Simulation and Offline Programming

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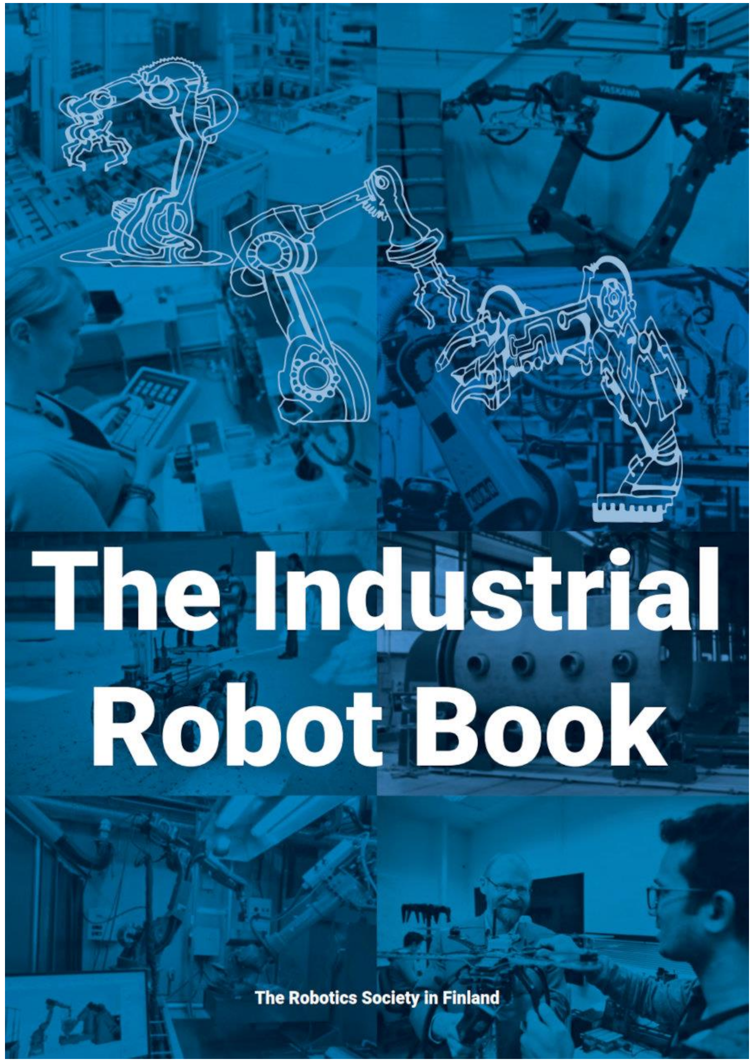
The Industrial Robot Book

- Lecture material is based on the book chapter
  - 12 – Simulation and offline programming
- You can buy the book from ellibs online shop or loan it from the university library
  - ISBN 978-952-65329-1-2 (EPUB)
  - ISBN 978-952-65329-2-9 (PDF)



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Definitions

- Simulation and model-based offline programming are digital tools for modeling, verifying, and programming the functionalities of industrial robots in virtual environments
- Using these tools together enables the design and programming of automated robotic systems without the need for real physical systems, ensuring the functionality of the designed systems before they are commissioned
- In industrial robotics, the functions of robots and robotic cells are simulated in an artificial environment, utilizing 3D digital simulation models and virtual controllers
- Model-based offline programming of robots means programming a robot without a physical robot, on a computer outside production using a graphical user interface, a simulation model of a robot cell and product manufacturing information (PMI), including the 3D CAD data and manufacturing method data of the product to be manufactured

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Main Steps of Simulation and Model-Based Offline Programming

- Main steps are listed at an approximate level, starting with the first step
  - Building a simulation model of a robot cell
  - Placing product model into a simulation model
  - Model-based offline programming based on product manufacturing information
  - Verification of an offline-programmed robot program by simulation
  - Calibration of the virtual robot cell
  - Transferring the offline-programmed robot program to a physical robot
  - Commissioning of the offline-programmed robot program
- The main steps of simulation and model-based offline programming may vary both in content and sequence from one type of software to another
  - Some steps may be overlapping or repetitive

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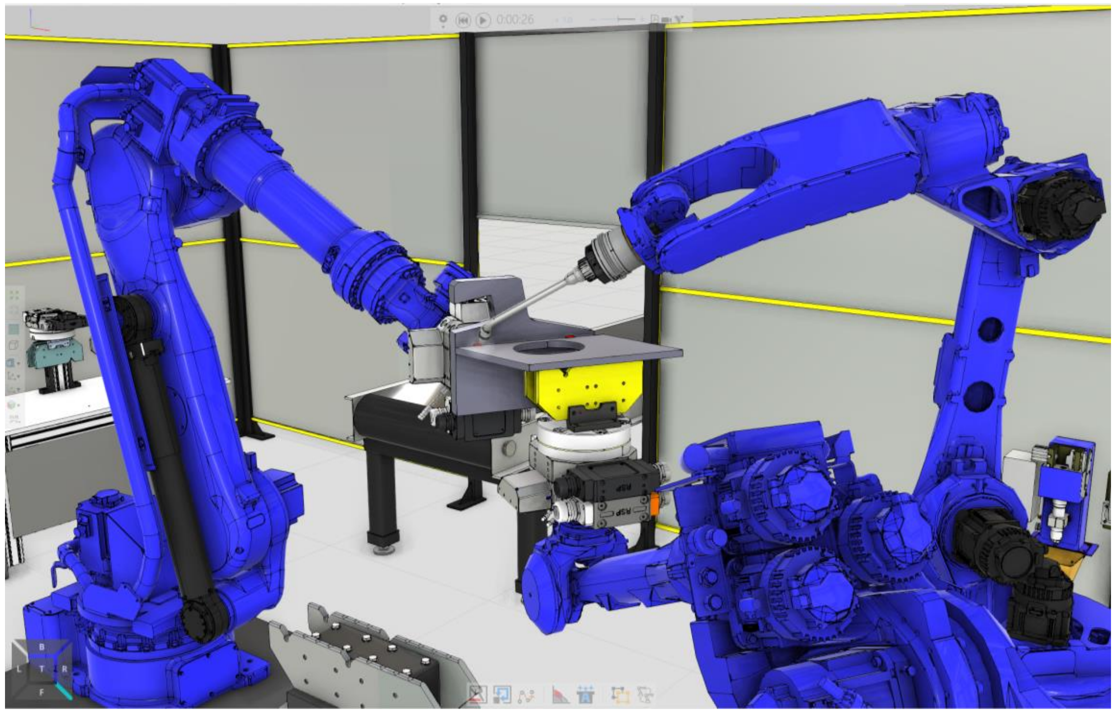
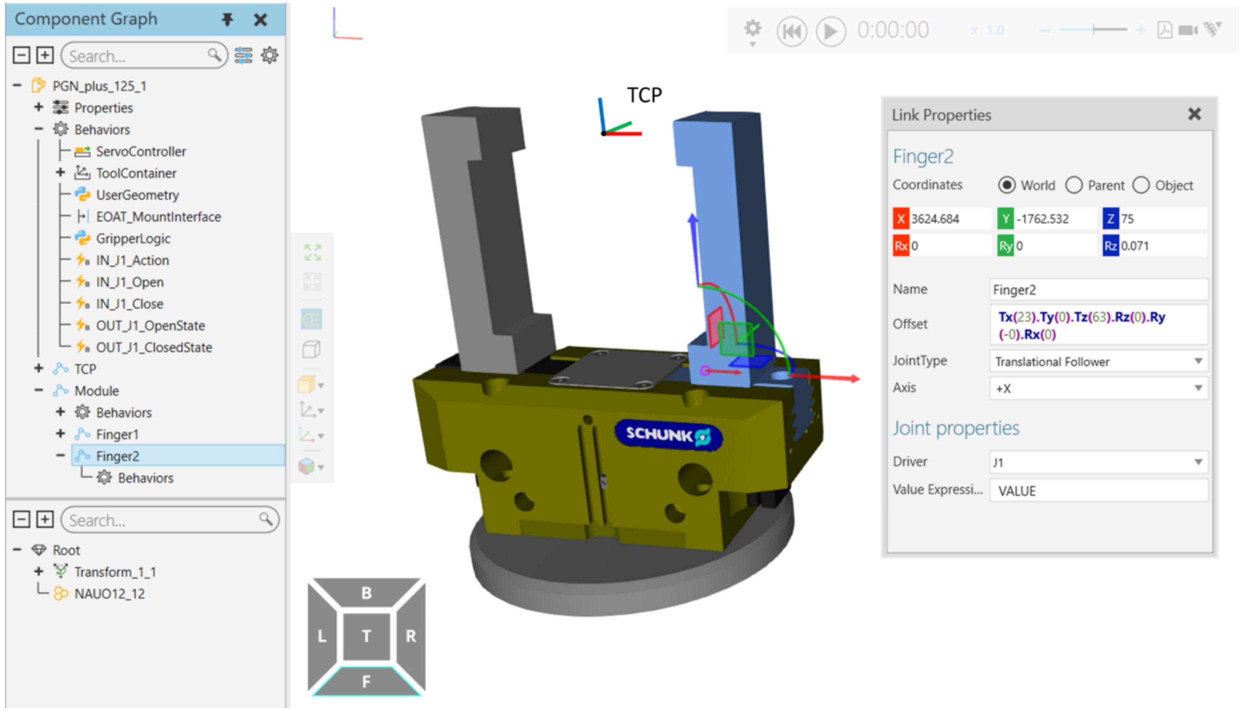
Building a Simulation Model of a Robot Cell

