
Development and deployment of forced controlled (sensitive) robot applications

Robotix-Academy Roadshow 2020

Marco Schneider, M.Sc.

ZeMA

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Agenda

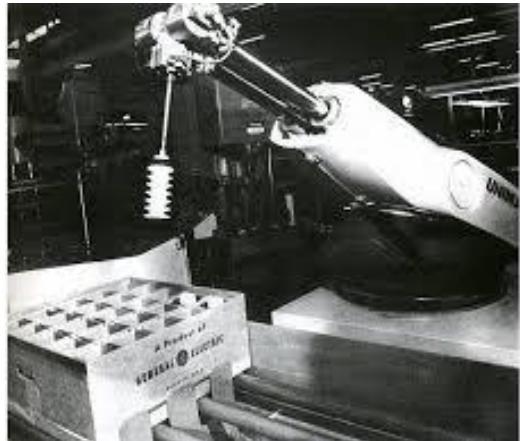
- 1 Introduction and State of the art
- 2 Fundamentals of robotics - control strategies
- 3 Development of a solution approach
- 4 Validation of the solution approach
- 5 Conclusion
- 6 Literature

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Introduction

First industry robot 1954



Conventional robots +
external sensors 1979



Sensitive robots 2013



source: [21], [81], [82], [83], [84]

Definition sensitivity



- DIN 1319: Change of the value of the output variable of a measuring device in relation to the causal change of the value of the input variable
 - Input variable: torque or force
 - Output variable: drive torque (electrical voltage or current)

- In the context of robotics:
 - A robot that does not run its program purely position-controlled, but allows a defined compliance
 - This allows the robot to react in real time to the feedback from a force sensor and thus deviate from its programmed path and speed

source: [17], [18], [19], [21]

Market analysis sensitive robots

KUKA LBR iiwa
14 R820



Rethink
Sawyer



IRB 14000
YuMi



Fanuc CR-35iA



KUKA LBR iiy



DENSO
COBOTTA



2012

2013

2017

2018



UR 10

Rethink Baxter



Yaskawa
MOTOMAN HC 10



UR 10 (e)

Franka Emika
Panda

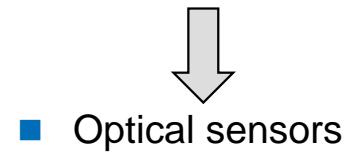
Doosan Robotics
M1013

source: [21], [22], [23], [24], [25], [26], [27]

Market analysis sensitive robots

Overview of the operating principles I

Robot Force/ Torque- recording	KUKA LBR iiwa	Universal Robots UR 10 (e)	Yaskawa MOTOMA N HC10	Franka Emika Panda	Fanuc CR Serie Fanuc CR- 35iA	Denso Robotics Cobotta	Doosan Robotics M1013
At the flange		✓					
In the joints	✓		✓	✓		✓	✓
In the base					✓		



- Force/torque measurement via strain gauges

source: [21], [22], [23], [24], [25], [26], [27]

Market analysis sensitive robots

Overview of the operating principles II

Robot compensating element	Rethink Robots Sawyer (passive)	4 by 3 (Passiv)	Active contact flange from FerRobotics Compliant Robot Technology GmbH
At the flange			✓
In the joints	✓	✓	



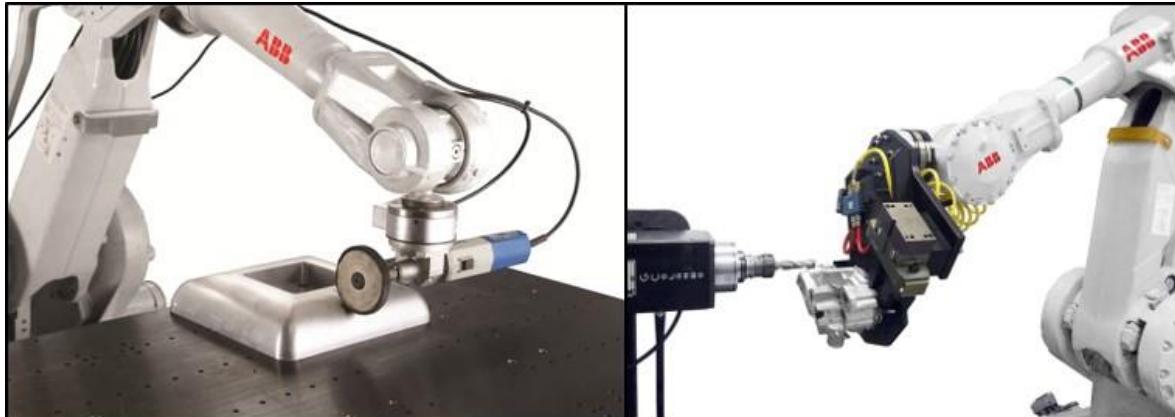
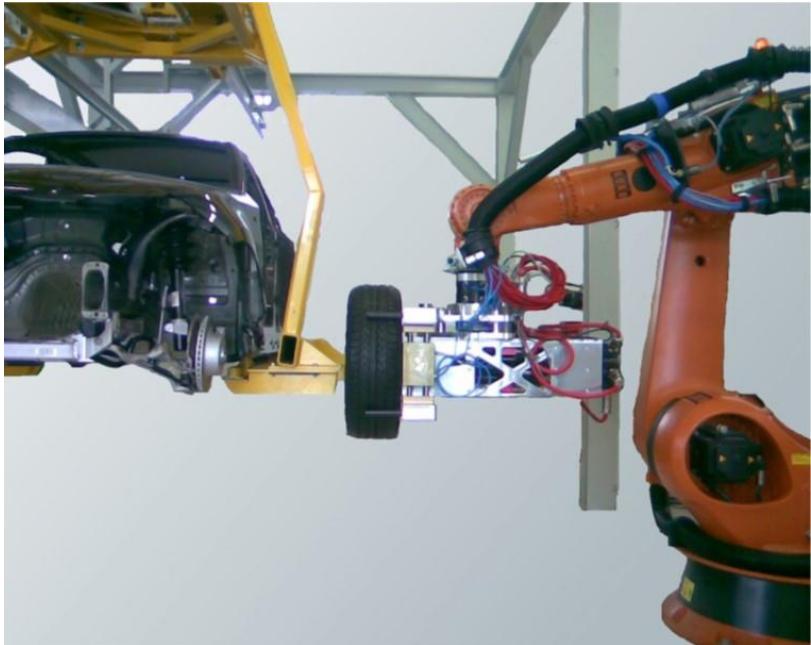
- Spring elements



source: [35]

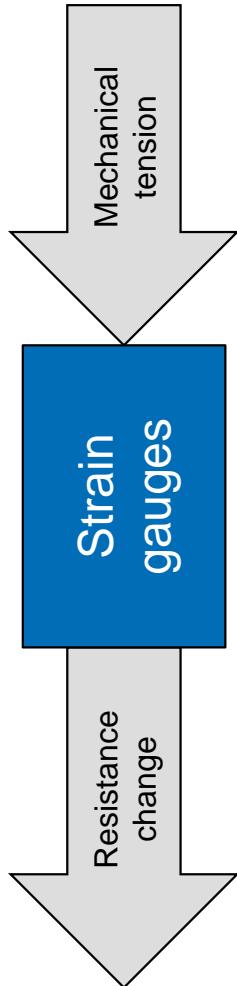
Application examples of sensitive robot applications

- Assembly and machining tasks



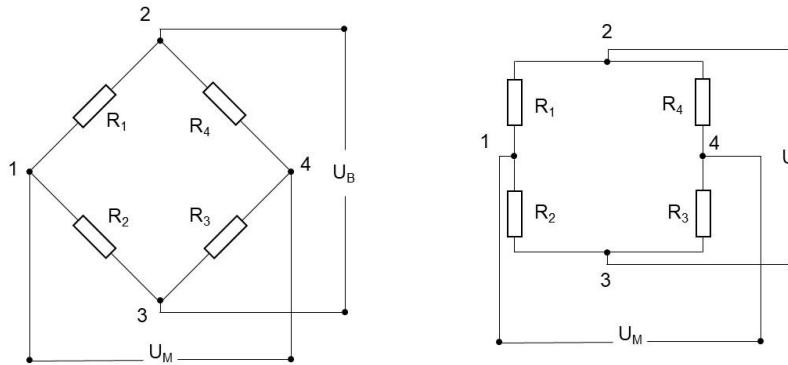
source: [29], [30], [35]

Torque and force determination based on DMS (strain gauges)



- Widely used technology for the determination of mechanical measurement parameters
- Metrologically attractive: electrical signal

→ Wheatstone bridge circuit



$R_1 \dots R_4$: Resistors in the bridge branches 1...4

U_B : Bridge supply voltage

U_M : Bridge output voltage (measurement voltage)

2 and 3: Connection points of the bridge supply voltage

1 and 4: Connection points for bridge output voltage

source: [36]

KUKA LBR iiwa

- Serial kinematics
- 7-DoF robot → redundancy
- Integrated torque sensors in each axis

