

A Collaborative Virtual Workspace for Factory Configuration and Evaluation

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Abstract—The convergence of information technologies (IT) has enabled the Digital Enterprise in which engineering, production planning, manufacturing and sales processes are supported by IT-based collaboration, simulation and enactment. As a result, borders between reality and its virtual representations become increasingly blurred. Advanced tools need to support flexibility, specialization and collaborative evolution of the design where the exchange of knowledge between domain experts helps to improve informed decision making. In this paper, we present a collaborative, web-based framework to create 3D scenarios for product design, simulation and training assisted by animated avatars.

I. INTRODUCTION

In recent years the trend towards networked organizations where businesses and companies are working (often remotely) together has been intensified [1]. Activities in networked organizations consist of distributed processes which include communication, exchange of resources and joint production of business artefacts. These artefacts now include assets such as product designs which in the past were kept under control of one company. The co-innovation and co-design of product families and production plants with a large number of part suppliers requires precise adjustment between contributing partners.

Supporting this precise adjustment of products and production facilities requires IT Systems for integrated product development. Engineering these integrated and interactive systems where interaction involves cooperation and collaboration of a potentially large number of contributors with complementary skills e.g. in product assembly design. This is an inherently collaborative process where multidisciplinary experts from different areas and geographically remote locations contribute to one product or resource.

Regarding collaborative engineering, Booch and Brown [2] highlighted the importance of a Collaborative Development Environment defined as: 'a virtual space wherein all the stakeholders of a project - even if distributed by time or distance - may negotiate, brainstorm, discuss, share knowledge, and generally labor together to carry out some task, most often to create an executable deliverable and its supporting

artifacts' (see especially [3]). Empirical investigations confirm this importance [4], [5].

Another recent trend is the usage of virtual techniques for product and production facility development which allows designing 3D representations that capture selected traits of products and production plants. 3D prototypes can be used to evaluate products in advance e.g. in order to reduce costs and time to market. Together with this trend towards virtual prototyping based on 3D design and engineering, a combined research area arises: collaborative virtual prototyping.

As cooperation, coordination and collaboration are often used interchangeably, a more fine-grained distinction between these concepts is required. There are two major lines of research which differ in the details of defining the relation of these concepts (contrasting vs. encompassing). One (older) approach stemming from organisation science defines the relation as continuum where cooperation falls on the low end and collaboration on the high, with cooperation in-between [6], [7]. Cooperation is defined as the least formal interaction, based e.g. on a simple verbal agreement. In cooperative work, the division of labour leads to processes where each person is responsible for a portion of a problem solving [8]. Cooperation becomes coordinated when the informal problem solving process is following an explicit or implicit joint planning where responsibilities and roles are assigned. Collaboration in a contrasting and narrow sense is the most formal interorganizational relationship involving shared authority and responsibility for planning, implementation, and evaluation of a joint effort and involves the "mutual engagement of participants in a coordinated effort to solve the problem together" [8].

In contrast, the other main approach on which we base our work defines collaboration as the encompassing process with cooperation, coordination and communication as its ingredients. Ellis et al. describe collaborative work as an iterative process of *communication*, *coordination* and *cooperation* (3C model [9], see Fig. 1). Based on this model, Fuks et al. describe collaborative work as an iterative, cyclic process [10]: Communication describes spontaneous exchange of information between team members, like for example in the planning

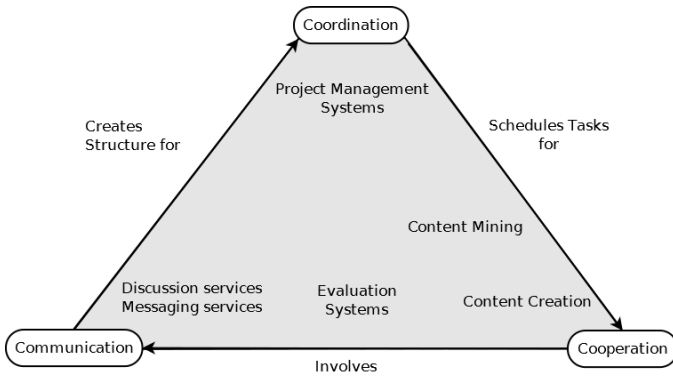


Fig. 1. Iteration cycle of collaborative work based on the 3C model as stated by Fuks et al. [10] and required services for each step as stated by [11]

phase of a project. Based on the communication, future work is coordinated in tasks which are then cooperatively accomplished. During the cooperation step new issues will arise. Those need to be discussed and therefore lead to a new iteration cycle until the project work is finished.

In general, design tasks are often *ill-structured problems* [12]. In contrast to well-structured problems, where options and goals are clearly defined, in ill-structured problems the options available and possibly even the goals are unclear and vague. For many ill-structured problems, generic routines and procedures for problem solving do not exist. Although considerable amount of research has been devoted to identify recurrent collaboration patterns (e.g. [13]), for ill-structured problems, a normative approach prescribing sequences of steps to solve the problem is not feasible. A collaborative engineering system for design tasks should be open to support different problem-solving activities and strategies.

Nevertheless, a common feature of design tasks is that they involve an iterative process of interactive decision making and model building [12], thus confirming the adequacy of the 3C model. To support this iterative process, a "wide range of sophisticated communication and content services" [11] are necessary. Examples include "customized **discussion services, workflow and knowledge management systems, and content creation, mining, and retrieval services.** [...] To create useful collaborative virtual working environments for communities, collaboration requirements need to be linked to services satisfying those requirements" [11].

