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# Design of a test environment for planning and interaction with virtual production processes

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**Abstract**

Rising complexity of systems combined with multi-disciplinary development and manufacturing processes necessitates new approaches of early validation of intermediate digital process and system prototypes. To develop and test these approaches, the modular digital cube test center was build. Usage of different Visualization Modules such as Powerwall, CAVE or Head Mounted Display allows immersive interaction with the prototypes. Combined with Haptic Interaction Modules from one axis assembly device to a hexapod simulator up to a full freedom kinematic portal and usage of different simulation modules of vehicle design, multi-kinematic, manufacturing and process-simulation allows early virtual prototypes validation in multiple use cases.



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*Keywords:* Virtual prototypes; Modularity; Early testing; Immersive interation; Haptic interaction

## 1. Introduction

Today’s production industries are influenced by several megatrends which have a massive impact on its established work processes. New technologies interconnect different research disciplines to generate innovations and result in a rise of the product complexity. Dynamic product life cycles reduce the available production time, in line with rising customer individuality. Furthermore, the augmenting technology diversification necessitates focused specialization of companies and the demographic change forces initiatives to support the qualifications and competencies in production of a growing elderly part of employees [1]. The digital factory, as it describes an early production planning and design of the factory closely coordinated with all corporate processes, is a lever to handle these challenges [1].

Production planning in this context refers to both - the planning of the production processes as well as the planning of the production systems. The aim is to develop and validate products, production processes and production sequences in an early phase of development and to accompany and accelerate the production development with digital models and tools. In a final step, the virtual instruments are utilized to monitor and improve the process excellence in the actual factory on a constant basis [2].

With well-established and stable production processes using a high automation level for assembly, handling and manufacturing processes in general, especially in large scale and mass production, automation changed the activities and position of humans in production processes within the last decades [3]. With the increasing system complexity and inherent unpredictability for the human operator, automized processes tend to generate situations, which are difficult to cope, especially in case of malfunction. This effect is known as the so called “irony of automation” [4]. When focusing onto small series or prototype-production, the intelligent and physical adaptability of humans can rather not been replaced by a highly automated production, ensuring an economic viability [3].

Therefore, the human is still the key element in both: the planning of the production and the production itself, assuming different roles in each step.


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Virtual reality (VR), as it describes a real or simulated environment in which a perceiver experiences telepresence [5] by using 3D visualization technologies is an opportunity to put the user and its interaction with the production process in focus and gain qualitative user statements [6]. As VR usage is common in industrial practice for certain applications as visualization of an early step planning as e.g. layout design, the opportunities and challenges of VR usage in production planning are inadequately investigated.

With this strategic perspective in focus, the chair of industrial information technology of Technische Universität Berlin performed its research project "Digital Cube Test Center" in order to investigate the VR based interaction of human with the virtual models of digital factory.

This paper describes the development process of the test environment "Digital Cube Test Center" (DCTC) from requirements gathering, through the derivation of solution elements and principles, the development of a test environment architecture integrating these elements to the use case based validation of the achieved results.

## 2. Analysis and Requirements Gathering

### *2.1. State of the Art of 3D Model application*

In today's applications of digital factory, 3D models are used for different tasks of static, Computer Aided Design (CAD) based modelling activities, various simulations based on these models and validation activities based onto the achieved modelling and simulation results [2]. 3D Models are used at the different production planning object levels from production facility over production system, production machine down to production process [6]. The static activities range from factory layout planning over facility and machine design until tool design.

Usual industrial simulation objectives are load analysis as ergonomic simulation, 3D movement as robot kinematic analysis or assembly simulations, process simulation as numeric control process or CAM simulations and control simulation used to investigate controller behaviour. For validation purposes, virtual reality is used for training and education, visualization for communication and validation purpose e.g. in design reviews, or virtual testing as for maintenance processes [3].