- In industrial robotics, building simulation models mainly focuses on designing the layout of the robot cell
  - Either creating a new robot cell or updating an existing one
- Required components, from robots to peripherals and manufactured products, are positioned within the robot cell
- Building a simulation model utilizes
  - Ready-made component libraries from simulation software
    - E.g., simulation models of the robots
  - 3D models from component and equipment manufacturers
    - E.g., material handling devices, bases of the grippers
  - Custom-designed and modeled parts
    - E.g., fingers of the grippers
- Various functionalities can be defined in the simulation models
  - Defining basic physics, such as gravity, makes the simulation more realistic
    - For example, defining functionalities for finger grippers is essential to simulate their operation effectively



Building a Simulation Model of a Component

- The creation of simulation models for components requiring functional properties, such as a robot's finger grippers, is typically divided into two phases
  - Modeling kinematic properties
  - Modeling logical properties
- The basis for modeling kinematic properties is the component's 3D model, which is divided into functional subassemblies. Each subassembly is assigned kinematic properties and degrees of freedom
  - For instance, with a finger gripper, this means defining the gripper fingers as separate movable subassemblies that move relative to the gripper base
- The purpose of modeling logical properties is to simulate the real component's behavior and interaction with the system's control
  - For example, in the case of a finger gripper, this involves defining the movement speeds and motion ranges of the gripper and its connections to the robot's control signals



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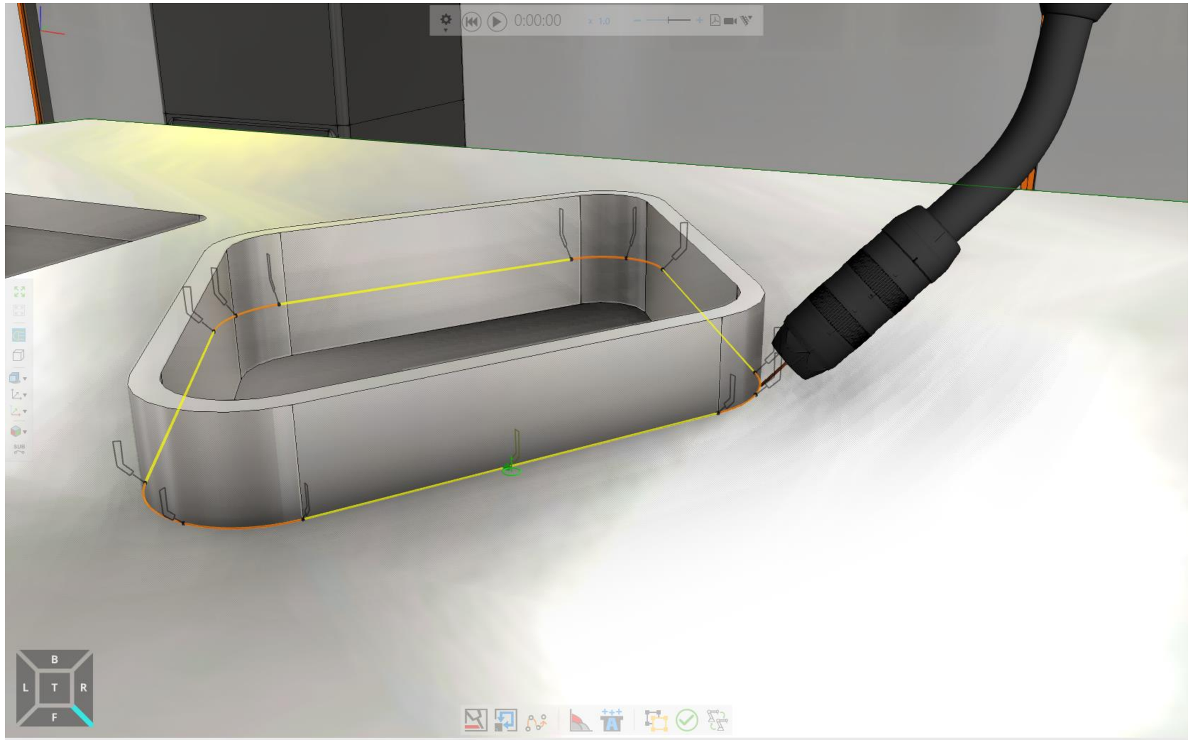
Model-based Offline Programming

- Model-based offline programming relies on the geometry of the product to be manufactured
- By selecting a feature or features of the modeled product, such as a point, edge, curve or plane, a robot's motion path is created
- Based on the geometry, motion commands and their parameters are defined for the paths, including
  - Target, approach, and departure points
  - Motion types, speeds, and accuracies (zones)
  - Joint configurations
  - Positions of tools and external axes
- In addition to programming motion paths, model-based offline programming involves programming the robot's complete operation, including
  - Defining the work cycle and necessary variables
  - I/O control between the robot and connected devices
  - Communication with the operator
  - Error handling



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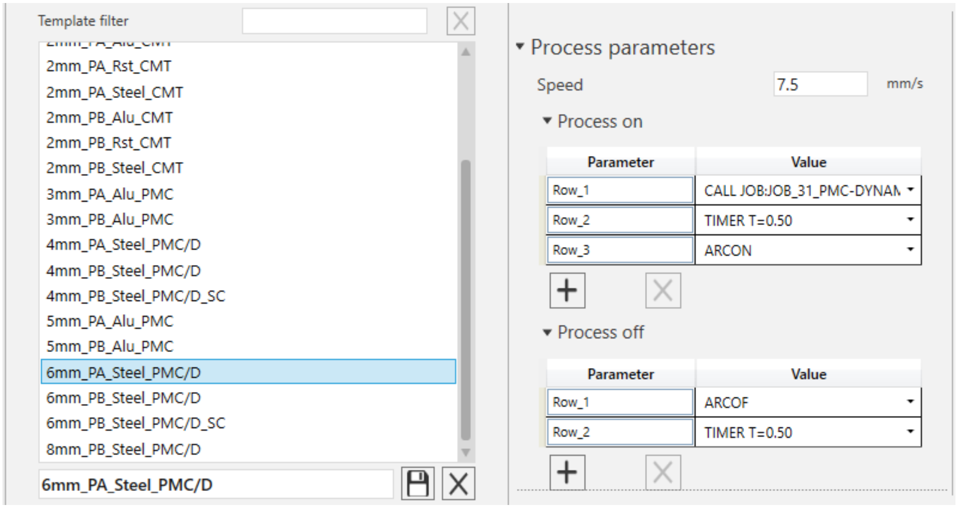
Model-based Offline Programming