Collaboration in 3D design and virtual environments has additional and specific requirements. Traditional collaboration systems already provide the possibility to jointly work on designing artefacts. In 3D environments, the central artefact is a *visible virtual model* of reality. As *visible* 3D artefact, the model is intended to be (possibly jointly) looked at. As *virtual* (in contrast to a physical mock-up) *model*, it is an archetype which represents selected and supposedly relevant features of the real resource(s) to be produced. In virtual prototyping of products and factories, these features include functional interdependencies and other aspects such as ergonomics which can be simulated or even aesthetic qualities. As in using physical

mock-ups, these functional and non-functional features and aspects in virtual models can be evaluated before the resource is actually produced. The joint and simultaneous evaluation of these visible virtual models is a possibility which needs to be supported in a much more refined way, especially when the visual experience should be shared in realtime.

Whereas many 3D systems present the final view of a product, a collaborative virtual prototyping system allows jointly creating, viewing, reviewing, modifying 3D artefacts and discussing alternative designs at all stages of the design process. The possibility to make changes in realtime as well as support for content creation and distributed storage retrieval are further requirements. In contrast to many commercial systems which often are monolithic and oversized, the system should be easily extendable and quickly adaptable to different use cases and scenarios.

II. OBJECTIVES

We developed *Collaborate3D*, a web-based collaborative development environment for virtual prototyping that supports and realizes the three iteration steps based on the 3C model by Ellis [9]. *Collaborate3D* provides collaborative workspaces with native support for communication, cooperation and coordination and enables a shared visual experience of the creation, modification and evaluation of a virtual 3D design.

Since in different contexts and scenarios, a variety of components and modules are needed, the system is intended to be extendable and customizable. Instead of a one size fits all approach (which is prevalent especially in the commercial tools), we developed a service-oriented platform which supports customizing and adding services as plugins when required. The result is a modularized and configurable collaboration architecture for 3D scene editing, evaluation and simulation.

Taking into account that design is an ill-structured problem, a specific configuration of system modules and services is open for different problem-solving strategies. The system is designed to be adaptable to a changing collaboration and task model and to support the whole continuum of cooperation and collaboration.

Apart from these general objectives, for implementing an effective collaborative workspace for virtual 3D prototyping, further goals include in detail:

- Ubiquitous accessibility via Web Page like implementation (central point of access)
- Simple inclusion of new 3D content and fast attachment of new code
- Attach established (open) project management including issue tracker tools for asynchronous collaboration.

The application scenario is based on a factory production line where collaborators design and evaluate a factory module. Evaluation in this case consists of checking functional features such as production capacities, velocities and safety properties. Additionally, activities of workers can be modelled and their performance simulated and evaluated according to different criteria.

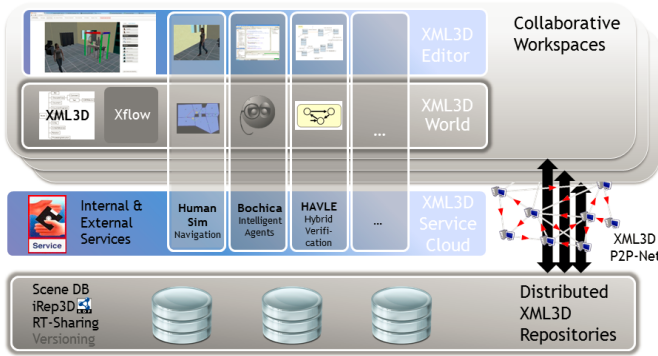


Fig. 2. Collaborate 3D architecture

The structure of the paper is as following. In section III we give an overview of the architecture of the web-based system for collaborative prototyping and the basic technologies used. In sections III-A - III-D, the XML3D-based layer for visualisation and content creation, the distributed search technologies for content retrieval, as well as verification and agent technologies for evaluation are presented. In section IV, we describe technical details of the implementation of the workspace components. Related work is discussed in section V. We conclude in section VI.

III. 3D COLLABORATION FRAMEWORK: ARCHITECTURE

Collaborative virtual prototyping calls for a fusion of several technologies in order to provide a shared visual experience of the design artefacts. Web and Web service technology is the up-to-date solution to enable distributed access and real-time sharing of contents and resources.

The Collaborate3D architecture (see Fig. 2) reflects the idea of introducing service orientation into the virtual environment. Platform components needed for the realisation of the virtual environment are encapsulated as services hosted in the Collaborate3D service cloud. The architecture consists of three layers: a project related collaborative workspaces with a 3D editor for creating and modifying content, a service cloud with application specific services and a storage layer. The 3D editor is based on an web-based framework for rendering 3D graphics. In the current implementation the service cloud consists of a verification component for evaluation of functional properties and an agent platform for evaluating dependencies when e.g. human workers are interacting with devices in production plants. Other components could be a physics engine, kinematics, etc. A distributed repository for content storage and retrieval provides access to semantically annotated 3D models which can be inserted into a scene.

A. XML3D World

The collaboratively created 3D artefacts are contained in the data layer which is based on the XML3D specification. XML3D is an open declarative XML format that extends the set of HTML web page elements by additional nodes to represent 3D graphics in a scene graph like structure [14]. All

nodes within this graph are also nodes in the web sites DOM tree representation (*Document Object Model*, [15]) and can be accessed and changed via JavaScript like any other common DOM elements as well. On these DOM nodes, HTML events can be registered similar to known HTML elements. Resources for mesh data can be stored externally in either JSON or XML format and referenced by their URL. The renderer that is used by XML3D is based on WebGL.