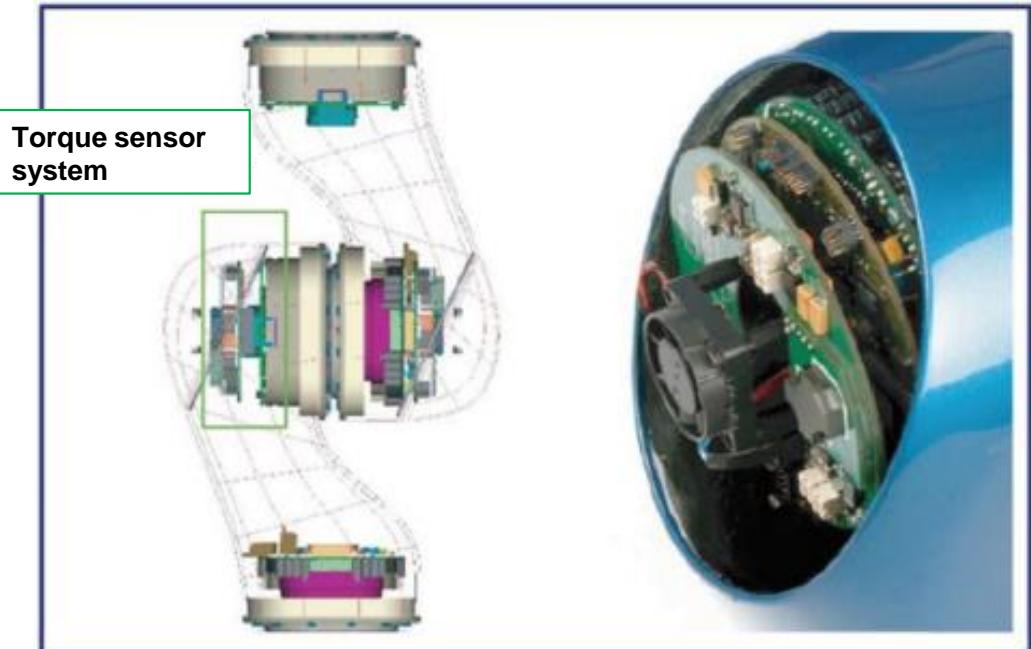
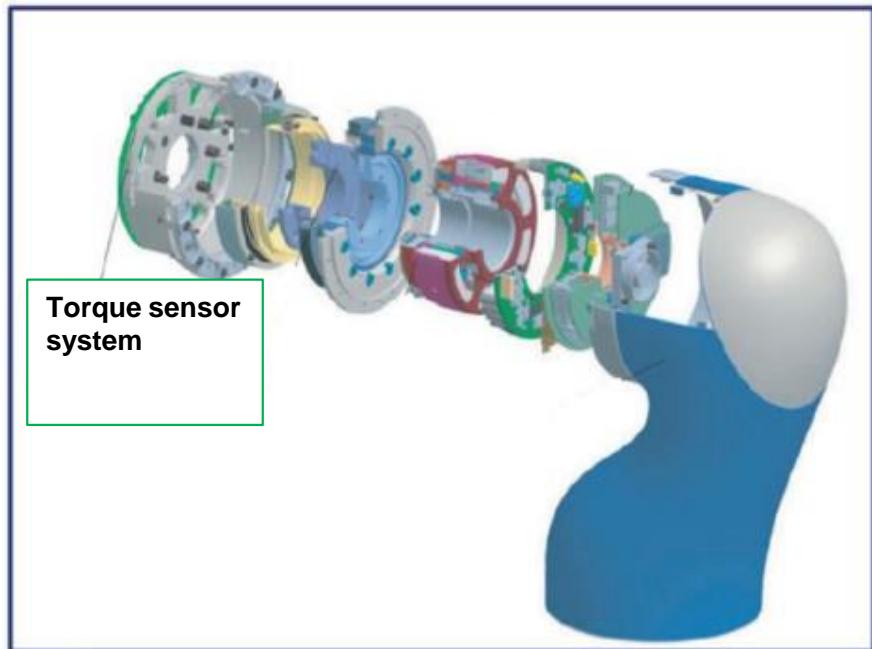


Property	Robot KUKA LBR iiwa
Number of axes	7
Payload [kg]	14
Own weight [kg]	29,9
repeat accuracy [mm]	± 0,15
Range [mm]	820
Sensitivity	integrated torque sensors in each axis

source: [14], [21]

KUKA LBR iiwa - Torque sensor system

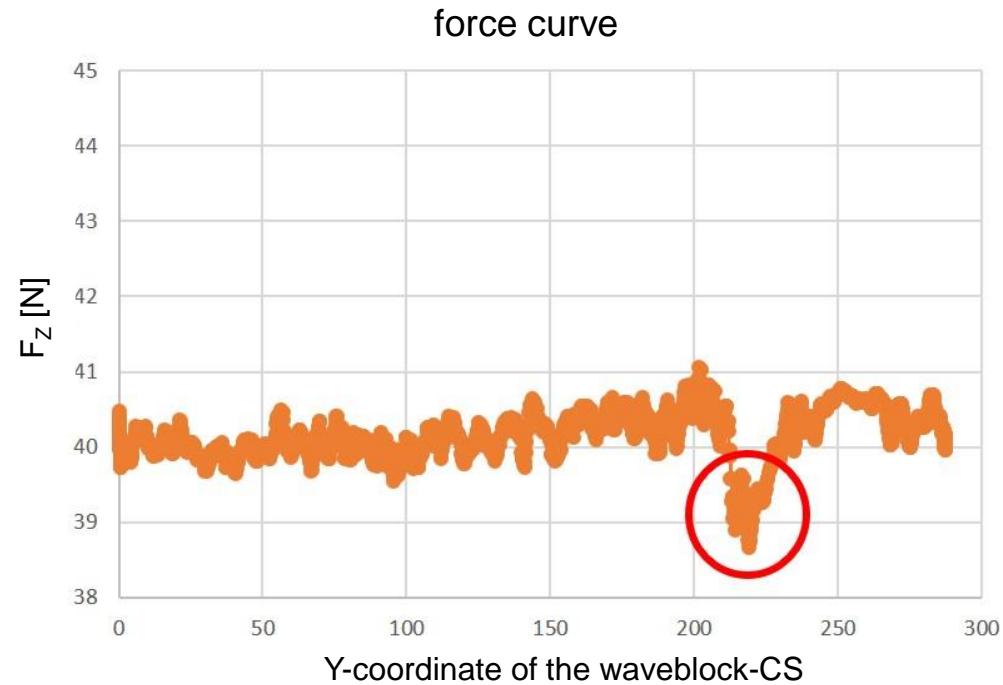
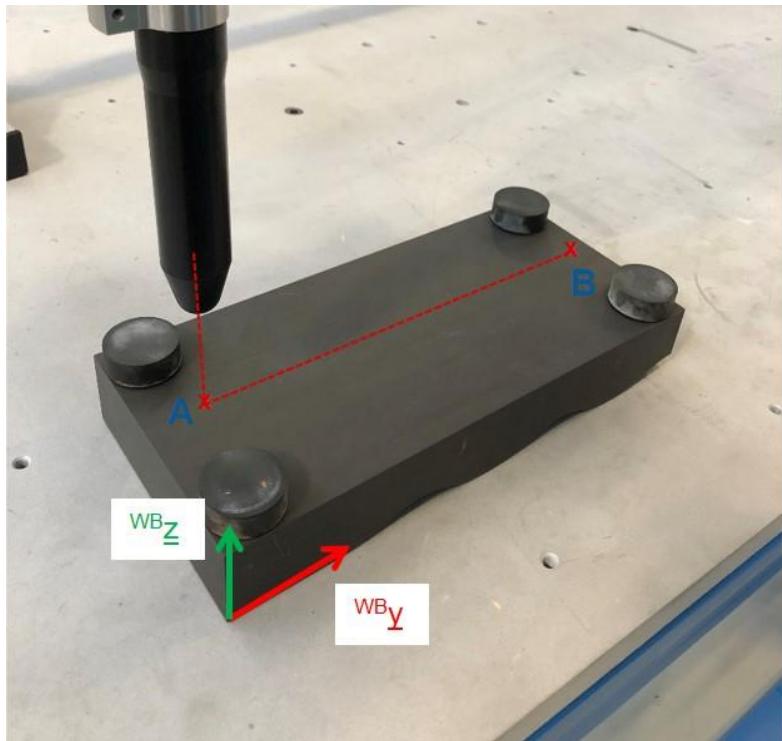
- Torque sensor system equipped in each axis



source: [14], [21]