- In addition to 3D CAD data, model-based offline programming uses manufacturing method information from the manufacturing processes
  - Method information includes information on the process parameters of the manufacturing method
    - E.g. orientation of the tool, process speeds
  - These parameters refine the robot's actions to achieve the required production quality
  - Method data is especially used for designing and saving manufacturing and programming methods for recurring features in the offline programming software's database
- At its best, offline programming paths for a new product can be highly automated, as the software analyzes the product structure imported into it and automatically generates the robot program based on the information stored in the database for features with existing programming methods
  - If a ready-made program is not available in the database, method data is set manually for the predefined motion path
- Model-based offline programming automates programming
  - “Ready programs with a single click"
  - Not all motion path parameters need to be set manually for each individual motion command
  - Programming becomes simpler and programming times are reduced when the manufacturing and programming methods for recurring features are defined and stored once
  - Programming errors, such as reach, joint configuration, and singularity issues, are identified during the creation of the motion path or at the latest during simulation
  - Reduces human errors by the offline programmer



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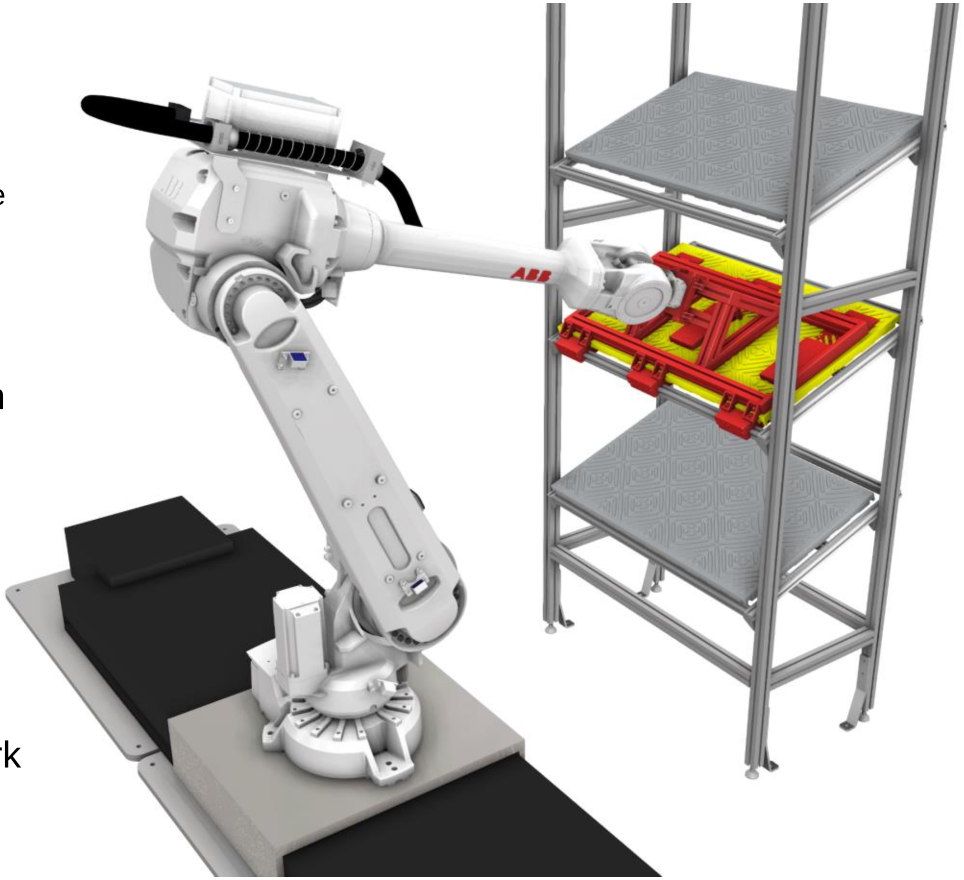
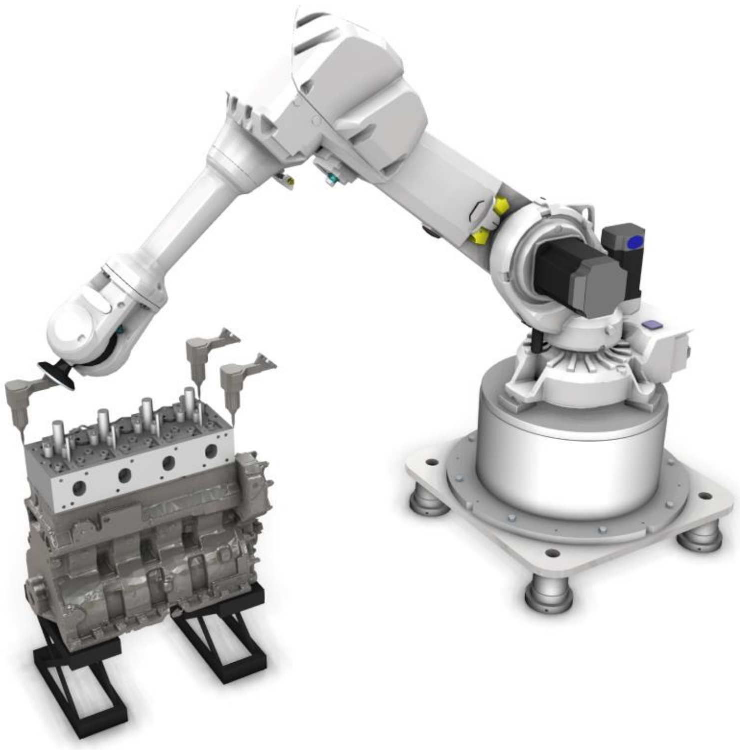
Simulation

- In this context, verification refers to ensuring the suitability and functionality of the robot and its task program in the specified task using a simulated robot cell
  - Simulation provides comprehensive verification of the robot task program, from correct program syntax to the desired work cycle and safe motion paths
  - Simulation is essential before commissioning the program in production, though it does not replace testing during commissioning
- The simulation is performed either in real time or at an adjusted speed, either running the entire program at once or each program command individually
- Typically, the progress of the simulation is monitored on a computer screen, but in some software, it can also be run in the background
- The simulation stops upon detecting an identifiable error, such as:
  - Incorrect program syntax, problematic motion paths, or a collision if the simulation software's collision-checking tool is enabled
- The identified error is corrected, and the simulation continues until the program runs without errors
- Simulation does not automatically detect all possible errors, such as incorrect work cycles, so it is the responsibility of the offline programmer to detect these errors during simulation