In addition to XML3D, *Xflow* allows to combine the scene graph with dataflows [16]. *Xflow* is a declarative data flow representation that was designed for complex computations on XML3D elements. These computations include for example skinned meshes and key frame animations. In these cases, the current key frame takes the role of a data source in the graph, whereas mesh transformations are sinks in the dataflow. By this, changing the value of a key frame leads to a change in the posture of a mesh, and thus a continuous change of the key frame over time results in an animated mesh.

By using XML3D with *Xflow* as foundation for data layer, we achieve both ubiquitous accessibility and high customizability: all scripts needed to display and use the 3D editor are automatically loaded by the browser as soon as the user opens the page in any web browser that supports WebGL. Furthermore, 3D models used for the scenario can be referenced by their URL from remote storage locations.

For evaluation services to be able to operate directly on the artefacts created in the editor, they must be able to access the data layer that contains the 3D artefacts. This access is directly provided by having both *Xflow* parameters and the 3D scene graph represented as part of the DOM tree by XML3D. External services can e.g. animate virtual characters by changing key frame values of *Xflow* graphs (in the case of the agent platform service), to generate the navigation mesh (using the geometry information contained in the DOM tree) or verifying the functional correctness of a module and display the trace witness via *Xflow* animation. The guiding principle for services such as the verification is that the functional specification of a composite module is based on the functional specifications of the parts contained which build up the composite module. The formal specifications of the parts are contained in the scene graph as annotations of objects.

B. XML3D Editor

The 3D artefact itself is created in the interactive 3D editor which is a web-based tool for creating and editing 3D scenarios. Those scenarios consist of a static base geometry (e.g. an empty factory hall) and several sets of 3D *assets*. Assets can be added, moved within or removed from the scene with simple drag and drop operations. Figure 6 shows the user interface of the editor: The interactive 3D scene is displayed on the left-hand side. Next to it is the sidebar which contains the selection of 3D assets that can be added, as well as already placed assets in a second tab.

Scenarios that share a common static geometry and the same set of assets are grouped in *projects*. In terms of the factory example above, this allows to create and store different

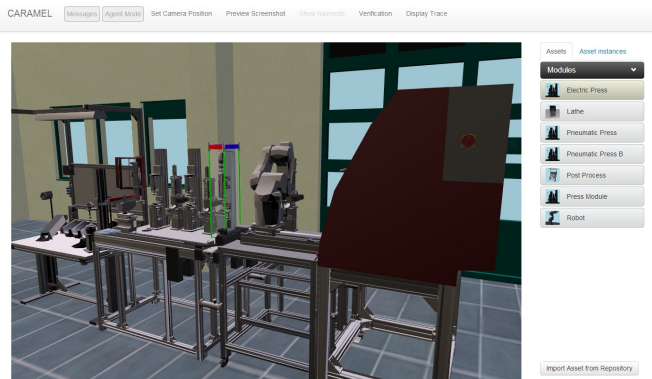


Fig. 3. Editor tool

configurations (*scenarios*) for the same factory hall (with the factory setting being the *project* in this case). The editor itself is part of a collaborative work space which allows a group of designers and domain experts to jointly construct and visit a 3D scene.

To provide seamless communication with collaborators during content creation, a basic personal messaging system is integrated into the editor. Using this system, team members can send each others short pieces of text. New messages are indicated as soon as a user enters the scenario in the scope of which the message was sent.

In addition, third party ticket and bug tracker systems that provide a REST API [17] for HTTP access (as for example *Mantis*¹ or *Trac*²) can be integrated into the work space. The step of actually choosing and integrating the tracker system in the overall application is not possible from the graphical user interface of the work space yet. However, the editor code is easily extendable via a provided API for third party services. As the editor is entirely written in JavaScript, and both 2D user interface as well as 3D elements are represented as DOM elements within this website, this extension can also be done by web designers with minor experience in website scripting. Information from third party system is them displayed directly in the work space's user interface.

Whenever more than one collaborator logs into the same scenario, the process of content creation turns into a synchronous editing session. Changes done to the scene by one user (including adding objects, moving existing objects or deleting them) triggers an update of the scene state in all connected clients. We employ two approaches to avoid update conflicts during concurrent editing. On client side, we use a locking mechanism: An object that is selected by one user is locked for editing for all his collaborators. This lock is indicated in both the 3D view of the scene by rendering the object semi transparent, and in the list of placed assets next to the editing window: list entries of locked objects carry a lock icon and are highlighted in red. In addition, the database performs a version control based on revision numbers for each

object. If an update is performed on an object with outdated revision, the update request is declined and the sending client is informed about the conflict.

External services from the XML3D Service Cloud (see also Section III-D) can be accessed directly from the editor's user interface.

C. Storage Layer

A collaborative work space is composed of different types of data (see Figure 4): First, an abstract representation of a scene that was created in the editor as described in the previous section. Second, 3D assets that contain the actual geometry and texture information of 3D objects from which the resulting 3D artefact is composed. Third, information for coordinated collaboration like for example open tasks or deadlines. For each type of data, we need a repository that provides the respective data to the work space.

1) *Scene Database*: Data about projects and scenarios that are created with the scenario editor are stored in a database that is directly connected to the editor. This project data includes projects and related scenarios, 3D asset sets and abstract representations of placed 3D objects, including an object's position and the URI that references its 3D asset data in XML3D format on the resource repository. Each object may moreover carry configuration parameters for attached services. Changes in data are automatically transmitted to all clients that are currently connected to a scenario that is affected by these changes to provide synchronous, collaborative editing of a scenario.