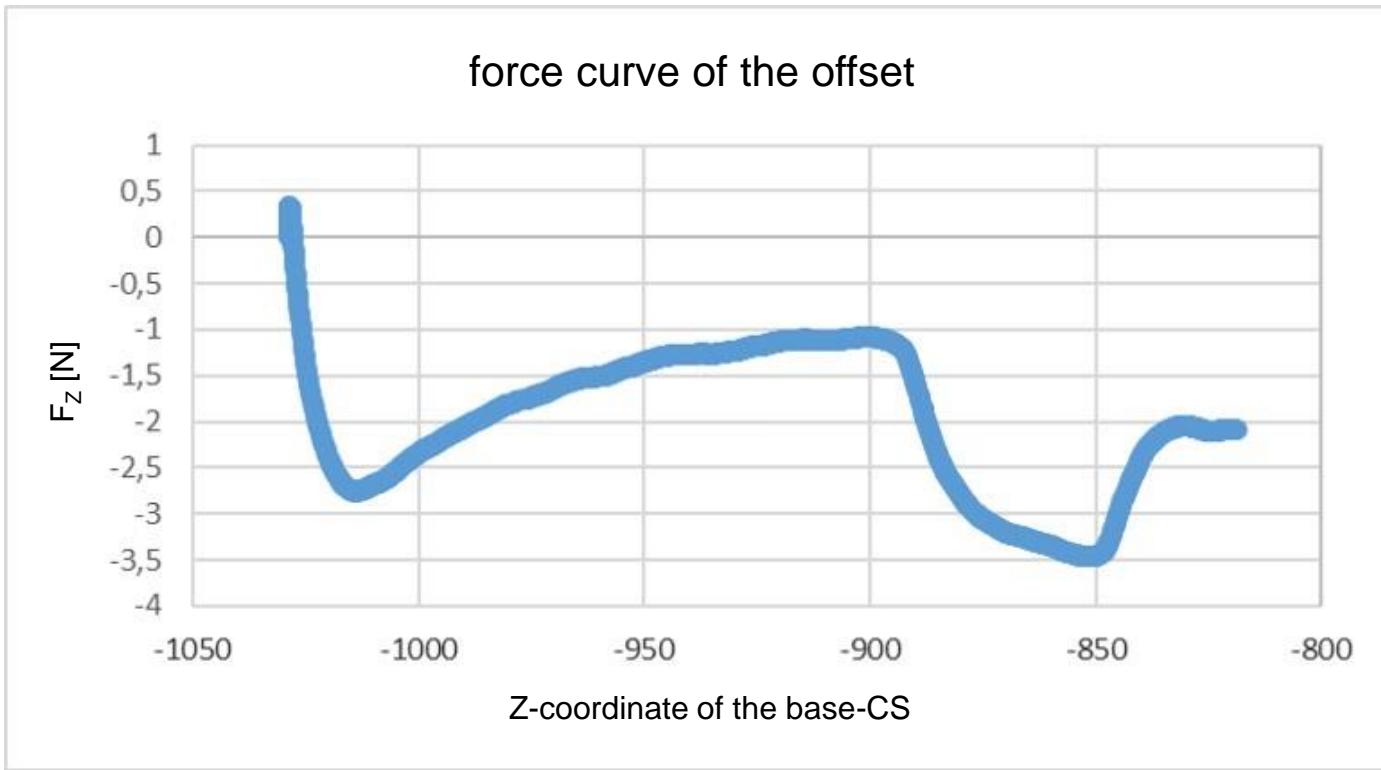
Problem definition and motivation I

- force controlled applications offer a high application potential in industrial environments
- Goal: Increase the accuracy of the forces applied by the robot



Problem definition and motivation II

- In the unstressed state, the external forces and torques of the Kuka LBR iiwa are unequal to 0
- Goal: Compensation of inaccuracies



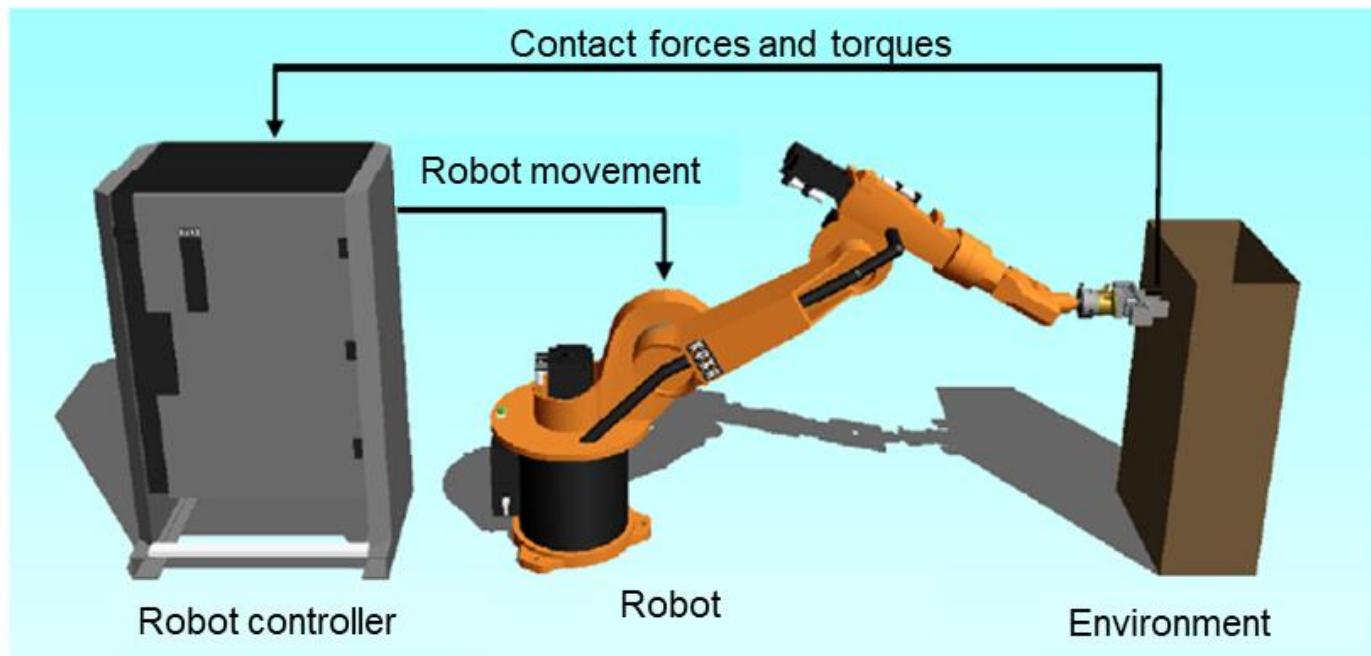
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Control strategies of robots with open kinematic chain

■ Most important control strategies:

1. Position control
2. Impedance control
3. Force and torque control



source: [13], [51], [61], [63], [64], [67]

Dynamic model of a robot

$$\underline{\tau} = \underline{M}(\underline{q}) \ddot{\underline{q}} + \underline{C}(\underline{q}, \dot{\underline{q}}) \dot{\underline{q}} + \underline{G}(\underline{q}) + \underline{J}^T \underline{F}$$

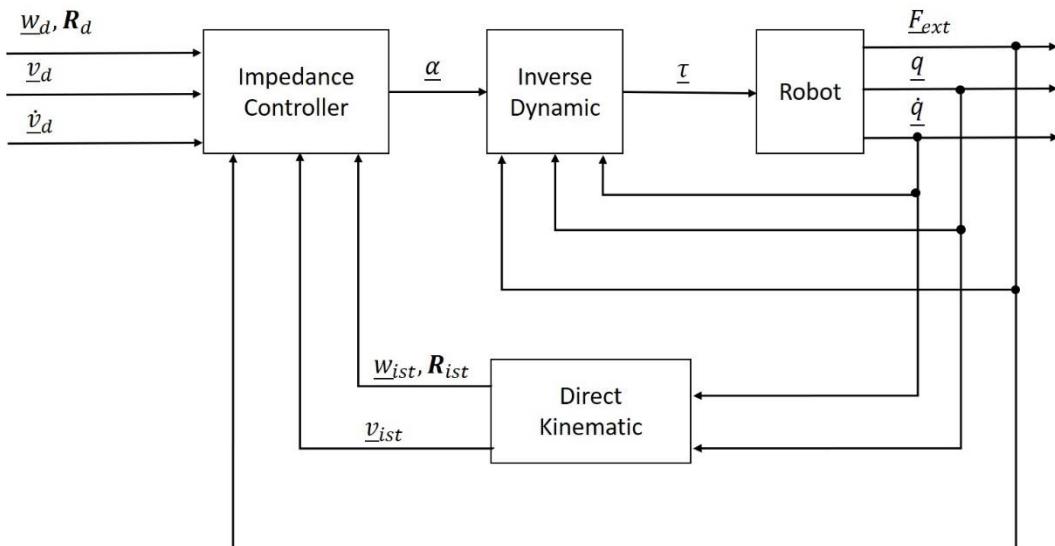
- Non-linear coupled equation of motion
- Parameters:
 - $\underline{\tau}$: Vector of the torques generated at the joint by the drive
 - \underline{M} : Mass inertia matrix
 - \underline{C} : Matrix of Coriolis and centrifugal moments
 - \underline{G} : torques caused by gravity (weight moments)
 - \underline{J} : Jacobi-Matrix
 - \underline{F} : Vector of the Cartesian forces and moments acting on the end effector
 - \underline{q} : Vector of the joint angles
 - $\dot{\underline{q}}$: Vector of the joint velocities
 - $\ddot{\underline{q}}$: Vector of the joint accelerations

source: [61], [64]

