation in VR, like adding a text note or highlighting individual parts.

3.2 Concept for Information Exchange in VR-Based Design Reviews

As detailed in the state-of-the-art section, initiatives like RAMI 4.0 or IIRA specify organizational frameworks and guidelines for these kinds of products or systems and introduce a uniform digital representation which contributes to interoperability. Therefore, this concept generally employs the model of the asset administration shell (AAS) from RAMI 4.0 [6]. According to their definition, an asset represents tangible or intangible objects and the respective information is stored digitally in the associated AAS. Transferred to this context, the main entities which have a specific AAS are the design review participants (user), the product to be reviewed (CPS 123) and the collaborative design review environment (VR-DR) as illustrated in Fig. 2.

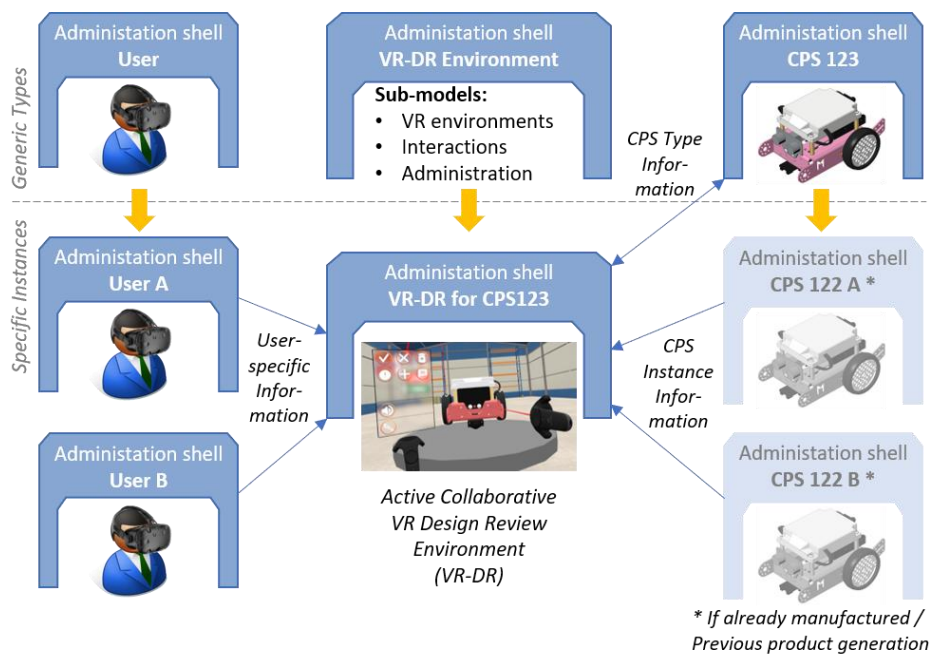


Fig. 2. Concept for information exchange in VR design reviews

Each asset is associated with its corresponding AAS, which describes the asset in the information world. According to [9], the AAS is composed of different sub-models, which represent different aspects of the asset (cf. Fig. 1). Here, the VR design review AAS (Fig. 2, top center) comprises specific sub-models to represent the general composition of the VR environment, available interactions with entities in VR as well as administrative capabilities to support the review process. In this regard, the differentiation between types and their instances must be noted. The type of an AAS (Fig. 2, top) serves as a structured template to derive an AAS instance with specific characteristics. For example, the AAS instances connected to the specific users "A" and "B" are created based on the generic user AAS type and holds individual information, such as identification, permissions and functions (see Fig. 2, left).

As described in our previous works [25], the immersive VR design review allows for user interaction, such as manipulating objects and giving feedback via text input, voice recordings, graphical highlights or interactive polls. During review execution, the information about an individual user (stored in its associated AAS) serves as an input for the AAS of the active VR-DR session (Fig. 2, center). This allows to identify a user and provide specific information and permitted interactions. At the same time, performed interactions during the review session can be stored together with the authoring information. This data is maintained in the respective sub-model of the VR-DR AAS and later referenced by the AAS of the reviewed product or system.

The various sub-models in the AAS of the reviewed product deliver additional input, that may benefit the review process. On the one hand, generic information related to the product type (e.g. 3D model, requirements associated with geometric features) have to be considered. In the case of developing advanced product generations or when adapting existing product designs, information of individual product instances in the field (operating or measurement data, maintenance data, fault reports etc.) can be additionally used during the design review, for example to discuss potential effects of operation conditions and agree on design alternatives.