2) *Semantic 3D Asset Repository*: 3D artefacts are assembled from 3D assets, available in *iRep3D* [18]. *iRep3D* is a repository for hybrid semantic indexing and retrieval of annotated 3D scenes in X3D, XML3D and COLLADA at any level of granularity, in near real-time and with high precision. *iRep3D* comes with a web-based user interface which supports the user in annotating 3D scenes with plain text as well as appropriate ontology-based concepts and services in order to describe the functionality of scenes and their objects [19].

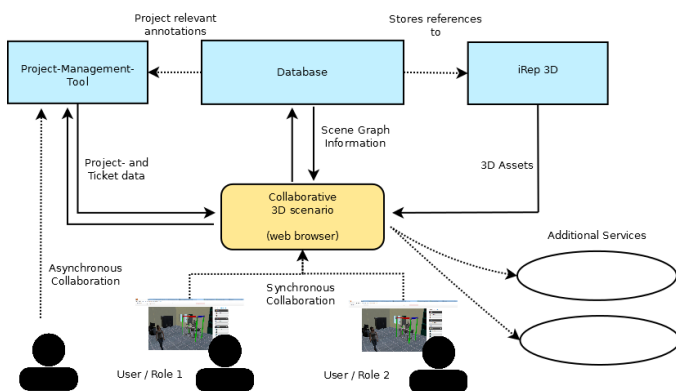


Fig. 4. Storage and Service Assembly serving the XML3D editor

¹<http://www.mantisbt.org>

²<http://trac.edgewall.org/>

iRep3D performs off-line semantic indexing and on-line query processing. The indexing process determines the relevant score of a stored 3D scene based on its semantic annotation and geometric features for the (a) scene concept index, (b) semantic service index, and (c) geometric index of iRep3D. The semantic similarity between scene concepts in standard OWL2 bases on their approximated logical subsumption relation and its information-theoretic valuation. The matching score for pairs of semantic services in OWL-S each of which describing the functionality of scene objects are computed with the currently most precise service selection tool iSeM [20]. The geometric feature index of a scene is a set of B+ trees each of which represents a standard feature-attribute pair which is instantiated by the scene according to the X3D, XML3D and COLLADA specifications, while geometric feature matching by iRep3D relies on classical approaches for this purpose. The repository applies a breadth-first-traverse-based pruning heuristic to efficiently maintain its scene indices in case the set of indexed scenes or their annotations change.

A query is a scene (in X3D, XML3D) that is annotated with the desired semantic scene concept, semantic services, and geometric features. iRep3D answers such queries by means of a parallel index-based subquery processing and final aggregation of resulting rank lists with a classical threshold algorithm. Besides, its search for relevant scene objects is performed even within indexed 3D scenes at any level of granularity while positive results are extracted and indexed as new scenes for further re-use, while the top most relevant scenes are then displayed to the user together with provenance information.

Indexed 3D scenes in XML3D, X3D or COLLADA are stored internally in a native XML database while the iRep3D repository itself provides a web-based user interface including a semantic annotation toolkit, and is also accessible via a REST API. Our experimental evaluation based on a test collection 3DS-TC 1.0 with more than 600 annotated XML-based 3D scenes revealed that iRep3D is significantly more precise and with the same average response time than its relevant and open-source competitors like Trimble3D, ADL and the Princeton3D search engine.

3) *External project management systems:* Data for work coordination is provided by external project management systems. This meta data includes user groups, messages that were sent in the scope of a project, issues and bug trackers. Those systems can also take the role of user authentication, if provided by the tool. Project management or bug trackers are connected to the work space via REST API. All data is displayed directly in the editor GUI and thus available during synchronous editing sessions. The benefit of using an external tool instead of using the scene database to store the meta data directly with the scene data is the asynchronous accessibility of the data from outside the editor. Existing tools like Trac, Mantis or Redmine come with a front-end GUI that can be operated from a Web-browser. That allows to contribute to

project coordination steps without having to use the actual 3D design tool.

D. XML3D Service Cloud

The XML3D service cloud contains several services which provide scenario-related simulation and evaluation functionality. The service cloud can be extended and new services can be added as plugins. In the current implementation, a verification service for functional evaluation of factory modules and an agent platform for controlling avatars are included.

E. Collaborative Evaluation through Formal Analysis

Physical systems that are controlled by embedded software like flight control systems, automatic braking systems, and production lines in factory environments are called hybrid systems as they involve both discrete and continuous behavior. A major goal in the design and implementation of hybrid systems is the ability to reliably verify functional properties of the system at hand. Flaws in the design of such complex systems occur regularly, especially when created in a collaboration of many different specialists. If they remain undetected and manifest themselves in the final implementation of the system they may lead to severe malfunctioning resulting in loss of money and reputation or even worse, injury or loss of life. A solution to this problem is the use of formal methods for a semantically unambiguous modeling of systems and their verification.

In our implementation we included a verification module that allows the collaborative evaluation of the system modeled in the configuration tool (see section IV-A). In communication with a collaborating specialist for formal methods and verification the system designer can formulate and verify the requirements for the system at hand. A tight integration of the formal and the 3D model allows a (partially) automatic generation of the formal model. On the other hand, the tight integration also enables the results from the formal analysis performed by the verification specialist to be presented to the designer in a generally understandable manner. The verification itself is performed by the verification tool HAVLE³ provided through a REST service. Figure 5 depicts the general workflow of the evaluation of a system modeled in the 3D Editor.