Impedance control

■ Impedance control (= indirect force control)

- The underlying model is a virtual spring Damping system with adjustable values for stiffness and damping



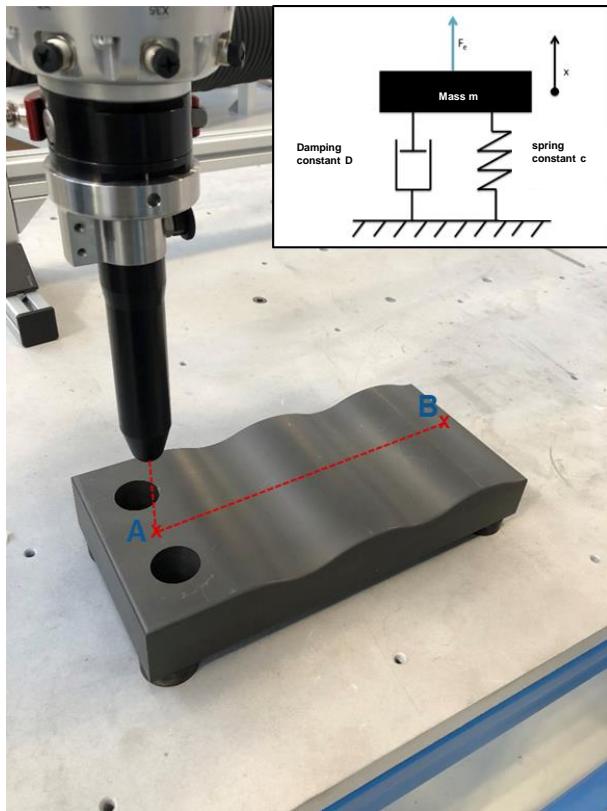
$$\blacksquare M_m(\ddot{\underline{x}} - \ddot{\underline{x}}_d) + D_m(\dot{\underline{x}} - \dot{\underline{x}}_d) + K_m(\underline{x} - \underline{x}_d) = F_{ext}$$

source: [51]

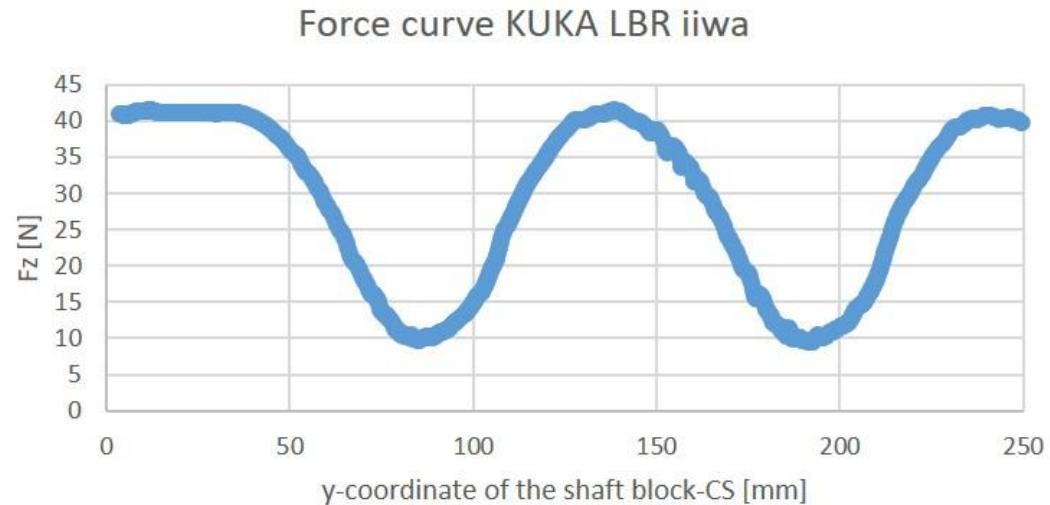
■ Parameters:

- \underline{w}_d : desired position of the end effector
- R_d : Rotation matrix with respect to base KS
- \underline{v}_d : desired velocity of the end effector
- $\dot{\underline{v}}_d$: desired acceleration of the end effector
- $\underline{\alpha}$: acceleration in cartesian space
- $\underline{\tau}$: Vector of the drive-torques
- F_{ext} : Vector of the external forces and torques
- \underline{q} : Vector of the joint angles
- $\dot{\underline{q}}$: Vector of the joint velocities
- \underline{w}_{ist} : current position of the end effector
- R_{ist} : Rotation matrix with respect to base KS
- \underline{v}_{ist} : end effector velocity
$$\underline{v}_{ist} = (\dot{\underline{w}}_{ist}^T \ \omega_{ist}^T)^T$$

Impedance control I



- In order to emphasize the importance of the impedance controller of the KUKA LBR iiwa and especially the parameterization, only the impedance-specific parameters stiffness and damping were varied.
- As the figure clearly shows, a force-controlled assembly task is only possible under certain conditions, namely the correct parameter identification of stiffness and damping constants

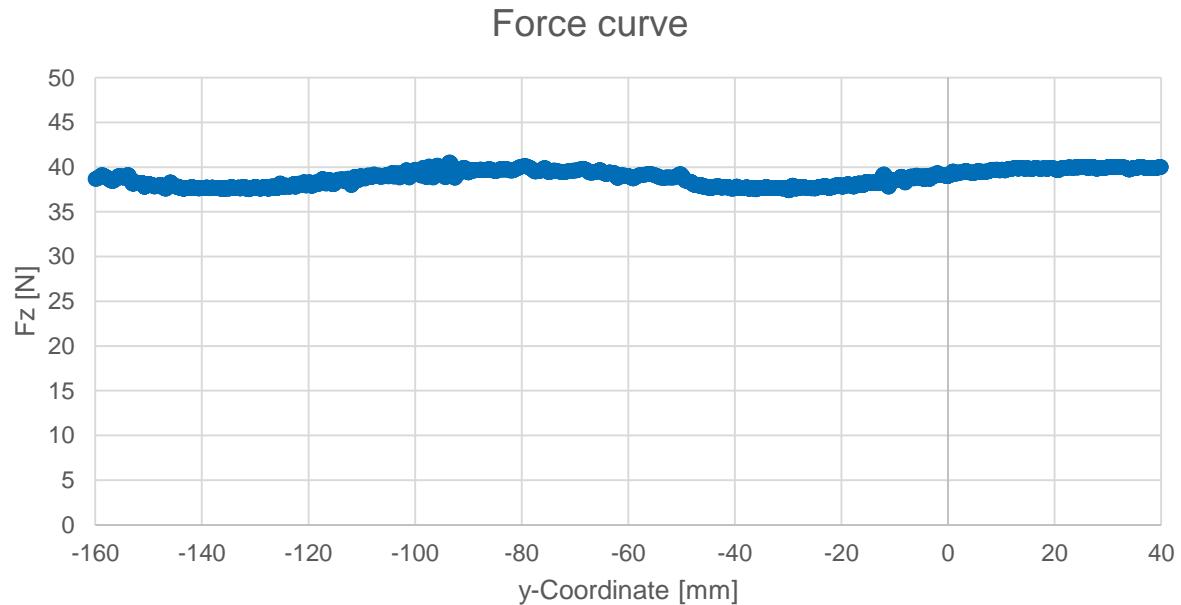
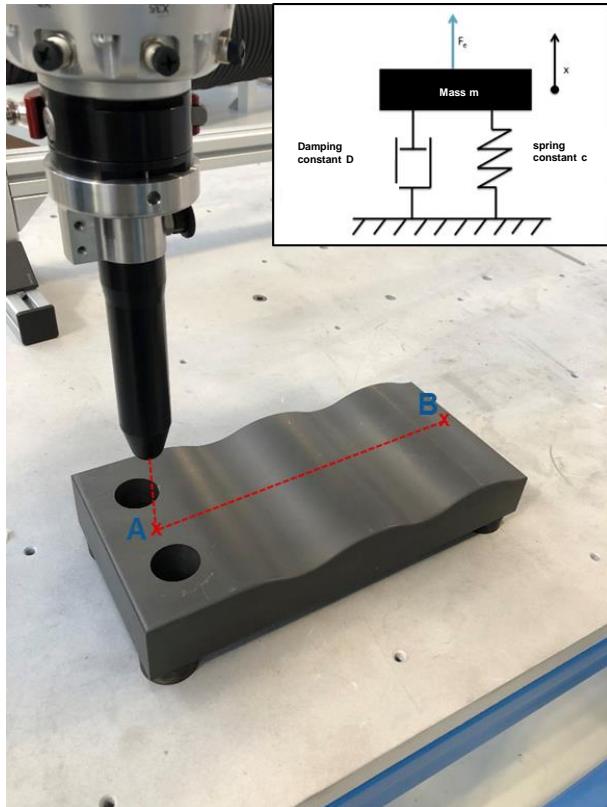