3.3 Identification of Relevant Concepts and Terms

A prerequisite to build a comprehensive data model is the identification of key concepts and terms referring to the domain of interest. In this case, relevant terms of design reviews and collaborative VR environments in general have to be identified as well as specific terms derived from the considered use cases described above. In a first step, a taxonomy has been designed according to the subject areas. One goal of this paper is to establish a semantic connection of the entities representing VR-based design reviews for CPS. To achieve this, general categories for context-aware information supply were used to identify and allocate related terms. Shen et al. [26] propose a classification of context concerning location, time, identity (user role), task or activity, used devices, available interaction capabilities, the distribution (of data), the type of data and according to privacy and security settings. Based on this, three main categories are suitable to classify relevant concepts and terms in the context of this paper: user-specific, administrative and technical aspects.

The first category “user-specific aspects” summarizes terms which are related to the participants of VR-based design reviews and the considered use cases (cf. Fig. 3). At first, a distinction can be made between the different roles of a user, since participants may have different permissions in the review session, such as the moderator and guests. The same applies to the function of a user, which is linked to the respective department or if external participants (e.g. customer or supplier) are involved, too. The user’s location delivers knowledge about the current time, which is an important aspect for distributed collaboration across multiple sites. Different permissions (e.g. create, read, update and delete) limit the user’s access to objects or information within the VR environment. On top of that, a user’s attendance, a name or identification may be attributed as well.

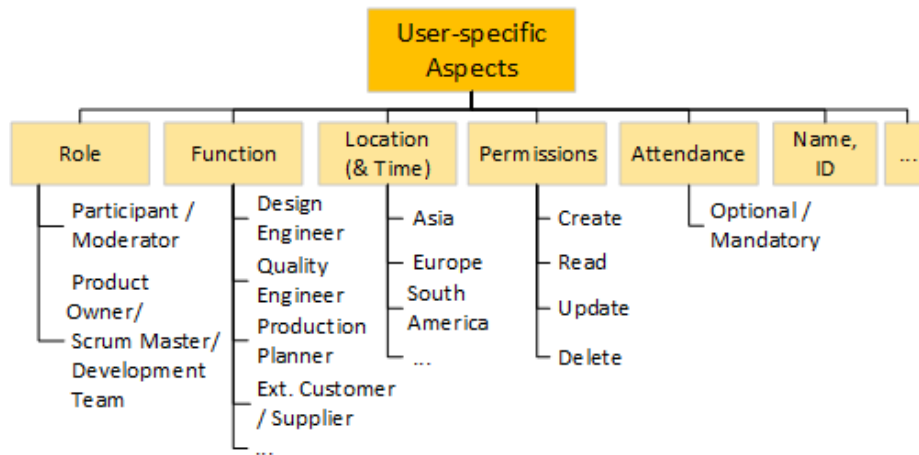


Fig. 3. Terms of user-specific aspects with exemplary characteristics

The second category “administrative aspects” addresses terms, which are connected to administrative characteristics of the design review. Among these, the collaboration type describes how the design review is performed. As mentioned in the use case description, the utilization of VR allows both, co-located and distributed collaboration as well as collaborating at the same time or asynchronously. The workflow progress captures the current stage of the design review, whereas the objectives have to be available as well.

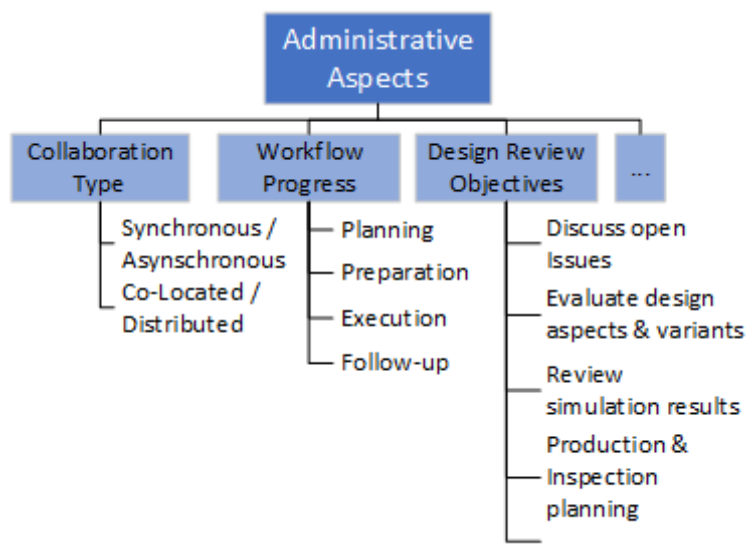


Fig. 4. Terms of administrative aspects with exemplary characteristics

The third category “technical aspects” contains essential information for conducting VR-based design reviews (cf. Fig. 5). They refer to the product, like its life cycle stage, related technical documents or engineering data as well as data from the product’s use phase (field data). Apart from this, a large portion of relevant information is delivered by the VR environment itself. As already mentioned, a common weakness of existing VR approaches is the lacking persistence of actions performed in VR. Based on the authors previous works [25], the subcategories shown in Fig. 5 can be identified. The avatar related to a specific user is mainly described by its position in the virtual environment or room. This room in turn may have variable dimensions depending on the number of users in the review session, the scale of the reviewed part or even the amount of shared information during the review.