1) *Hybrid Automata:* HAVLE uses Hybrid Automata as they are a language particularly well suited to formally model hybrid systems in that they allow to specify both the continuous and discrete behavior parts of the system in one model. Our version of hybrid automata is very similar to the language of rectangular hybrid automata as they are known from [23], however with some extensions to provide an easy to use and extensive approach to model hybrid systems. Their main contribution is the support of a high degree of modularity. All possible system behaviors are defined by the composition of the different components. Since the language of hybrid automata is a formal one with formal semantics, verification is possible on systems specified in this language. For a detailed introduction into hybrid automata we refer to [22].

³Hybrid Automata Verification by Location Elimination [21], [22].

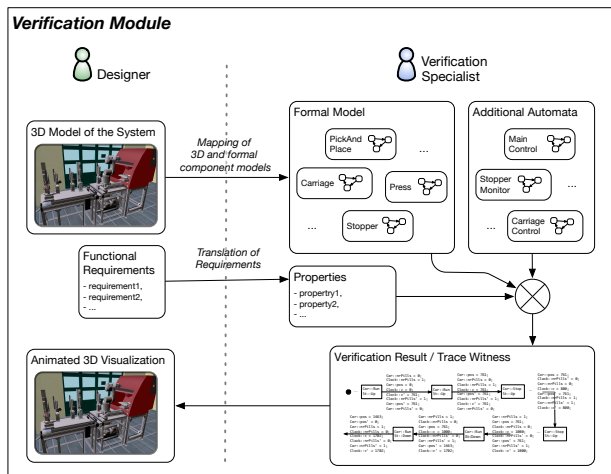


Fig. 5. Collaborative evaluation

2) *The Verification Module*: Models of the system can be constructed in the 3D editor by putting together component parts coming from a library of components. To allow verification and at the same time provide a seamless integration, additionally to the 3D description of their looks and physical dimension, they come with a formal description of their possible behavior. Adding a component to the model in the 3D Editor implicitly also adds the hybrid automaton assigned to this component to the formal model. A mapping that also comes with the component describes how the parameters of the 3D object correlate with the parameters and the initial states of the formal model. It translates position and rotation of the 3D object into values for the template parameters and initial locations of the automaton template. Applying this for all objects added to the system allows us to automatically generate a projection of the formal model from the system modeled in the 3D editor onto its visual parts.

After constructing the system the designer can ask the verification specialist using the available communication mechanisms, e.g. the messaging system presented in section III-B, to verify certain requirements given for the designed system. Due to the shared workspace and the included seamless synchronization the verification specialist can immediately access the current model of the system. If required (or desired) she can adapt the automatically generated formal model by, e.g. adding automata describing the non-visual parts like controllers or automata for the interrelation between the physical parts. She then formalizes the required properties submitted by the designer and verifies them.

Depending on the verification result (in case of the rejection of a safety property or the approval of a reachability property) HAVLE provides a *trace witness* (out of a constructive proof). Essentially a trace is a formal description of the behavior that the system has to show to reach a certain desired or undesired state. However a formal trace is very hard to read and can only be understood by specialists.

Due to the tight integration of the formal and the 3D model

through the verification module we are able to map such traces to animated visualizations of the behavior⁴ described by the trace in the 3D model of the system. Using basic modularized *Xflow* keyframe animations we perform a stepwise interpretation of the formal trace as pictures in an animation sequence. As soon as the verification has been performed by the verification specialist the visualization is also available for the designer and provides it with a tangible feedback of the performed verification.

Apart from collaborating with a specialist the designer can also formulate the properties to be proven by himself or choose from an existing list of required properties⁵. This is especially useful in case a previous version of the system that had already been verified has been modified. Similar to the idea of unit testing, by so called unit verification one can verify after every modification whether the system is still correct. Modifications like adding, removing, or moving of components are directly reflected in the formal model and need no further adaptations.

A more detailed description of the 3D visualization of verification results, the automatic generation of formal models from 3D models can be found in [22].

3) *Agent-based avatars*: In order to simulate interactions between workers and the production assets, the editor allows positioning animated avatars into the scene. The behaviour of avatars is controlled by an agent platform which is provided as a service. Agents in our context are the abstract entities representing the avatars in the scene. Agent models containing the behaviour can be modelled in advance and assigned to virtual characters. For modeling agent behavior, we use the Jadex agent platform⁶. The agent platform is based on the BDI (belief - desire - intention) [24], [25] approach for describing agent behavior. The BDI approach with its incorporation of reactive and goal-based behavior is especially appropriate for controlling avatars, because avatars in a 3D scene need to react quickly to a changing environment while exposing goal-directed behavior at the same time.

When a user wants to place an avatar into the scene, first the avatar asset is selected. After placing the avatar into the scene, one or more behavior capabilities behavior can be assigned to the avatar. The available capabilities are based on the agent behaviors which are provided by the agent platform. By assigning concrete goals (the intention) to an agent, the corresponding avatar tries to achieve this goal according to the behavior description. Agent-controlled avatars can be used to simulate workers, e.g. for evaluating the reachability of modules, time constraints for production processes, etc.

Since the objects in the scene can be moved using the editor, they constitute possible obstacles for avatars. Therefore, in the framework, a navigation service is associated to the agent platform which generates a navigation mesh on demand each time the scene layout is changed and prevents collisions of the

⁴In fact the projection of the trace onto the physical components occurring in the 3D system.