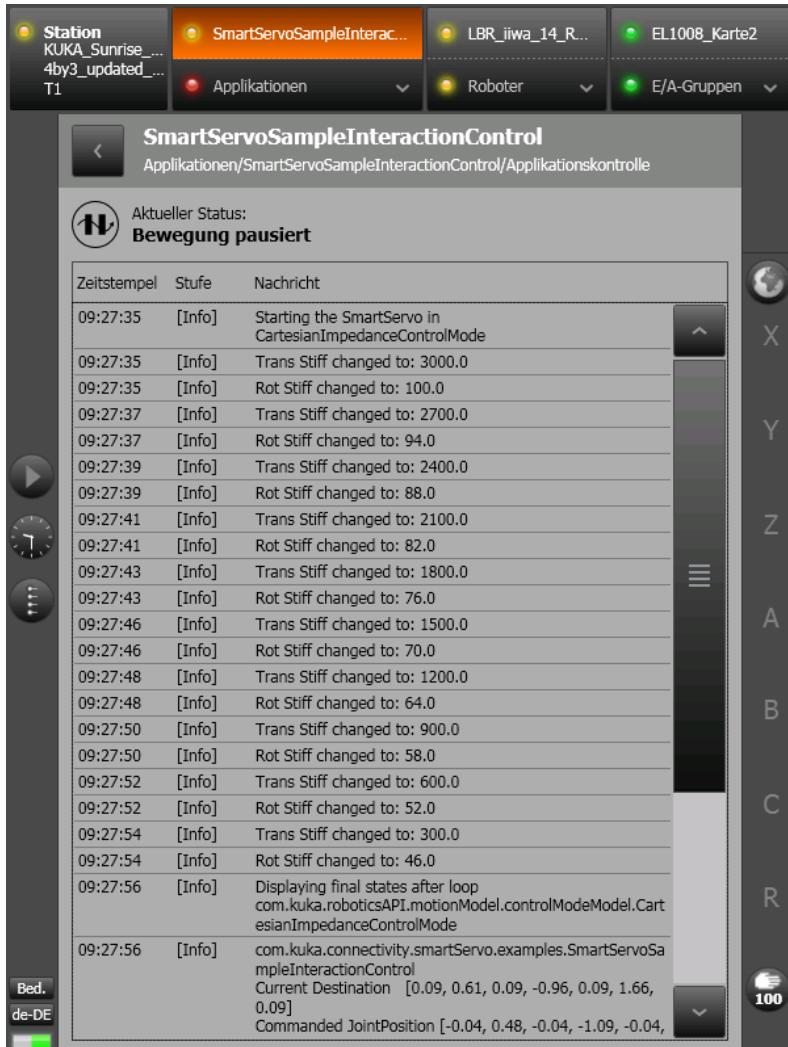
Impedance control II

- Adjust the Stiffness parameter to $200 \frac{N}{m}$

→ Improvement of the force guided movement



Impedance control III

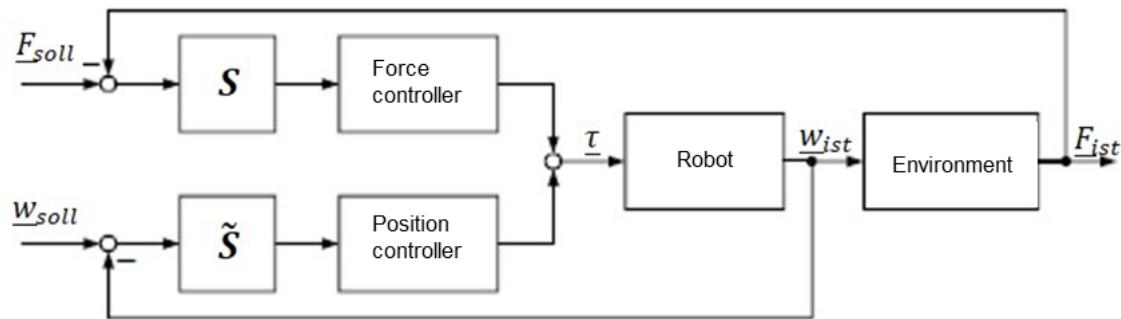


- Possible to change e.g. Stiffness parameter while movement
 - without stop of the movement
- Division into translatory and rotatory stiffness
- Selection of individual degrees of freedom X, Y, Z, A, B, C → comparable elements of a pose in space



Hybrid force/ position control I

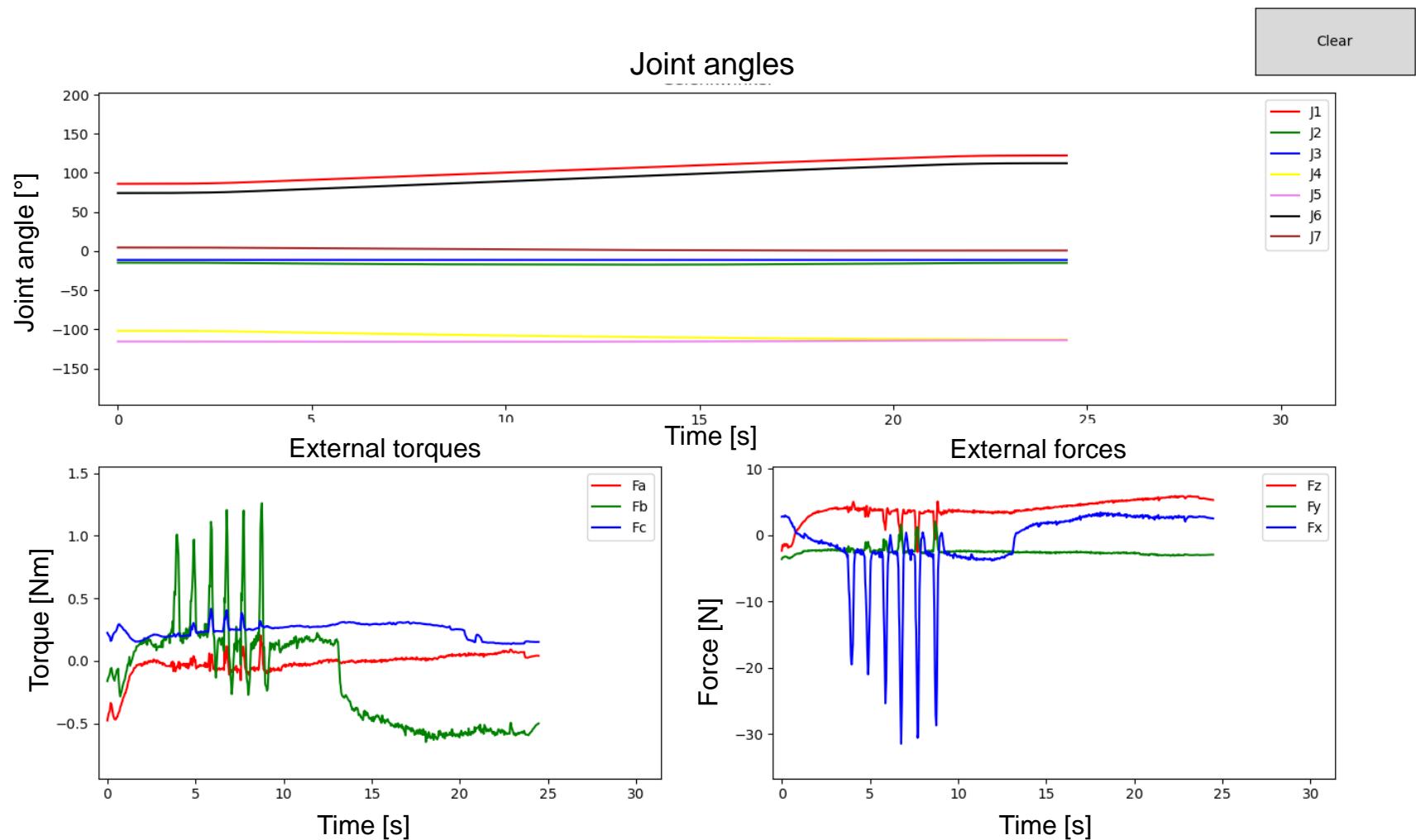
- Hybrid force and position control
- Determination of the translational and rotational degrees of freedom, which are either position or force controlled (task dependent)



- Parameters:
 - S = Selection matrix of the force-torque controlled degrees of freedom
 - \tilde{S} = Selection matrix of the position controlled degrees of freedom
 - τ = correcting variable vector
 - w = position vector
 - F = force vector

source: [13], [51], [63], [64], [67]

Hybrid force/ position control II



Hybrid force/ position control III

- Already integrated in KUKA Sunrise

CartesianSineImpedanceControlMode

```
com.kuka.roboticsAPI.motionModel.controlModeModel.CartesianSineImpedanceControlMode.createDesiredForce(CartDOF degreeOfFreedom,  
double force, double stiffness)
```

createDesiredForce

```
public static CartesianSineImpedanceControlMode createDesiredForce(CartDOF degreeOfFreedom,  
double force,  
double stiffness)
```

Creates a new CartesianSineImpedanceControlMode with a desired force. The desired force can be set for each dimension (X,Y,Z in N, A,B,C Nm).

To achieve a constant force, the amplitude, frequency and phase are set to zero, the bias is set to the given values.