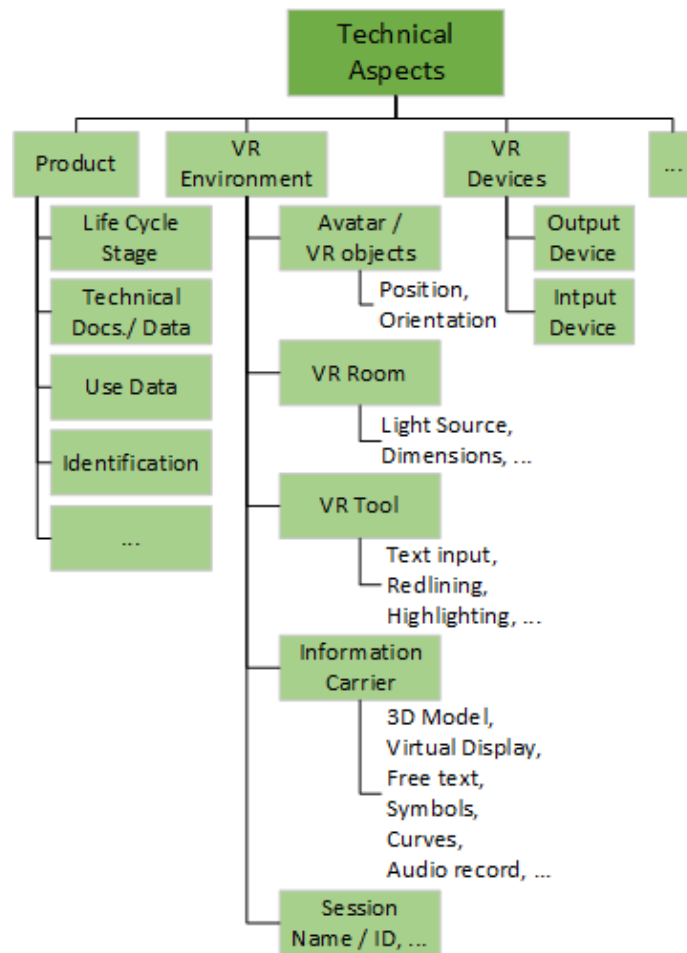


Fig. 5. Terms of technical aspects with exemplary characteristics

Further subcategories contain the used tools in review, such as text input, highlighting or redlining, as well as the objects for carrying the essential review information, e.g. the 3D model to be evaluated, virtual displays or free text for non-geometric information (including charts and figures), as well as symbols, curves or audio records for capturing annotations.

3.4 Semantic Data Model for VR-Based Design Reviews

The proposed concept (cf. Fig. 2) aims at facilitating knowledge exchange and context-sensitive provisioning for VR usage from heterogeneous data sources with a specific focus on CPS characteristic. In order to guarantee a “common language”, this concept generally employs the model of the asset administration shell (AAS) from RAMI 4.0 [6]. Recent activities related to the AAS introduced RDF- or ontology-based concepts to promote semantic interoperability of Industrie 4.0 components. In order to comply with this, the proposed concept also rests upon ontologies for knowledge representation and sharing in VR design reviews (VR-DR). Due to the general nature of ontologies being modular and reusable by other ontologies [14], an integration with the aforementioned ontologies is given.

Therefore, this ontology-based data model forms the basis to manage and exchange information between various data sources (engineering authoring systems, the products’ operation data), the VR-based design review application and the participants of the review. This uniform data model serves as a reference for the integration of heterogeneous information from and into the different systems.

In order to establish this data model, the identified concepts and terms in the presented taxonomies lay the foundation for modeling the VR-DR ontology by transferring concepts into classes or subclasses and related data properties. The main entities in the context of VR-based design reviews are the reviewed product, the VR-DR session itself and all participating users. These three entities build the top level class structure of the VR-DR ontology shown in Fig. 6. For reasons of clarity and comprehensibility, Fig. 6 illustrates only an excerpt of the complete ontology with exemplary classes and relationships.