### *2.2. Requirements Analysis and Gathering*

The requirements analysis encompasses the tasks that go into determining the needs or conditions to meet for a new or altered product or project, taking account of the possibly conflicting requirements of the various stakeholders, analyzing, documenting, validating and managing software or system requirements [7]. For the test environment design, thus the different "requirement sources" have to be identified and analyzed in order to extract and determine requirements usable for the test environment design process.

The following requirements sources were identified during analysis:

- State of the art applications of 3D Models for planning purpose. The 3D models are designed and simulated by the human in order to plan the different object levels.
- Requirements from research in the field of planning improvement. The major research question is how to enable the human planner to achieve "better" planning results as they might be achieved in shorter time, in a higher quality or with less resource usage than today.
- State of the art applications of 3D Models for process steps including humans. The 3D Model based process planning includes humans in order to plan its operation in the process. In state of the art applications, usually virtual human models are used for this purpose of "human centred design".
- Requirements from research in the field of achieving better process integration of humans than with today's digital factory simulation tools. Due to the limits of today's virtual human models this research field aims at allowing humans to interact with virtual models. The major research question is how to improve the interaction between a human process participant and a virtual model in order to get more valid test results.
- The usability of the test environment in order to design a test environment that allows easy usage and maintenance by user and operator.

Analyzing, structuring and detailing the requirements lead to the following list of seven top level requirements to be achieved for test environment design (see table 1). Each top level requirement has several sub-requirements which are not shown for reasonable space. The top level requirements are divided in three levels of priorities: Achieving the results that fulfil the first priority requirements will result in a test environment able to perform the state of the art applications of virtual reality. The second and third priority requirements define the area of research to be conducted at the test environment with priority 2 requirements achievable with medium and priority 3 with high effort.

Table 1. Top level requirements for DCTC

| | Requirement | Priority 1 | Priority 2 | Priority 3 |
|---|---|---|---|---|
| 1 | Opportunity to move though whole production facilities | X | | |
| 2 | 3D Visualization of virtual models from production process to production facility | X | + in spec. planning software | |
| 3 | Simulation of running processes from production process to production system | X | + Real Time | + in spec. planning software |
| 4 | Real Time Interaction between Human and functional virtual production system or machine | X | + Haptic interaction | + in spec. planning software |
| 5 | Usage of planning tools from all state of the art application fields | X | | + without exchange formats |
| 6 | Flexibility - Easy Exchange of elements and user test setup | X | | |
| 7 | Easy Use and Maintainability of Test environment | X | | + less expert knowledge |

## 3. Test Center Design

### *3.1. Overall Architecture*

Following a top-down development approach, the first step of the design process is to define the overall architecture of the DCTC test environment to define its elements and their interrelationships. The requirements No. 5, 6, and 7 can be described as "test environment top level" requirements, as they define the structure and the general layout of the test center. The approach of modularity seems to be an appropriate solution element to fulfil these requirements as it promotes interchangeability and thus provides the requirement of flexibility. The benefits of modularity include ease of product updating, increased product variety, decreased order lead-time, and ease of design and testing [8]. Besides the advantages of easy exchangeability by using modules, flexibility allows for delaying design decisions until more information is available without delaying the product development process which is useful especially in research projects. By providing standardized interfaces, the usage of modules furthermore eases the use and the maintainability of the test environments elements as it helps to handle complexity and supports the user with a manageable amount of different interfaces. Providing standardized software interfaces also allow the usage of planning tools from all state of the art application fields.

The static product architecture and the resulting lack of performance optimization as same as an increased unit variable costs, as they were described as "costs of modularity" [8], were accepted in the test environment design process.

Based on these considerations, the three-part modular architecture shown in Fig. 1 was developed. It divides the elements of the DCTC test environment into the three main modules "Simulation Core", "Visual & Acoustic Core" and "Haptic and vestibular core" and describes the interaction between user and test environment for the two different application fields "User plans process" and "User in process" by showing information and energy flow between the main modules and the respective user.