⁵Possibly formulated before the system was even constructed resulting from a requirements analysis.

⁶<http://jadex-agents.informatik.uni-hamburg.de>

avatars with each other and objects in the scene. The editing and simulation of agent activities can be done collaboratively in the shared workspace.

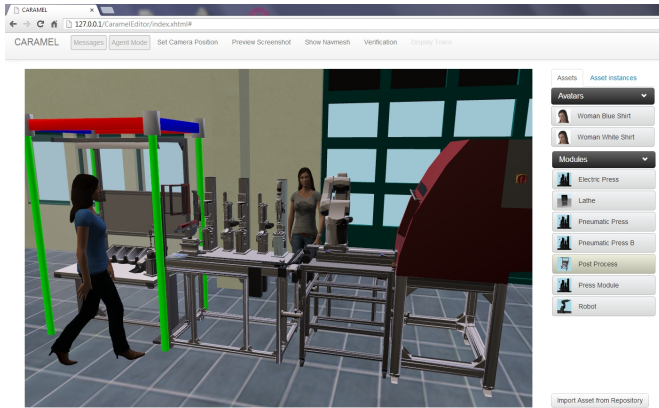


Fig. 6. Editor for agent-controlled avatars

IV. IMPLEMENTATION

A. Configuration Tool

To fulfill the requirement of ubiquitous accessibility, the implementation of the editor tool is completely based on XML3D with Xflow and JavaScript. The implementation of the web editor client uses the *Backbone.js* framework [26] to render both the 2D and 3D content from the data in the database. Backbone.js implements the *Model-View-Controller* (MVC) pattern [27]. For each data object in the data base (*model*), backbone creates DOM elements (*view*) to render for example both the XML3D element of an asset instance in the 3D scene and the respective entry in the list of asset instances on the right hand side of the editor view.

We chose Apache's CouchDB⁷ as storage unit for scene data. This NoSQL ("not only relational") database stores data as key-value-pairs with no fixed scheme. These values can be hierarchical objects with a number of attributes, usually accessed by a unique ID.

CouchDB adds a revision number for each object to avoid update conflicts when data is accessed by numerous users [28]. When a request to save data is sent to CouchDB, the request has to include the latest revision number of the updated data set known to the submitting client. If the revision number is different from the one stored in the database, the data update is rejected to avoid conflicts from concurrent updates.

CouchDB provides a RESTful web service to query data. It returns data as JSON (*JavaScript Object Notation*) objects. These objects can directly be used in a browser application's JavaScript code, without any overhead to parse the data. We keep the number of requests needed to keep in sync with the database low by using *long polls*. Requests that are sent as long polls do not return immediately, but remain at the receiving entity (in our case, the database), until the requested data is available. This approach reduces the work load in the browser

by the reduced number of database polls. In addition, once a long poll is returned, the delivered changes can directly be used to change displayed data accordingly. This keeps the displayed system state in the application consistent with the actual data stored in the database. The database is accessed by both editor and services from the XML3D service cloud.

3D assets are stored and managed by iRep3D. In order to import a new 3D asset to a project in the editor, the user opens iRep3D from within the editor GUI and queries for the desired asset. Once he concludes the import by mouse click, iRep3D adds the reference URL of the respective 3D asset to the list of asset documents in the database. By synchronous long poll updates as described above, the imported 3D asset is immediately available for placement.

We included Redmine⁸ exemplary for existing project management systems to the work space. Redmine is a Web-based project management system, implemented using the Ruby on Rails framework⁹ and published under the GNU general public license. Project descriptions as well as issues and issue trackers for projects can be queried via a REST API. In the terms of the introduced 3D editor tool, we map Redmine projects to configuration projects and Redmine sub-projects to scenarios. For personal messages, we introduced a respective tracker in Redmine and model messages in the configuration tool by issues in Redmine. The link between Redmine projects and the 3D work space is realized by respective parameter attributes for objects in the scene database. Redmine provides moreover HTTP Basic Authentication [29] via REST and can therefore be used for user login. By taking this step, the set of projects provided to a user when entering the 3D work space is determined by rights granted by the Redmine configuration.

B. HAVLE

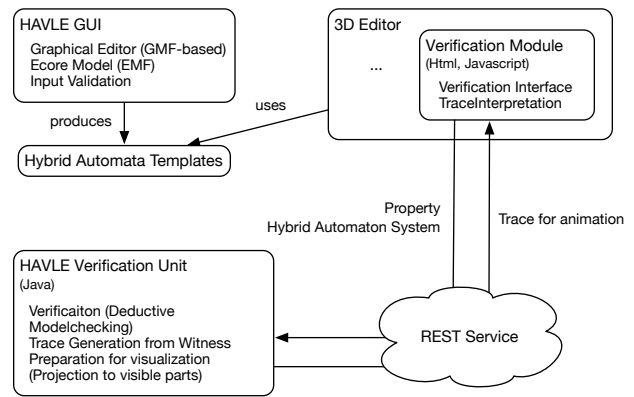


Fig. 7. Components of the Verification Module

The verification tool used in the implementation is HAVLE. The specification unit of HAVLE provides a graphical user interface for modeling hybrid automata in a graph-like manner. The graphical editor is a GMF¹⁰-based Eclipse plugin.