According to the definition of RAMI 4.0 [6], the generic types of the three entities “product”, “VR-DR” and “user” are associated with an AAS, which is inherited for the specific instances. As described in section 2.1, the exchange of information between assets is performed via sub-models of their respective AAS (cf. Fig. 1). For example, the reviewed product is represented by a 3D CAD model, which can be part of a “Mechanical CAD” sub-model in the product’s AAS. On the other side, the VR-DR is also associated with an AAS, where one of the sub-models represents the aspects of the VR environment. One entity within the VR environment is the product’s “VR model”, which corresponds to the product’s tessellated 3D CAD model, i.e. after conversion of the native model (cf. Fig. 6). This implies, that two different models are considered in each AAS, but a semantic mapping between them is established. The same applies to a VR avatar, which represents a user in the VR-DR session and a real person in the physical world. In this way, the entities of the respective sub-models can be connected

according to their relation properties, for example a “USER” “creates” a “TEXTNOTE” (see Fig. 6).

Based on this approach, the VR-DR ontology enables a common understanding for the mapping of different components or sub-models, when referring to the definition in RAMI 4.0 [6]. Finally, the ontology was implemented using the software Protégé.

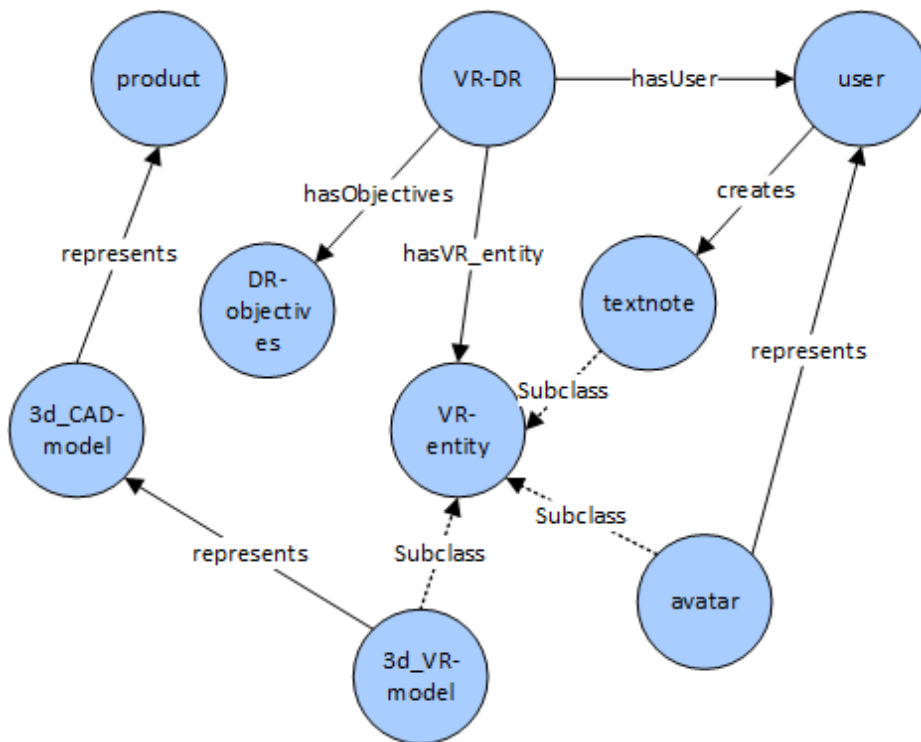


Fig. 6. Excerpt of the ontology implemented in Protégé

4 Conclusion and Outlook

Today, VR is a common tool for several industrial tasks, which focus on immersive visualization and user interaction. Nevertheless, the necessary information is often integrated statically and isolated. The knowledge that is created during a VR session is also rarely available afterwards.

The current shift towards increasingly connected CPS in the era of Industrie 4.0 leads to ever larger amounts of information. RAMI and its AAS delivers a framework for a uniform digital representation of so-called assets, which contributes to interoperability between the assets. The presented concept employs the AAS model to support information exchange and persistence especially in the light of VR-based design reviews for CPS. As a first step, the knowledge formalization is achieved with the help of an

ontology. Since ontologies are suitable for sharing knowledge about a specific area with other ontologies, the specific knowledge is not only limited to this concept, but can be reused at other stages of the product life cycle or for different applications as well.

Currently, the authors work on implementing a complete asset administration shell-based demonstrator of a smart factory training model from a German industrial education supplier. This demonstrator includes the holistic AAS representation of all the production system's components, organizing the communication between those components via OPC-UA through services in the AAS, tracking and tracing of the products via their administration shells and finally connecting both virtual and augmented reality frontends to monitor current and aggregated data directly on either the physical or virtual representation of production system or product. To facilitate the exchange of information between a variety of engineering authoring systems, the production system (representing a CPS) and the virtual or augmented reality applications, the ontology will be transferred into a graph database that supports reasoning of RDF stores.

This demonstrator case will then be used as a cyber-physical use case for the VR-based design review, giving us access to real operational data of the produced products and production system itself and yielding the opportunity to embed the VR design review data into existing asset administration shells.

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