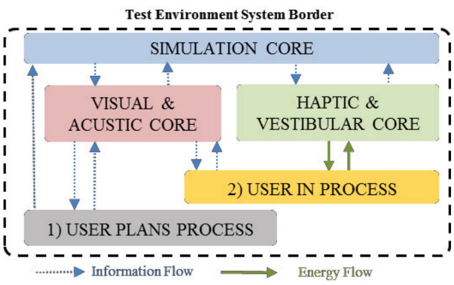


Fig. 1. DCTC modular architecture (main module level)

Each main module consists of several second level software and hardware sub-modules connected with specific standardized soft- and hardware interfaces. In the following section the three main modules are described in detail by presenting the realized and determined technical solutions.

### *3.2. Simulation Core*

For an easy integration of new tools and application the standardized TUI framework interface is the base of the simulation core. The TUI framework is an object-centric Interaction Framework and was developed at Fraunhofer IPK in 2011. It integrates a device abstraction layer, a lightweight application programming interface and full duplex communication between the TUI-application and interaction devices [9]. The TUI Frameworks enables easy integration of new software elements and provides their communication with standardized interfaces.

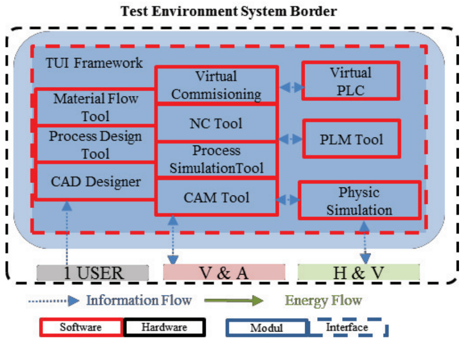


Fig. 2. Simulation core architecture (sub-module level)

The available planning tools shown in Fig.2 range from CAD, CAM modelling, including process simulation up to virtual commissioning coupled with a virtual plc provides a wide spectrum for product and process validation for the planning user.

Physic simulation tools enables the implementation of physical model behavior and forms the base for the haptic human-model interaction abilities provided by the haptic and vestibular core. A PLM tool provides consistent data management functionalities to handle the large amount of planning and control data.

The simulation core uses a modular hardware base consisting out of multiple decentral computers. This architecture enables both a hardware flexibility by simplifying the integration of new hardware and the exchange of single computers as such as a work and research environment enabling multiple users to work parallel.

### *3.3. Visualization & Acoustic Core*

Aiming to enable the 3D visualization using different state of the art technologies and developing a research environment for the interaction with 3D models, the definition of the room for human-model interaction was the primary target in development. Based on these considerations and limited by the available construction surface, a cubic room with 3 meters edge length was designed. This Test Centers labeling "Digital Cube" is framed by four projection screens enable a 360 degree projection surface via back projection technology. Fig. 3(b) shows this interaction room. The usage of stereoscopic projectors allow the use the projection screens for both two and three-dimensional 360 degree visualization. The TUI

Framework enables the easy integration of different visualization technologies, thus the usage of Head Mounted Displays (HMD) in the interaction room is possible as well.

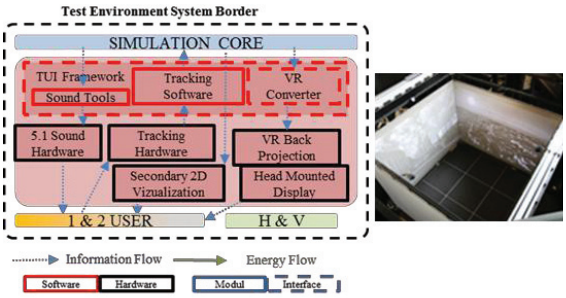


Fig. 3. (a) Visualization & Acoustic Core architecture (sub-module level), (b) "Digital Cube" interaction room

As state of the Art planning tools are usually optimized for using 2D visualization technology on monitor-based workplaces, an interface to convert these data into 3D visualization data usable for the 3D visualization technology. For this purpose, the VR converter interface is used. It enables the direct use of the planning tools in virtual reality and thus makes the use of exchange data formats unnecessary.