⁸<http://www.redmine.org>

⁹<http://www.rubyonrails.org>

¹⁰Graphical Modeling Framework, <http://www.eclipse.org/modeling/gmp/>

⁷<http://couchdb.apache.org>

Automata entered in the graphical editor are transformed into Ecore models using the Eclipse Modeling framework (EMF¹¹).

The verification unit itself is written in plain Java. In the verification process the automata that the system consists of are composed and translated into a logic based representation. The algorithm that performs the actual verification is a combination of deductive techniques and model checking and produces additionally to the answer whether a property holds or not, a witness (if possible). From this witness it computes a formal description of behavior that leads to the desired or undesired state.

The verification module of the collaboration environment presented in this paper is implemented in Javascript with HTML as GUI front end. It accesses HAVLE through a REST service sending the formal model extracted from the system model designed in the 3D editor and the property to be evaluated to HAVLE and receiving the formal trace as a result. This trace is then processed by a trace interpreter written in Javascript: it goes through the formal trace step by step¹² and produces the according state in the 3D model using the basic (Xflow) animations and the mapping that describes how values of variables and locations in the formal model correlate to basic the animations and values of variables in the 3D Model.

The separate components and their functions are sketched in Figure 7.

C. Agent platform and navigation service

As already outlined in Section III-D, the service for agent simulation consists of an agent platform provided by Jadex and an associated navigation service for navmesh generation and agent positioning. The associated navigation service is *HumanSim*. Jadex and HumanSim communicate with each other by TCP Socket connections. HumanSim consists of two parts: a service platform that is implemented in Java, and a browser-side part written in JavaScript that interprets the messages sent from the platform (see Figure 8). The browser-side JavaScript implementation moreover provides an API to access agents managed by Jadex, create new agents in Jadex, or assign plans to existing agents directly from the browser application, in our case, the 3D editor.

When an agent-based simulation is started, the geometry of the scene that is stored in the XML3D data layer is automatically collected and sent to the HumanSim platform. Out of this geometry, a navmesh is created that is used to check for collisions between Jadex agents and obstacles in the 3D environment during agent simulation.

This setup allows us to run a BDI engine for agent simulation with taking the structure of the user generated 3D artefact into account.

D. iRep3D

We have designed and implemented our first prototype of iRep3D repository in Java based on Springframework¹³,

¹¹Eclipse Modeling Framework, <http://www.eclipse.org/modeling/emf/>

¹²Every time a new frame is demanded by the renderer a new step is computed.

¹³<http://www.springsource.org/spring-framework>

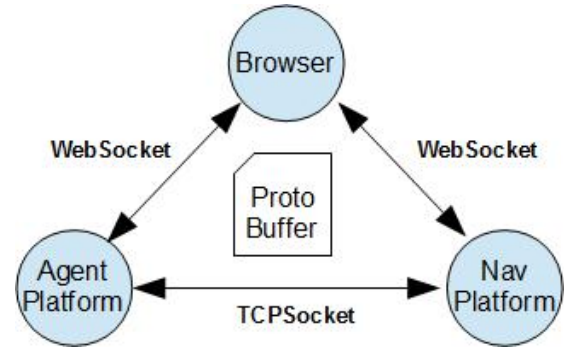


Fig. 8. Agent platform and navigation service infrastructure

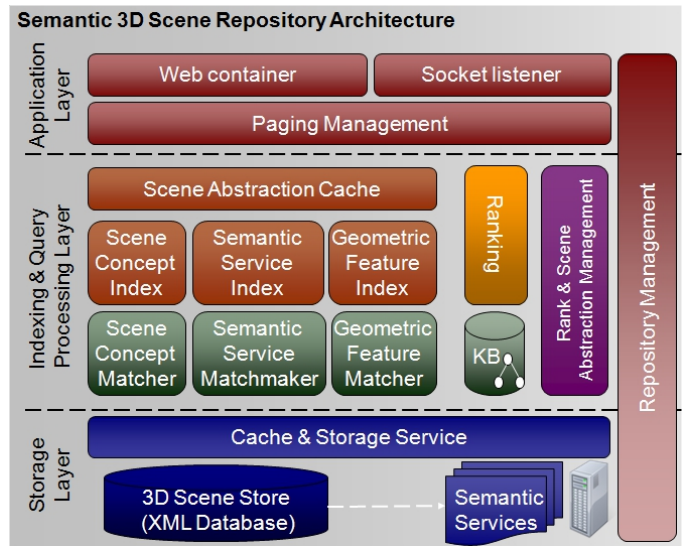


Fig. 9. Architecture of the iRep3D 2.0 scene repository.

Ehcache¹⁴ and JPA 2.0¹⁵ with Hibernate 3.0¹⁶. We briefly introduce, in this subsection, the implemented facilities for in particular the real-time semantic query processing. For this, the syntactic, conceptual, semantic service and geometric features of 3D scenes are extracted in advance during off-line indexing creation phase. Each ranked list of scenes is persisted as a disk file. The latter is further used for query processing by a lazy-loading mechanism, which loads the top T entries (T is configured with 50 in the prototype) into memory during system initialization and reads the next T entries when they are needed by rank merging process. Besides, the extracted features of 3D scenes are organized as scene abstracts that are further stored in a MySQL database for the purpose of showing 3D scene details (not scene selection) on demand. By means of pooling the connections to database, this performs quicker than the XML-based on-line query on 3D scene files.