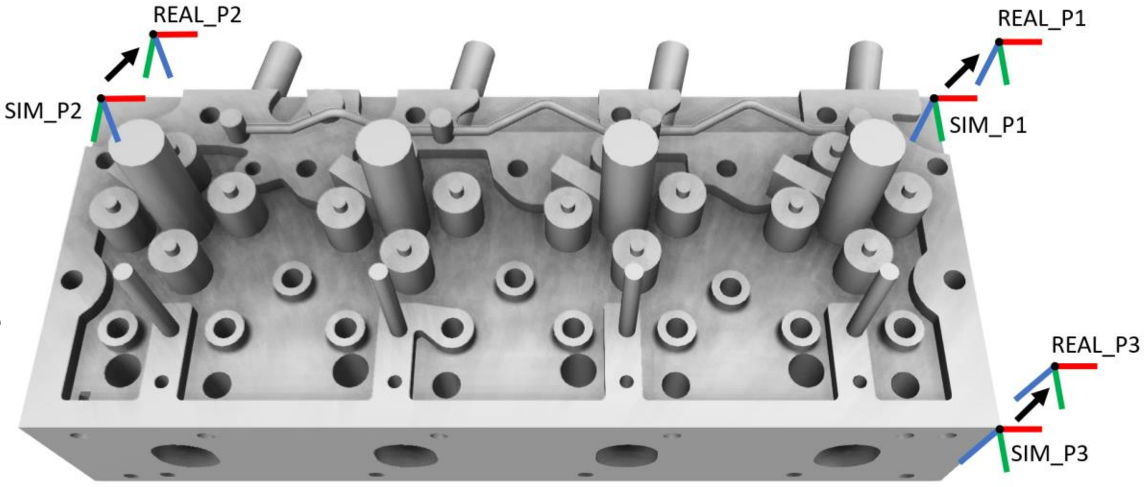
Calibration of Robot Cell

- In calibration, the simulation model of the robot cell is corrected to correspond to the actual system, because there are always differences between these two
  - For example, location and orientation of the user frames, TCPs and components
- In calibration, the actual robot cell is measured, and the measurement results are transferred to offline programming software, where discrepancies between the actual system and the simulated system are identified and compensated in the simulation model
- From the actual system, the locations and orientations of tool center points, user coordinate systems, workpieces and other critical equipment in relation to the robot are measured and determined
- Detected location and orientation errors in the positioning of devices in relation to the robot are corrected and compensated in the simulation model either manually or automatically
- Calibration is necessary for offline programmed robot program
  - Without calibration offline programmed task programme may need to undergo significant changes during commissioning in order to compensate differences between the simulated and actual systems



Calibration of Robot Cell

- Typically, robot is used as a measurement tool for the calibrations. In this case, robot’s tool center point have been precisely calibrated, for example, using the robot's own calibration methods
  - Usually, the robot’s tool center point is calibrated by moving the tool to a reference point from several different directions
  - Alternatively, separate calibration devices are used if the robot’s accuracy is insufficient for performing the calibration
- Calibrated robot tool is then used to determine the locations and orientations of other components in the robot cell relative to the robot at a few measurement points
- The measurement results are transferred to the simulation model, where the reference points of the components in the model are adjusted to match the measured actual points
  - The positions and orientations of components in the simulation model are updated to correspond to those of the real system
- Calibration is generally a one-time procedure, except for workpiece calibration, which is done for each product being manufactured
  - If the workpiece’s positioning relative to the handling device’s measured reference is unambiguous, workpiece calibration may not be necessary
- Calibration can be performed before programming if the robot cell is available or after programming if the robot cell is still in the design phase



SIM: Reference point of the simulation model
REAL: Actual measured point by the robot

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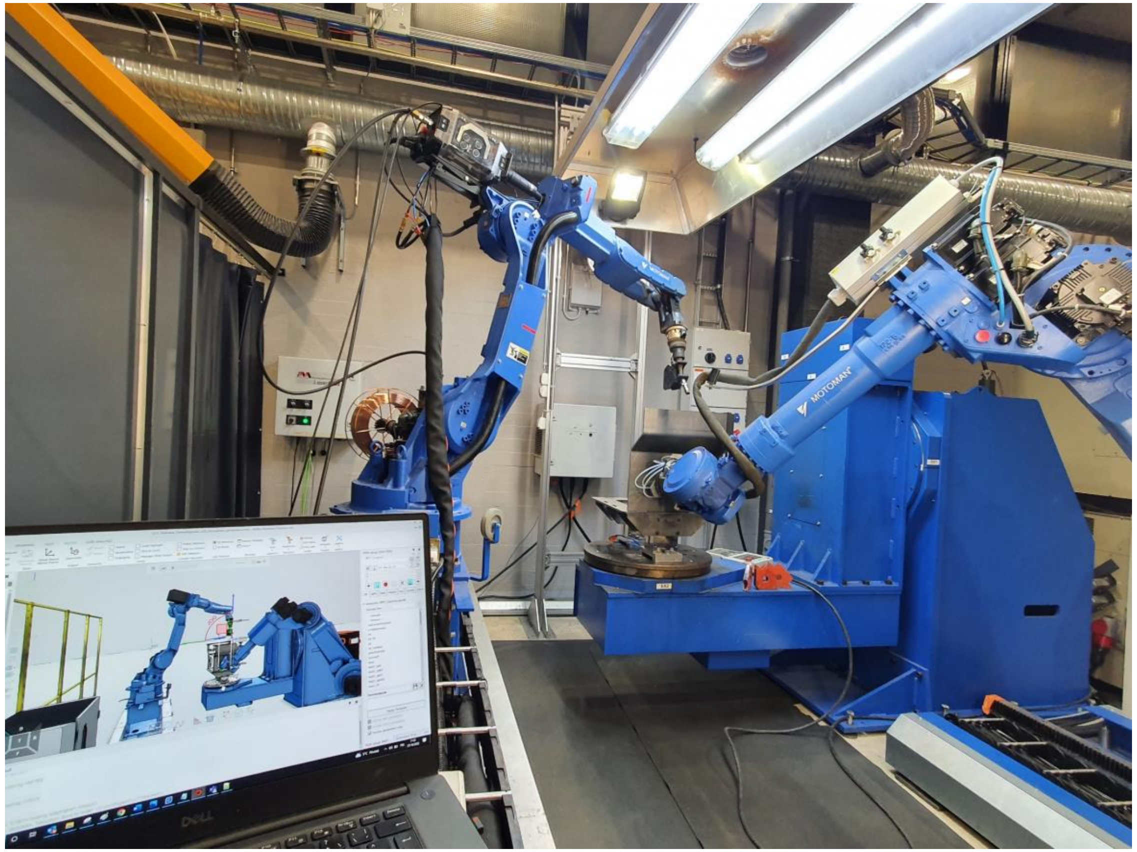
Commissioning

- In commissioning, robot cell's operation is verified and fine-tuned in the real system
  - The goal is to meet the quality and performance requirements set for the robot cell
- Commissioning is essential due to differences between the real and virtual systems, which is result from various dynamic characteristics
  - A motion command that works in offline programming software may not function as expected in the real system, especially at the robot's reach limits
  - In the real system, the robot is integrated with other devices, control systems, and interfaces that cannot always be fully simulated
- Before commissioning, offline-programmed robot program is transferred to the production robot
  - Program is translated into the robot's specific programming language if a generic programming language independent of the robot manufacturer was used in programming
- Commissioning begins with manual operation-mode and reduced speeds, testing one subprogram and command at a time
  - Speeds are gradually increased until the system can run in automatic mode and finally in production mode
  - Program's operation is fully checked in the same way as in the simulation
  - Necessary adjustments are made to the program