Parameters:

- `degreeOfFreedom` - The degree(s) of freedom for performing the desired force.
- `force` - The value of the desired force. For X,Y,Z in [N] and A,B,C in [Nm]
- `stiffness` - The value of the stiffness. CartDOF X,Y,Z [N/m] / A,B,C [Nm/rad]

Returns:

`CartesianSineImpedanceConotrolMode`

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 3.3 Design of an offset in a dynamic environment

 3.4 Optimization of the configuration along a defined path

 3.5 Graphical User Interface (GUI)

4 Validation of the solution approach

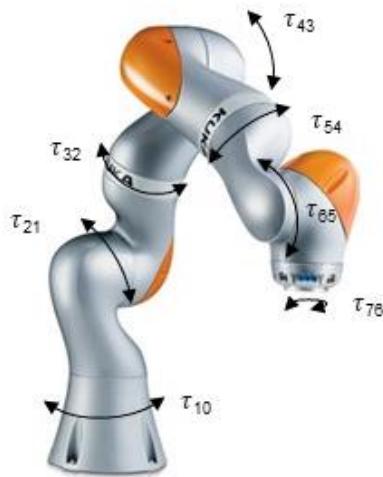
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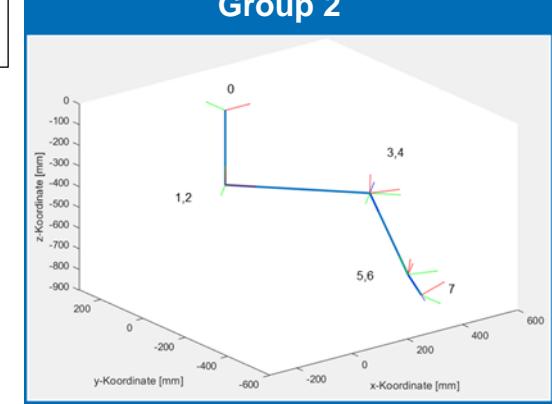
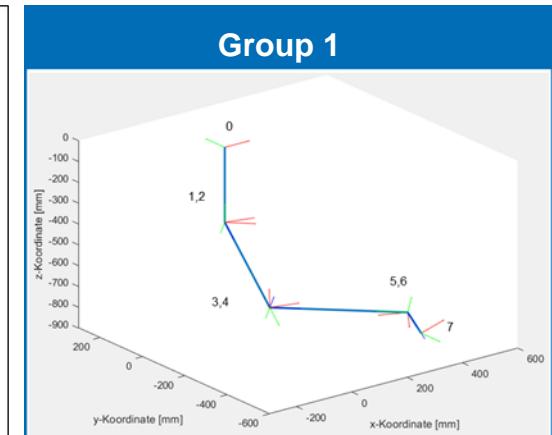
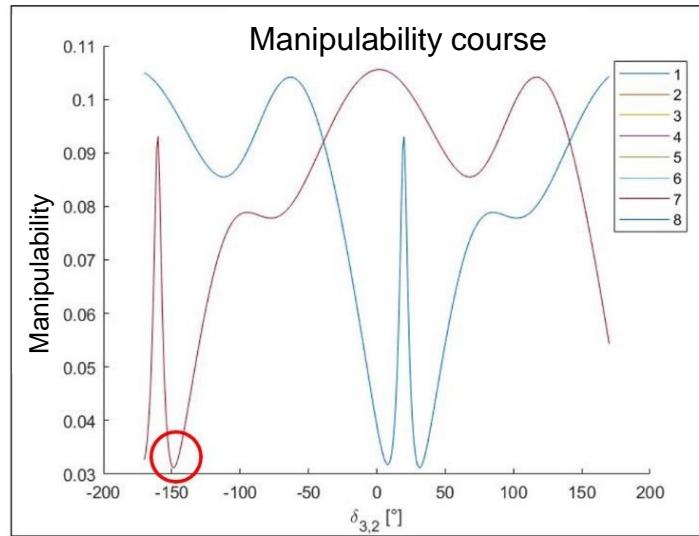
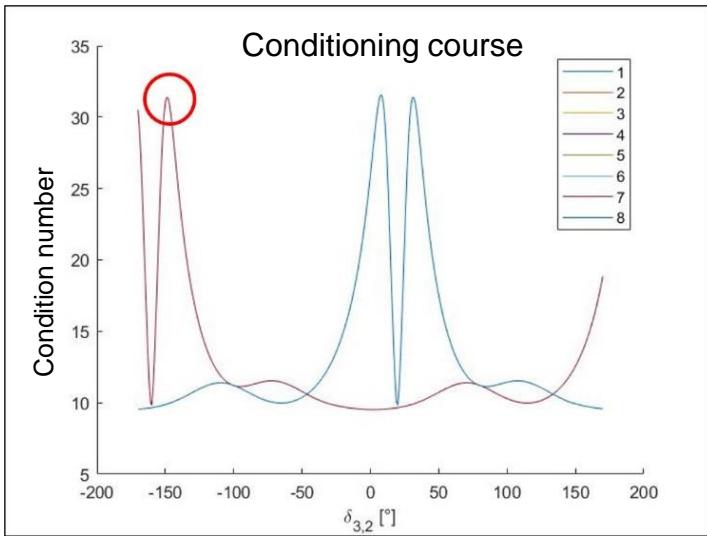
Solution approach



- External forces and torques acting on the robot are calculated
- $\underline{\tau} = (\mathbf{J}_G)^T \cdot \underline{F}_{ext}$
- Conditioning of the Jacobi matrix
- $\kappa(\mathbf{J}_G) := \|\mathbf{J}_G\| \cdot \|(\mathbf{J}_G)^{-1}\|$
 - Jacobi matrix \mathbf{J}_G has the dimension: $6 \times 7 \rightarrow$ not invertible
 - Solution: Pseudoinverse or singular value decomposition
- Manipulability of the kinematics
 - primarily used for redundant kinematics
 - Based on determinant of Jacobian matrix not directly calculable
 - $\omega = \sqrt{\det(\mathbf{J}_G \mathbf{J}_G^T)}$

source: [77], [78]

Evaluation of the kinematic performance of the robot configuration

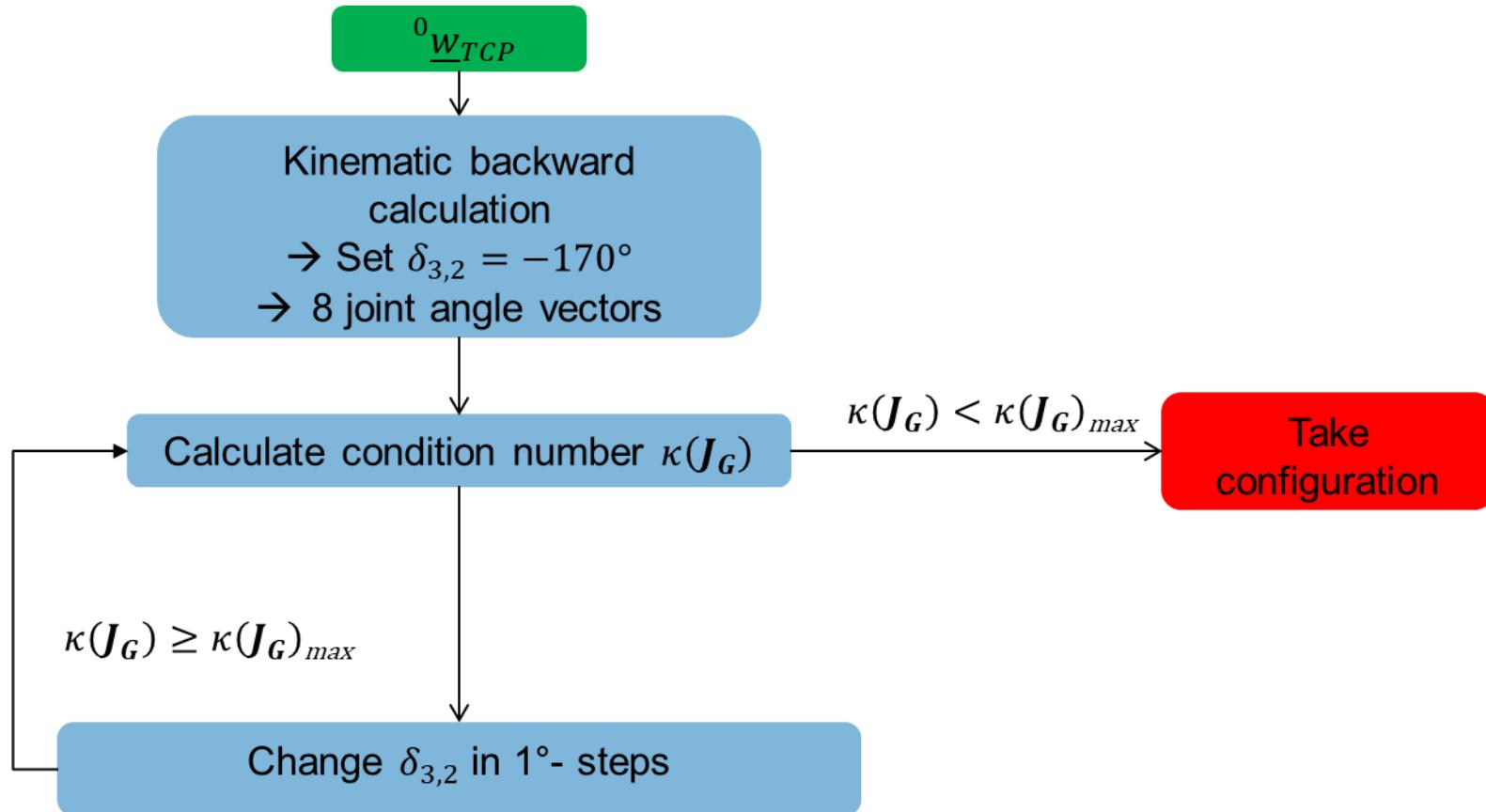


- The course of the number of conditions shows characteristic points at the same places (joint angle $\delta_{3,2}$) as the course of manipulability