It is possible to integrate further "secondary 2D visualization" modules such as screens or portable devices to enable further interactions between user and model.

To detect the user position in the interaction room, an optical tracking system is used. With this system, up to ten different users and objects can be detected into the interaction room.

Beside the visualization, the visualization & acoustic core includes a six channel dolby surround 5.1 system controlled by sound software tools to integrate different sound sources into the virtual environment.

### *3.4. Haptic & Vestibular Core*

The Haptic and vestibular core aims to provide capabilities that enable the direct, haptic interaction between user and model. This field of "computer haptics", the combination of virtual models with physical elements to realize real-time force feedback interaction, is a relatively new research topic with different approaches existing. The Smart Hybrid Prototyping (SHP) approach, developed 2009 at TU Berlin, uses the linking of Digital Mock Ups extended with kinematic and dynamic behavior models and haptic interaction devices to enable this interaction [10]. The SHP approach aims to use industrial standard hardware to design cost efficient, modular prototypes consisting of functional virtual models and connected haptic interaction devices.

The use and the flexible exchangeability of the haptic interaction devices define the border conditions for the test environment. At the floor of the interaction room the Motion Platform Module is installed. Being based on 2 engine driven linear profiles, the module enable the 2-axis movement of end effectors though the interaction room. The hexapod module can be coupled onto the motion platform to extend the available degree of freedom (DOF) of the system to an 8 DOF kinematic system. With its modular design, the hexapod enables the installation of different elements. The functional drive simulator module integrates vehicle specific haptic interfaces as steering wheel, pedalset or gearbox onto the hexapod. To enable other test setups, the hexapod can be uninstalled through the removable test center roof hatch and the modular platform can be installed covering the motion platform.

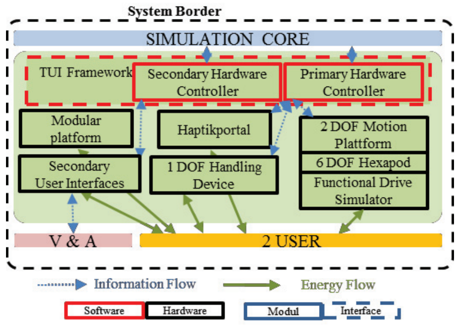


Fig. 4. Haptic & Vestibular Core architecture (sub-module level)

Onto this platform, other haptic devices as the 1 DOF handling device or the hexapod can be installed. The 1 DOF Handling Device consist out of two jointed levers driven by an electric engine and can be used for one axis handling interaction such as the application of a manual drilling machine.

At the top of the digital cube the Haptikportal module is installed. It consists out of a 2-axis platform with 2 longitudinal and 1 lateral installed engine driven linear module connected with 1 vertical engine driven linear module. This design provides the opportunity to install different end effectors at the verticals module lower end and the applicability of forces on them. Thus the Haptikportal module enables the haptic interaction between user and model into the whole digital cube.

These different "primary haptic devices" can be extended with further "secondary user interfaces" as portable devices, control panels or touch screens.

As for the 2 other cores, the TUI Framework is used to integrate the different hardware controller for primary and secondary haptic devices.

## 4. Use Case based Evaluation

### *4.1. Use Case Design*

In this chapter, the application of a set of use cases to the test center is described and will be analyzed to evaluate the extend of requirement achievement by the developed "Digital Cube Test Center". As guideline, the operation level "production facility" is addressed by using a factory building as common element with four different use cases located into. By describing different object levels from process over production machine and production system onto production facility and being located in different process steps of factory planning, the use cases are designed to enable the quantitative validation of requirements fulfilment.