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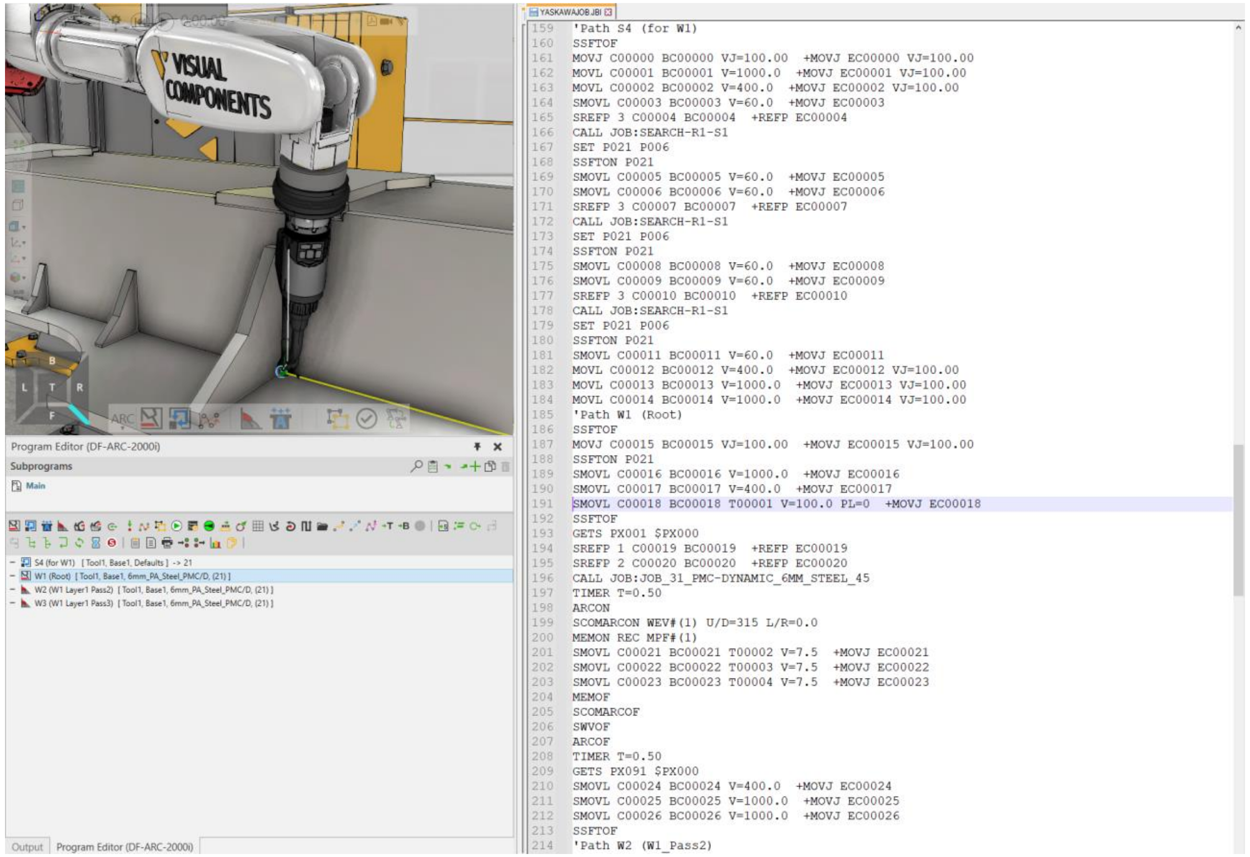
Simulation and Offline Programming Software

- In industrial robotics, software used for simulation and model-based offline programming can be divided into three categories:
  - Brand-specific simulation and offline programming software
  - Generic simulation and offline programming software
  - Add-ons for simulation and offline programming software
- There are differences as well as similarities between the features and functionalities of simulation and offline programming software
- Typically, software include tools for
  - Building simulation models
  - 3D modeling or at least importing 3D models in various file formats
  - Defining basic physics and the functional properties of simulation models
  - Model-based offline programming
  - Simulation
- Software also include component libraries, the scope of which varies by software
  - Libraries contain at least simulation models of robots



Simulation and Offline Programming Software

Brand-specific software

- Programming and simulation of robot systems from the specific robot manufacturer
  - Programming robots from other manufacturer’s isn’t possible
- Virtual equivalents of real robots and controllers
  - Exact replicas of real hardware, excluding some of the dynamic features of real systems
- Robot programs are programmed in the robot's own brand-specific programming language, which means that the programs can be directly transferred to production
  - Programming tools specific to the robot brand are used
- ABB RobotStudio, Fanuc Roboguide, KUKA.Sim and Yaskawa MotoSim

Add-ons

- The range of add-ons available for simulation and offline programming software is very wide
- More extensive programming, e.g. ROS, VR and PLC plug-ins
- Application-specific programming, e.g. welding, painting, 3D printing
- Detailed simulation of peripherals, e.g. robot dressing

Generic software

- Programming and simulation of robot systems from several different robot manufacturers
- Robot manufacturer independent controllers and programming languages
  - Programming is parametric, based on geometry and visuality
  - Programs are always translated into a robot brand-specific programming language to transfer the programs to production
  - In individual cases, robot program running in generic offline programming software may not work as specified when translated into robot brand-specific programming language
- The available programming tools do not always fully correspond to robot-specific programming tools, which means that programming may be more limited than in brand-specific software
  - For example, programmable safety features of a robot or robot brand’s integrated machine vision applications cannot usually be programmed in generic offline programming software

    → These are programmed afterwards with brand-specific software
- Delmia Robotics, RoboDK, Siemens Tecnomatix Process Simulate and Visual Components

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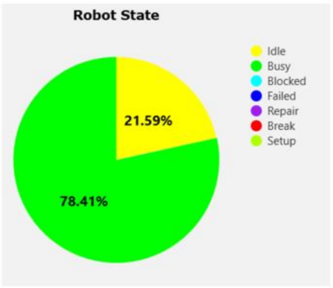
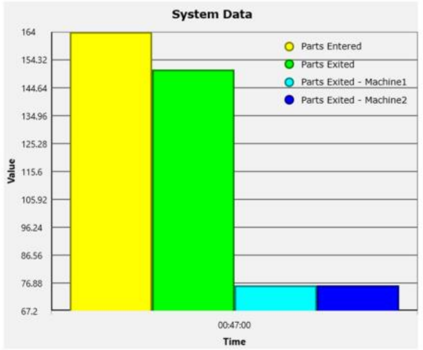
Opportunities and Constraints

- Model-based offline programming and simulation offer numerous opportunities
  - Examination of individual robot cells or larger robot systems
  - Designing and updating of both new and existing robot cells
  - Time- and location-independent programming without the real system, allowing production to continue without interruptions
  - Programming and testing of robot programs before commissioning
  - Efficient, flexible, high-quality, and partially automated programming compared to traditional programming by teaching
- Opportunities lead to
  - Iterative comparison, optimization, and testing of design and programming solutions without disrupting real system
  - Early detection of design and programming errors, making error correction typically easier, faster, and more cost-effective
  - Reduced setup, downtime, and commissioning times for real systems
  - In-depth understanding of the designed robot system's functionality, limitations, and possibilities without examining the real system
- Modeled robot systems are utilized in marketing and sales
  - The visual aspect of simulation serves as a selling point
  - Charts derived from simulations, such as robot cell’s cycle times and utilization rates, demonstrate the performance of the designed systems





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Opportunities and Constraints

- Effective utilization of model-based offline programming and simulation requires
  - Business models and design processes that support simulation and offline programming
    - Ideally, the building of simulation models and model-based offline programming are integrated into product development and system design
  - Resources for building simulation models, e.g. time, work, costs, skills
  - Integration of programming and manufacturing process expertise
    - Without manufacturing process expertise, it is impossible to program a robot to perform the required task, such as welding
- Model-based offline programming automates programming and improves programming quality, but it is the programmer's responsibility to ensure that the programmed robot program operates as intended

- Phrase *“All models are wrong, but some are useful”* applies to model-based offline programming and simulation
- Simulation models never fully match their real counterparts in terms of geometry, functionality, and dynamics
  - Virtual controllers for robots cannot fully replicate the dynamics of real systems
  - Modeled products do not take into account the manufacturing tolerances of physical products
  - The locations and orientations of workpieces and peripheral devices in simulation models do not fully match their locations and orientations in the actual production cell, despite calibration

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Applications

- Simulation and model-based offline programming are suitable for a variety of applications
  - Customer-driven production
  - Small-batch production
  - Production of short life cycle products
  - Manufacturing processes where large numbers of points are required
  - Programming for hazardous tasks
  - Education and training
  - Product, device and system design

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Applications

- Model-based offline programming is a prerequisite for robotized customer-driven production, small batch manufacturing, and the production of short lifecycle products
  - From the perspective of robot cells, this requires short commissioning and setup times to make the production of a large product variation, customer-specific products, and small production series cost-effective
  - With offline programming, robot programs are pre-programmed, minimizing production downtime and setup times when changing the product, resulting in more efficient operation than with the traditional programming by teaching
- From the perspective of manufacturing processes, model-based offline programming is suitable for programming robotic applications that require many target points from the robot
  - E.g., welding, laser cutting, deburring, polishing, grinding, painting, and coating
  - Model-based offline programming enables rapid and efficient creation of motion paths based on geometric features, resulting in high-quality products
- Offline programming is essential for programming tasks that could pose safety risks to operators
  - E.g., casting, and large welding systems
- Using simulation and offline programming training of new robot cell operators and robot programmers is conducted in a safe environment before moving into production
- Model-based offline programming and simulation support product and system design