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Optimization process to identify the best configuration in a pose



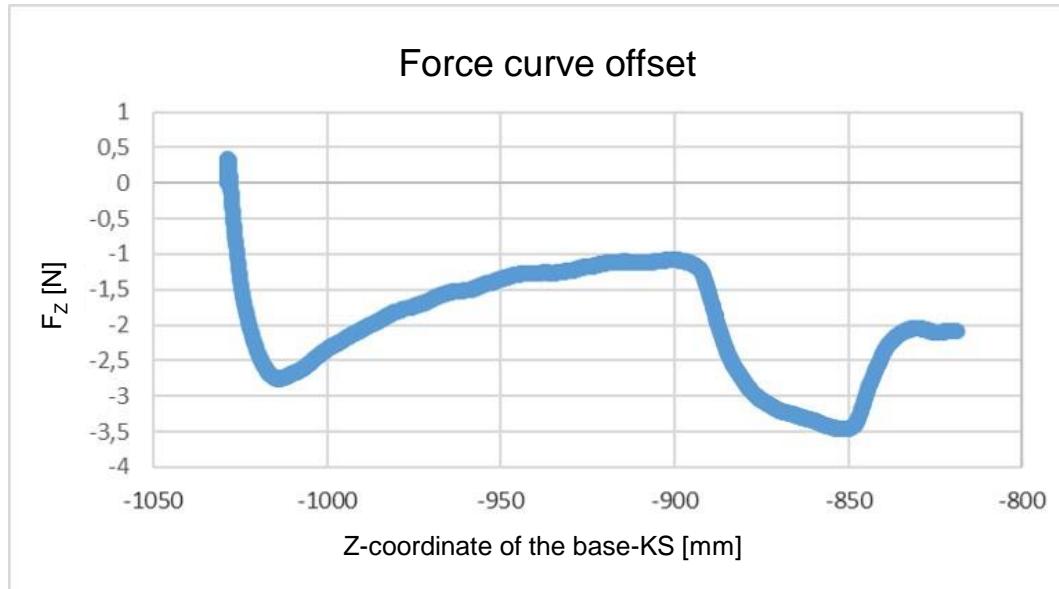
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Design of an offset in a dynamic environment

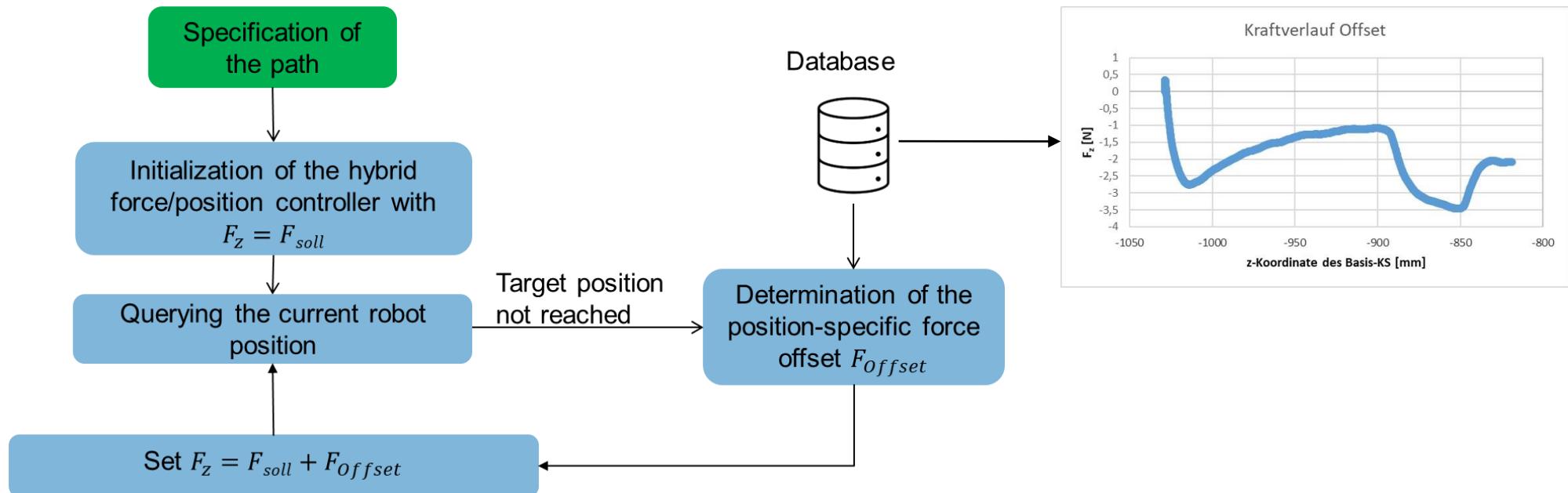


- Starting point: Calculated external forces and torques of Kuka LBR iiwa are unequal to 0 without contact
- Reasons:
 - Inherent inaccuracy of torque sensors
 - Inaccuracy of the dynamic model of the robot
- Compensation through look-up-table



Design of an offset in a dynamic environment

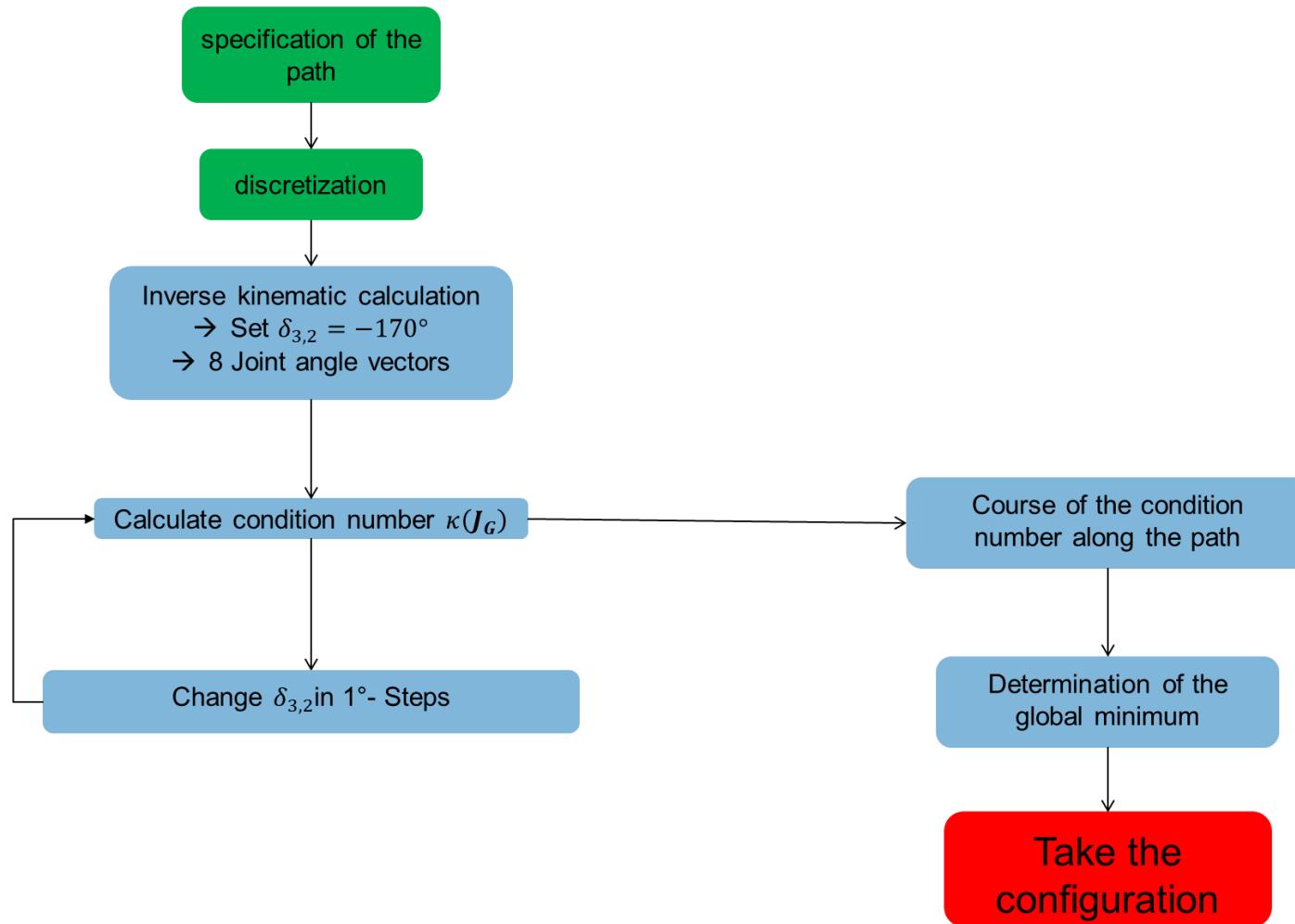
- Change force component of hybrid force/position controller online
 - SmartServo environment
 - allows changing the force component during motion (without stopping) by accessing the robot's fine interpolator