Three layers of iRep3D repository are implemented in a loose-coupled fashion. They can be deployed in separate

¹⁴<http://ehcache.org/>

¹⁵<http://jcp.org/en/jsr/detail?id=338>

¹⁶<http://www.hibernate.org/>

servers. Each of them is able to communicate with the others via IP sockets. To increase their throughput, each layer maintains a first-in-first-out request cache. Pooled acceptor threads put their received requests from upper layer to the cache and the processing threads serve the requests out of cache. A query is processed by four joined threads in parallel. Each of them responses to the searching of scenes in syntactic, conceptual, semantic service or geometric aspect. In addition, we enabled a result caching heuristics for storing selected scene files and abstracts that would be used on demand. The list of selected 3D scene identifiers is also cached in query processing layer. When a page is displayed on demand, the contents for the next one are preloaded. For speeding up the simulation of reality, 3D scene files are (pre-) cached if they were (will be) requested (by the next page).

V. RELATED WORK

A. Research and Prototypes

A project that thoroughly dealt with collaboration in virtual environments is the DiFac project as described by Sacco et al [30]. They developed a factory design tool in VR, which integrates additional services for communication and project coordination. In addition, visualization of evaluation processes on a factory setup helps to find drawbacks in a specific factory setup. Information from all external services is directly visualized in the virtual environment. In contrast to the work presented in this paper, DiFac is run in a standalone VR application and not integrated in any web browser. Moreover, the set of additional services is fixed, whereas we aimed at providing a flexible API to append services of users' choice.

Pappas et al presented *DiCoDev* [31], a web-based collaborative editing tool for 3D data. It includes user management with user roles, access management and provides file exchange for documents and 3D data. The workspace is embedded into a virtual reality application based on the commercial PTC Division MockUp platform¹⁷. Within this VR environment, multiple users can create 3D content in real-time in a collaborative session.

Based on DiCoDev, Smparonis et al. created a *Collaborative Prototype designer* that adds functions for collaborative review sessions to the original application [32]. In these sessions, users can inspect created models by navigating freely around them in 3D space, share their current view points with others or navigate to previously defined fixed view points. The review and evaluation process is supported by a decision support module.

Menck et al. introduced a system for collaborative factory planning in a virtual environment [33], implemented using VRUI, a framework to implement VR applications in C++. The system provides an immersive virtual factory environment for several users. Users can add objects to the virtual factory, change their positions and remove them again. Objects can be annotated to point out open issues or as documentation of the

design process. Moreover, virtual meetings can be held in the virtual world, while the annotated 3D factory is explored.

While the latter examples make use of third party platforms to display 3D content, we provide a web-based 3D scenario editor that does not need any software or libraries installed but the web browser itself.

Wan et. al presented WebMWorks, a browser-based tool for collaborative design, modeling, simulation and knowledge sharing [34], building upon Modelica, an object-oriented language for modeling physical systems¹⁸. While models in this system are usually expressed by an equation based language, there also exists a schematic, diagram-like visualization of respective models. The WebMWorks system introduced by Wan et. al allows to create these models collaboratively in a Web-browser, and run simulations based on created systems. The actual models are served from a cloud storage. In contrast to the approach presented in this paper, WebMWorks does not provide any 3D visualization of created systems. Moreover, the system is built to work on Modelica, and does not provide any possibility to extend the existing platform by additional external services.

B. Commercial Applications

The topic of collaborative work on 3D visualizations is not only topic in research. Many commercial CAD (*Computer Aided Design*) and 3D modelling tools nowadays include collaborative features: Autodesk's *AutoCAD 360*¹⁹ provides a collaborative 2D-workspace for CAD design. Work can be saved to a cloud storage and shared with co-workers. There exist versions for desktop PCs, mobile devices and a prototypical Web-browser-based frontend to allow ubiquitous access of the data. By decoupling access of the data from a specific machine and providing a browser-based implementation, designers are no longer bound to a licensed machine. However, AutoCAD 360 does not provide 3D visualization of data, but is limited to 2D sketches.

A popular tool for 3D CAD design is *CATIA* by Dassault Systèmes²⁰. With *Instant Collaborative Design 1 (CD1)*²¹, *CATIA* is extended by capabilities of sharing a workspace interactively with co-workers. Data transfer is realized either via peer-to-peer or client-server connection. Communication features are included by a real-time chat and personal messages for asynchronous collaboration. Whereas CD1 offers sophisticated solutions for concurrent product design, its use is limited by the fact that in order to participate in the work, software for each participant has to be licensed and installed on a specific machine. This obviously slows down the process of introducing a new member to the team or to allow a remote expert to temporarily participate in design decisions.

¹⁸<https://www.modelica.org/>

¹⁹<https://www.autocad360.com/>

²⁰<http://www.3ds.com/products/catia/>

²¹<http://www.3ds.com/products/catia/portfolio/catia-v5/all-products/domain/Infrastructure/product/CD1/>

¹⁷<http://www.ptc.com/product/division>

VI. CONCLUSION AND FUTURE WORK

In this paper, we presented a web-based collaborative development environment for virtual prototyping. Whereas commercial systems often are monolithic, we developed a Web-based, distributed, service-oriented and extendable collaboration framework which provides a shared visual experience for collaborators. We described the services included in the framework that can be used for evaluation of the designed artefact. The collaborative development environment has been implemented and applied to a factory design scenario.

As future work, we will extend the framework to enable mobile access to the collaborative workspaces, using tablets and smartphones as devices. Furthermore, we plan to include virtual reality devices, e.g. head-mounted displays in order to provide a more immersive experience of the 3D scenes.

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