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Simulation as Support for Design

Production system level

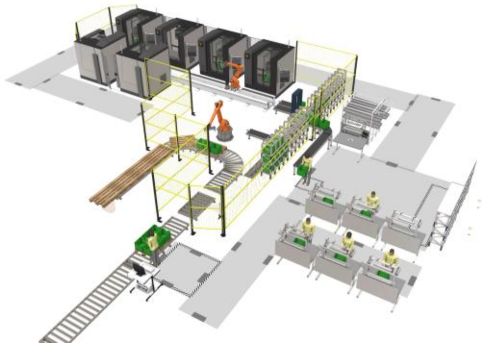
- Focus is on achieving key performance indicators set for production, such as production volumes, lead and takt times, and utilization rates of production resources
- Investigating what kind of production resources, production system structures and production solutions are needed to achieve set goals
- Robots are simulated at a coarse level, and detailed programs for robots may not be necessary

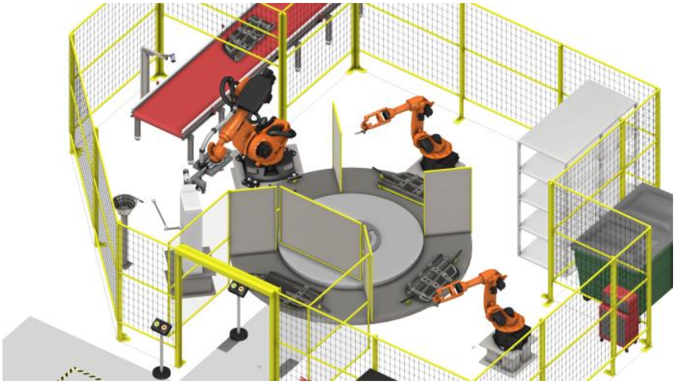
Production cell level

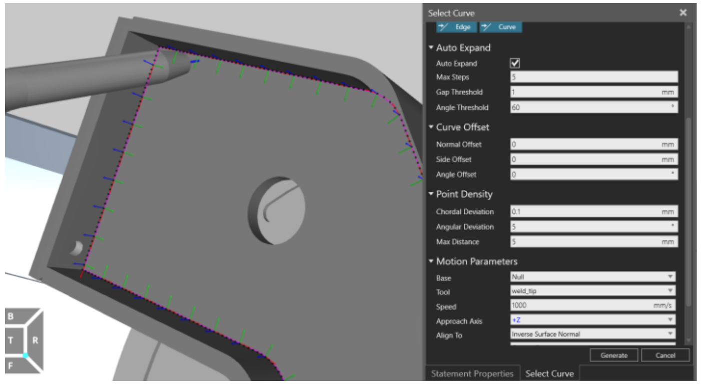
- Focus is on the technical implementation of a robot cell
- Design, analysis and optimization of the production cell, from the product to be manufactured to the robot itself, taking into account the integration to peripheral devices
- Robots are offline programmed, which takes into account 3D CAD data and the robot's connections to other devices and systems in the robot cell

Manufacturing process level

- Focus is on developing manufacturing processes and identifying and optimizing suitable manufacturing parameters
- Analyzing the effects of robot trajectories and process parameters, for example in welding applications
- Robots are offline programmed which take into account 3D CAD data and manufacturing method data







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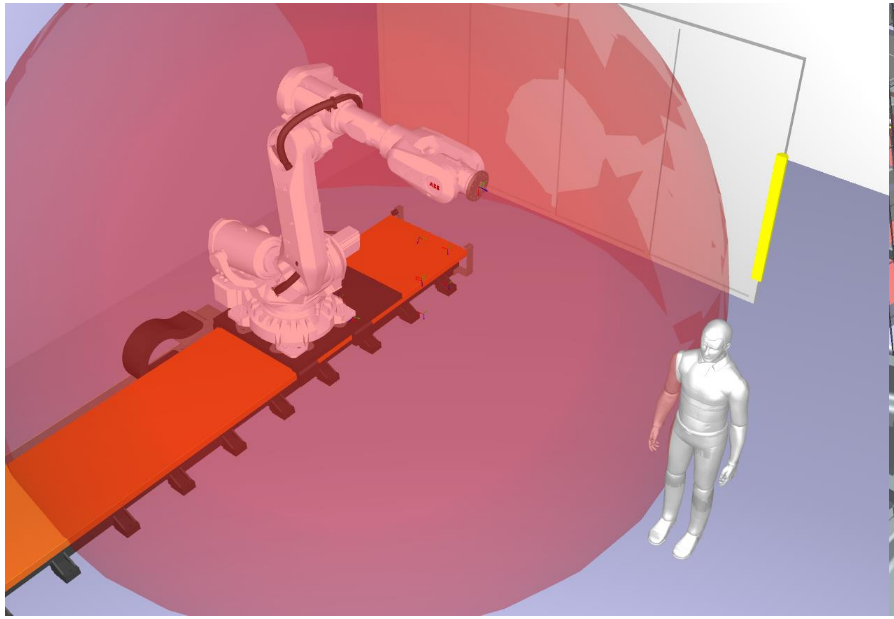
Simulation as Support for Design

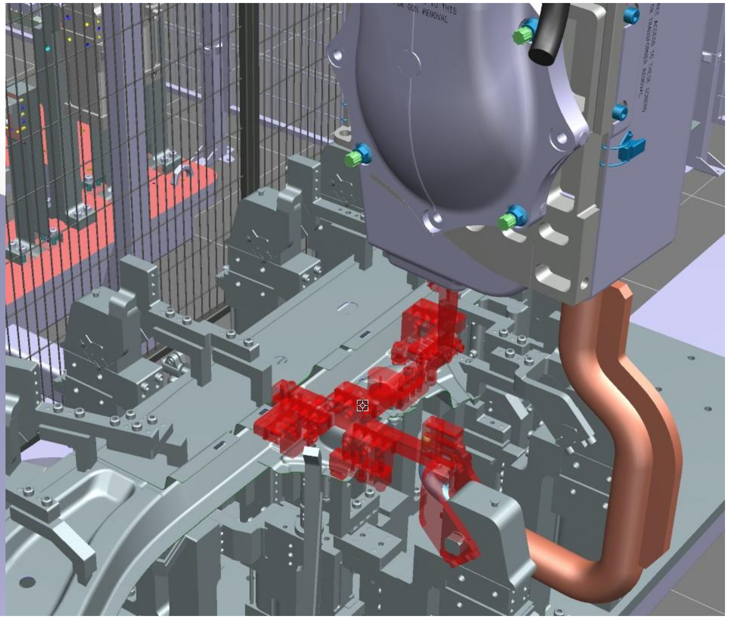
Layout Design

- Designing and visualizing layouts
- Comparing and evaluating different layout configurations
  → By adjusting the positions of robots and substituting components, various layout options can be quickly and efficiently visualized
- Conducting reach analysis and collision detection
  → Placement of the necessary components within the reach of the robot without collisions

Product and Device Design

- Assessing the manufacturability of the product
  → Is the product suitable for robotized manufacturing?
- Developing robot tools, fixtures, feeders and other peripherals
  → Are the designed tools and fixtures etc. suitable for robotized part handling?
- Early detection and correction of errors without expensive physical prototypes