- Use case 1: Usability of vehicles in the context of a production facility – new handling concepts for a fork lift tested in a virtual environment

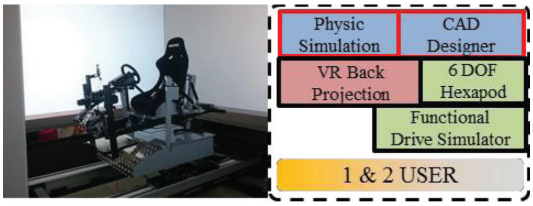


Fig. 5. (a) Usability of vehicles in factory context; (b) Use Case 1 core modules

With use case 1 the design and validation of vehicle cockpits in the context of a virtual factory can be examined. New concepts of designing future workplaces in mobile vehicles (forklifts, mobile working machines inside and outside a factory) can be evaluated. Major validation topics in this context can be handling of the vehicle concerning navigation, turning and parking but also evaluation of the vehicle within its environment. Thus both user groups, the planner as well as the process integrated user are addressed. This ability can be used for material flow related investigations within a virtual factory, dependencies with layout planning and the spatial accessibility of storage areas and delivery spaces. Core modules of use case one are the VR Back Projection for visualization, extended by the functional drive simulator assembled to the 6DOF hexapod. This configuration allows a physical interaction of the user with the virtual environment that is linked with a physic simulation.

- Use case 2: Visualization of a production system and interaction with the real-time process simulation

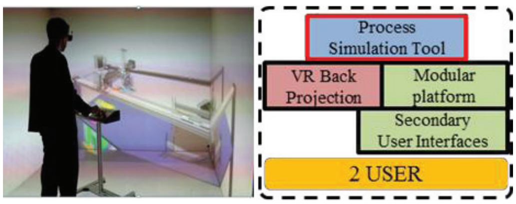


Fig. 6 (a) Real Time process simulation; (b) Use Case 2 core modules

The second use case covers the topic to experience a process simulation of a production system in Virtual Reality. With the help of the VR Back Projection for visualization and a connected, physical HMI as secondary user interface, it is possible to visualize an interactive animation and simulation of the production process.

Therefore it is possible to support the development process of the production system starting from an early generic design with stereoscopic visualization of the model up to a late, detailed design phase, where also correct kinematics, precise physical behavior and signal processing can be considered. This use case offers an interactive, virtual environment for the development of the production system but also training and optimization aspects in cooperation with machine operators.

- Use case 3: Haptic validation of manual assembly processes – multi-axis simulation with the “Haptikportal”

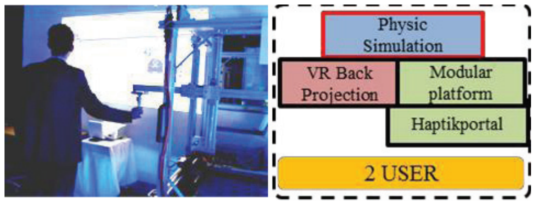


Fig. 7. (a) Interaction with virtual production machine using the Haptikportal; (b) Use Case 3 core modules

For the functional validation of manual assembly processes used within the production system, haptic feedback can be applied to the virtual production system. Under consideration of use case 3 an early validation method of functional process elements can be addressed. Within this use case a single process step is analyzed more in detail. With a corresponding, real-time physical behavior simulation linked to the used VR Back Projection visualization module and the physical interaction module Haptikportal, a manual assembly task can be validated by the user in a virtual environment. With the help of haptic interaction in the context of virtual commissioning different functional elements of the production system as positioning and assembly tasks, the safety architecture or ergonomic aspects can be evaluated.