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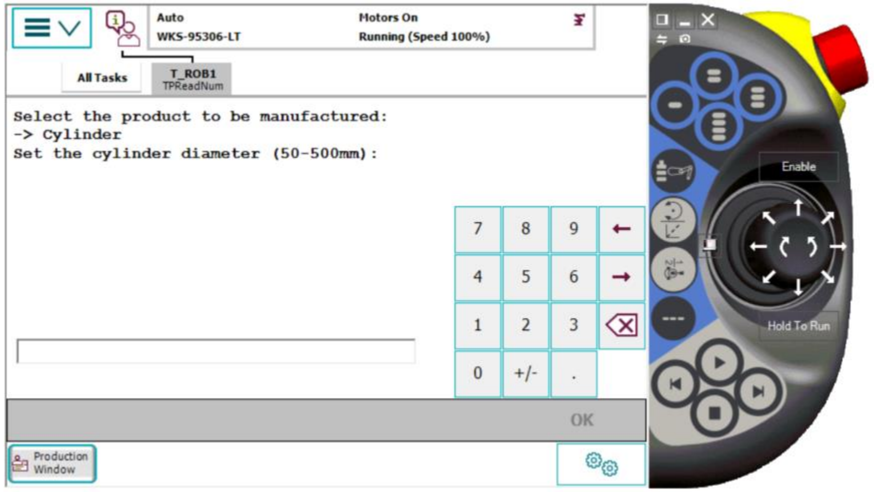
Simulation as Support for Design

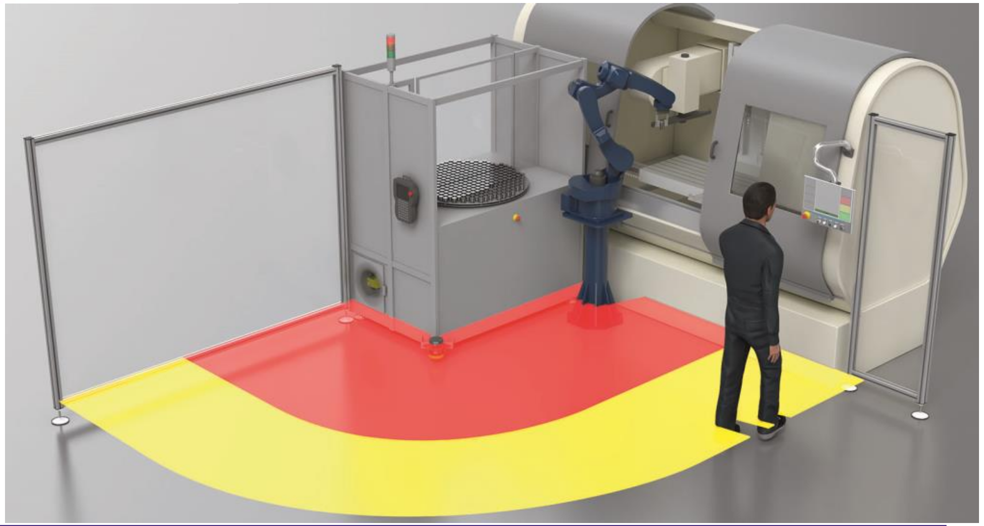
Control System and Human-Machine Interface Design

- Design and programming of communication between robot and peripherals with simulated I/O's
- Design and testing of robot cell control
  → Virtual commissioning
- Robot and production cell user interface design and simulation

Safety System Design

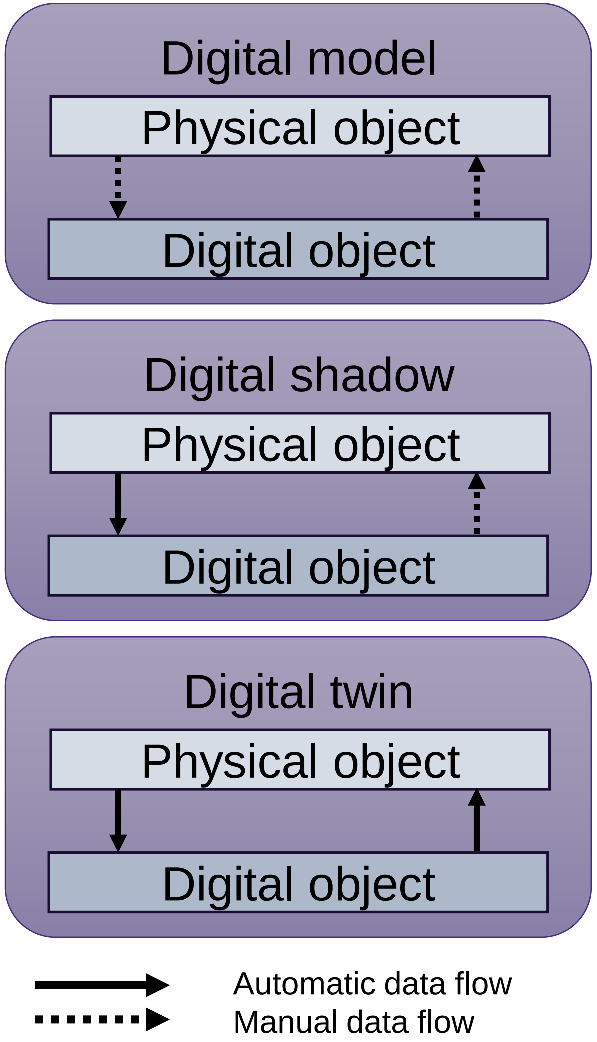
- Risk assessment of robot cells
- Selection, evaluation and testing of safety devices such as safety fences and light curtains
- Programming and configuring robot safety features, e.g. ABB SafeMove
- Design and simulation of human-robot collaboration





Digital Manufacturing

- Digital Manufacturing
  - Digital Manufacturing refers to the use of digital technologies and software to improve production processes
- Digital Model
  - Digital Model is a virtual representation of a physical object without automatic real-time data transfer between the physical and digital objects
- Digital Shadow
  - Digital Shadow is a combination of digital and physical systems with automated, real-time data transfer in one direction, while data transfer in the other direction is manual and delayed
- Digital Twin
  - Digital twin is a combination of digital and physical systems based on automated, real-time, two-way communication



Source: Kritzinger et al., 2018

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Digital Twins in Industrial Robotics

- In industrial robotics, simulation models are often classified as digital twins, which is not the case in most cases
  - Simulation models are mainly digital models without real-time automated data transfer
- Simulation models do not usually benefit from real-time data
  - The digital twin can utilize sensor data from a real system, learn from the data and generate suggestions for improving the system or process
  - The collected data can be used, for example, to develop robot programming
- Digital twins and shadows can be used for real-time monitoring of robot cells
  - Remote control of robots based on digital twins is currently being researched

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Virtual Commissioning

- Virtual commissioning refers to testing a virtual or real control system with a virtual model of a machine or production cell before the system is commissioned at the factory floor
- Virtual commissioning is used for the simultaneous development and testing of
  - Logic control of the robot cell and
  - Robot programs
- With virtual commissioning
  - Commissioning of the robot system can be started before the physical system is even assembled
    - Reduces the costs of the “real” commissioning and shortens the commissioning times for the real system
  - Errors are detected at early stage, making them easier, cheaper and faster to correct
  - Commissioning is also safer in a virtual environment
- Virtual commissioning requires resources to build needed simulation models
- Virtual commissioning does not replace traditional commissioning
  - Real system needs to be calibrated, and the robot’s offline programmed task programs tested and optimized with the real system