- Virtual commissioning of production systems with VR

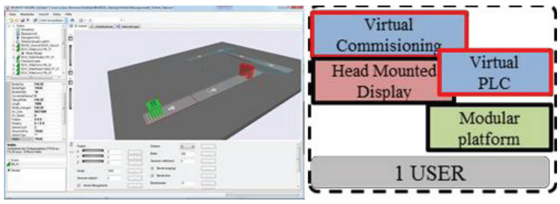


Fig. 8. (a) Virtual commissioning of production systems; (b) Use Case 4 core modules

Use case 4 handles the validation of the final control architecture. The generated PLC code for the sequence of the production process can be tested in the virtualized production system. The focused topic of use case 4 enables an easy conversion and use of the validated code between the virtualized and physically planned production system. Therefore a shortening of the development process can be achieved. In addition to the validated control design the identified signals of the production system can also be linked to the kinematics of the spatial, geometrical representation of the production system. Based on this signal mapping the accurate behavior of the virtual production system can be visualized within a realistic environment inside Virtual reality.

The core elements of use case 4 are the visualization module Head Mounted Display, where the kinematic and spatial design of the production system can be visualized. In combination with the described signal mapping and the generated plc code a control unit can operate the virtualized production system.

### *4.2. Evaluation*

Performing the use cases and receiving test results enables a quantitative evaluation opportunity in comparison with the requirements identified in chapter 2.

It was shown by Use Case 1 that it is possible to move through whole 3D virtual models of production facilities in the large scale facility DMU generated from specific CAD Design Software. Extending them with physic models enable the opportunity for haptic real time interaction between functional virtual machine and human user. Use Case 2 shows the ability to simulate a production system real-time inside a specific planning software with the opportunity to interact with the process with secondary user interfaces. Use Case 3 shows the ability of haptic interaction with a specific production machine and a detailed analysis of the production processes proceeded with it. The final Use Case 4 shows the ability to simulate running processes of production systems with a Head Mounted Display. Being well comparable to Use Case 2 regarding its requirements and modules, the usage of the virtual plc adds the ability of virtual commissioning to the test center. This ability extends the usage of 3D models to later factory planning phases compared to the state of the art.

Thus it was shown that the top level requirements 1, 2, 3, and 4 are fully achieved in priority 1. The priority 2 requirements, as they are the medium effort area of research, are achieved and even the priority 3 requirement of “simulation of running processes in specific planning software are shown to be achieved. With a broad range of planning tools was shown from CAD Designer over process simulation and physic simulation up to virtual commissioning, the top level requirement 5 could be defined as achieved, because although not showing all state of the art application field, the use case planning objects are representative for the 4 production planning object levels described in chapter 2.

With its modular structure, the test environment shows a good flexibility in reassembling the test setup between the use cases, thus also requirement No. 6 can be described as achieved.

Regarding the No. 7 requirement of ease in use and maintainability, the test environment modular architecture delivers acceptable results although it still depends on expert capabilities of their users. Thus it can be described as partially achieved but still have to be improved.

## 5. Conclusion & Outlook

In the chapters 2, 3 and 4, the development process of the test environment “Digital Cube Test Center” (DCTC) was processed successful from requirements gathering, the development of a test environment architecture to the use case based evaluation. It was shown, that the requirements onto a test environment usable to investigate VR based interaction of human with the virtual models of digital factory can be achieved by using the chosen solution approaches of modular design and smart hybrid prototyping. With its key technologies TUI framework and the VR converter, the DCTC is usable for a broad range of modeling, simulation and validation activities with both, the user planning the process and the user being a process part respectively planning object. To validate the results of the requirements analysis and prove the usability of the DCTC in real industrial use cases, the most important next development step will be an application of real industrial use cases in cooperation with industrial partners. To prepare this, the robustness and usability of the DCTC abilities have to be improved and enhanced.

As the DCTC in its actual development status is usable for various state of the art applications and planning activities, it has the potential to explore new application fields of 3D models in factory planning. The field of virtual commissioning is identified to be such an application field and is addressed in the research project VIB SHP conducted since 2014. Further abilities such as “X in the loop”, other visualization technologies as augmented reality or virtual material flow may have these potential and have to be analyzed to become an reasonable field of further research.

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