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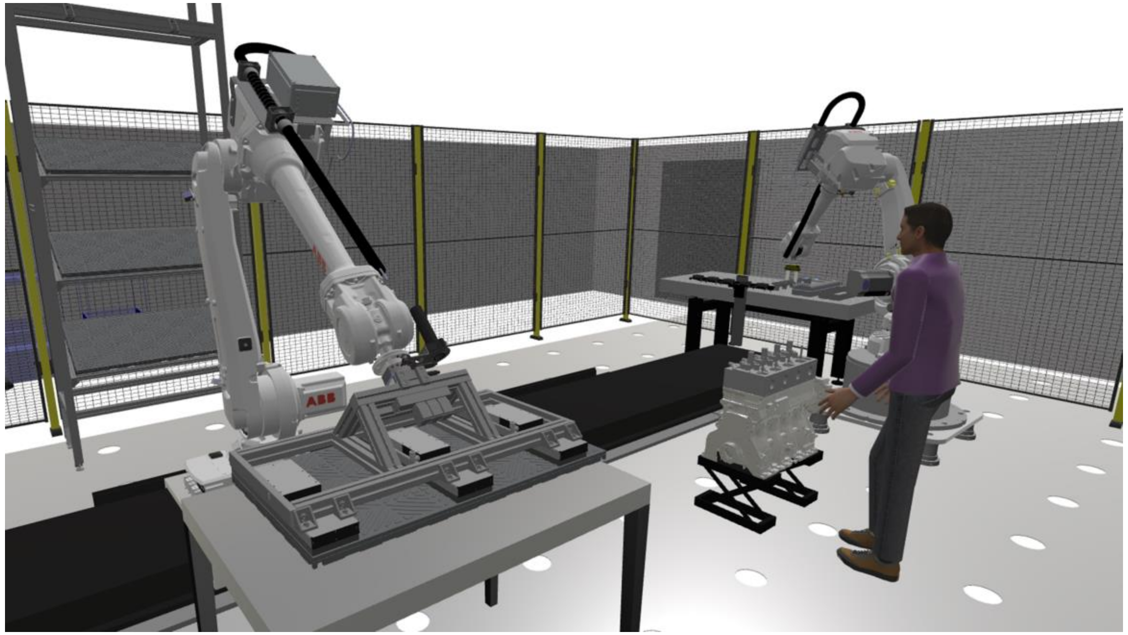
Virtual Reality in Industrial Robotics

- Virtual reality (VR) refers to a simulated, artificial, interactive environment that is mainly presented to the user by means of various display devices, such as VR headsets, and interactive control devices, such as hand controllers
- User actively interacts with the simulated environment, generating a sense of artificial presence and immersion
- In industrial robotics, virtual reality is used to review, verify and validate robot cells and robot programs
- Virtual reality helps to perceive the dimensions of the robot cell and the distances between individual components, as well as the actual trajectories and speeds of the robot already during design phase
- In marketing and customer meetings, virtual reality offers a visual and interactive way to convince customers of the benefits of the designed solution



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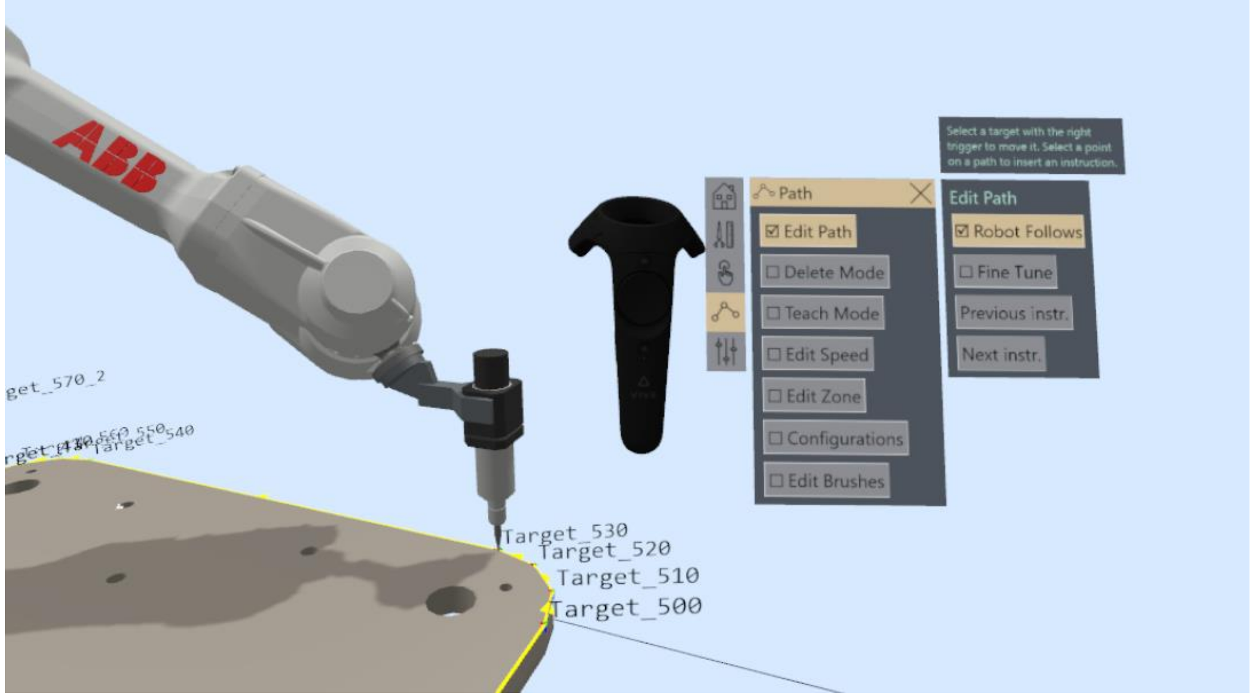
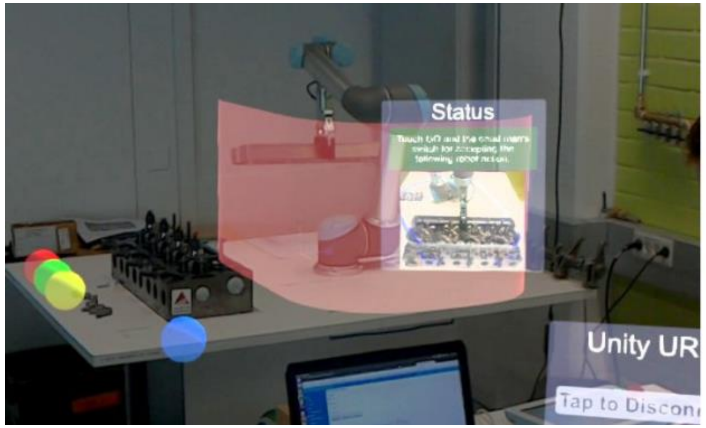
Virtual Reality in Industrial Robotics

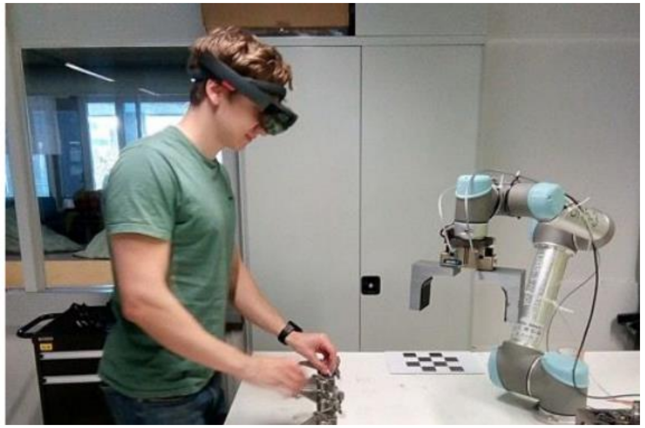
- Virtual reality is suitable for offline programming, in which case programming can be based on guiding
  - This method is useful, for example, for programming robot tasks that require repetition of human hand movements
- Virtual reality is used to train operators for robot systems
  - Interactive user and safety trainings in virtual environments allows operators to learn process tasks and safe principles for working with robots before moving into production
- In the future, virtual reality can also be used to control robots remotely, when a real robot is combined with its virtual counterpart



Augmented Reality in Industrial Robotics

- Augmented reality (AR) refers to computer-generated information — such as images, videos, instructions, and 3D models — displayed in the real environment using devices like AR headsets, smartphones, or tablets
- In practice, users view the environment through a device, such as a tablet, which overlays digital content (e.g., simulation models of robot cells or instructions for safety and user training) onto a real robot cell
- Like virtual reality, AR is useful for design and customer reviews, user and safety trainings, and offline programming of robots, although offline programming is still largely in the research phase





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