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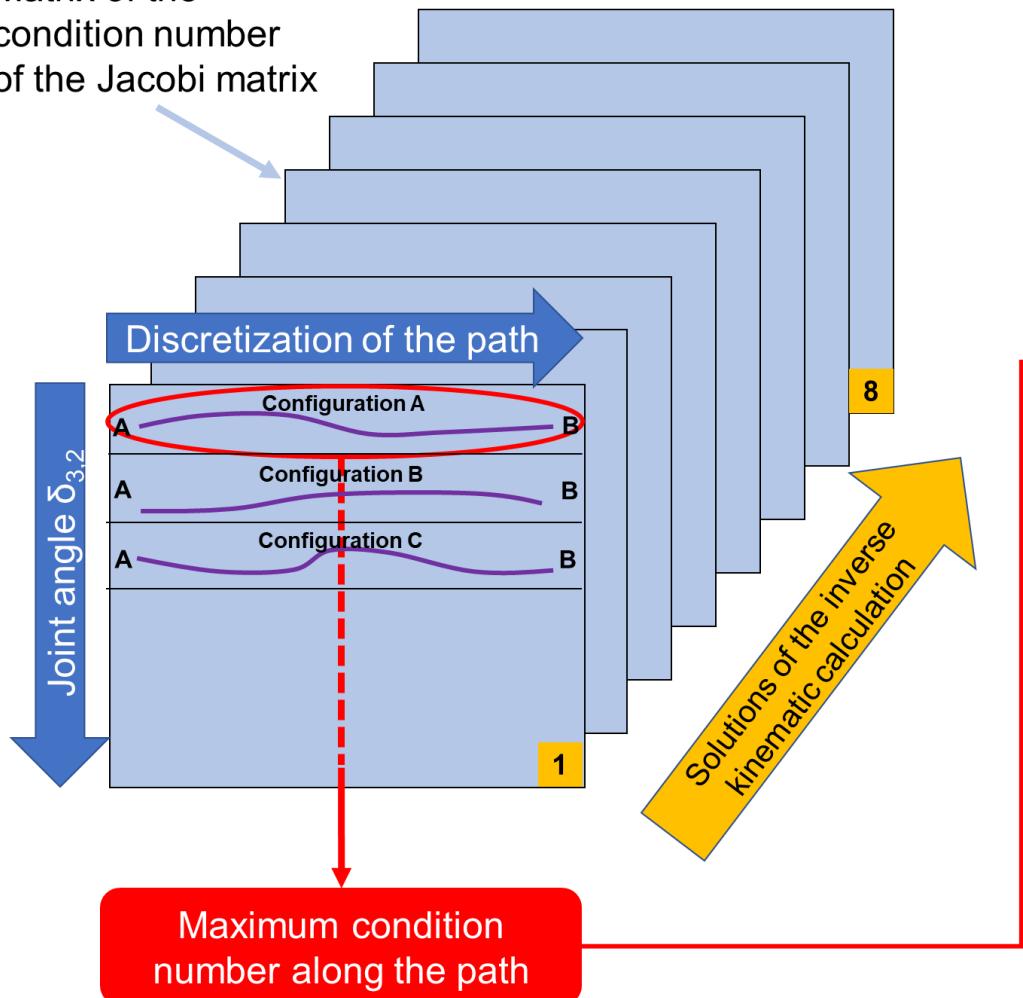
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Optimization of the configuration along a defined path

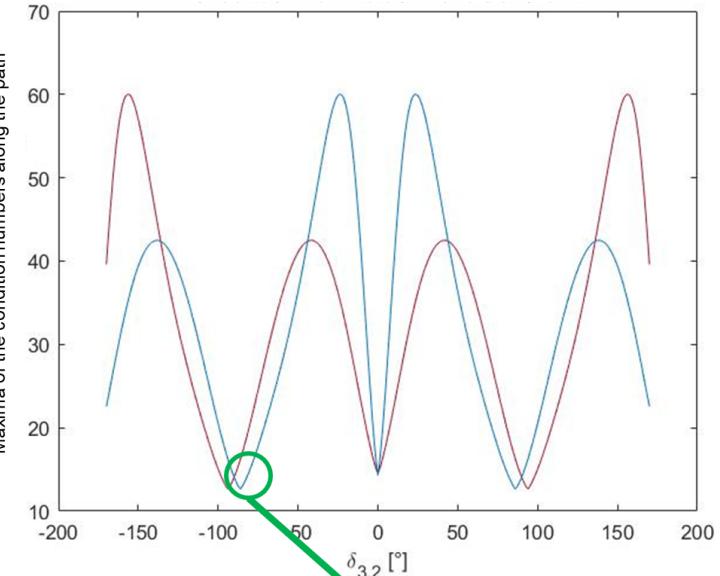


Scheme of the optimization process

Matrix of the condition number of the Jacobi matrix



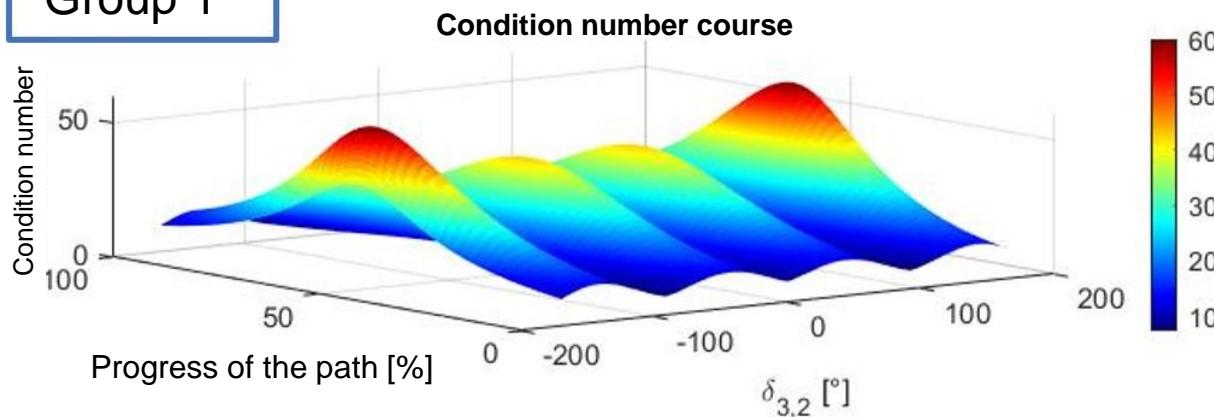
Course of the maxima of the condition numbers



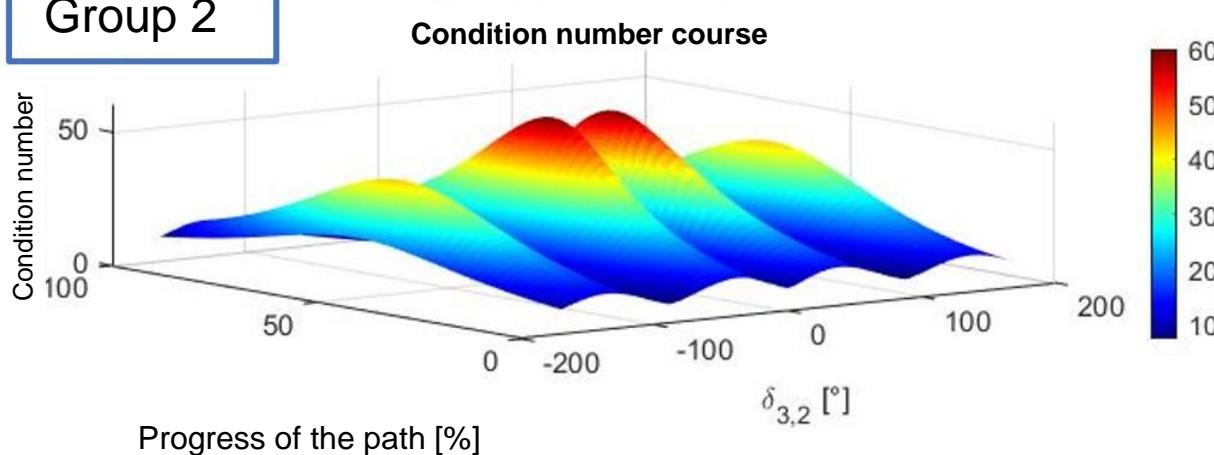
Minimum condition number of the maxima along the path

Display of the number of conditions along a straight line as a 3D profile

Group 1



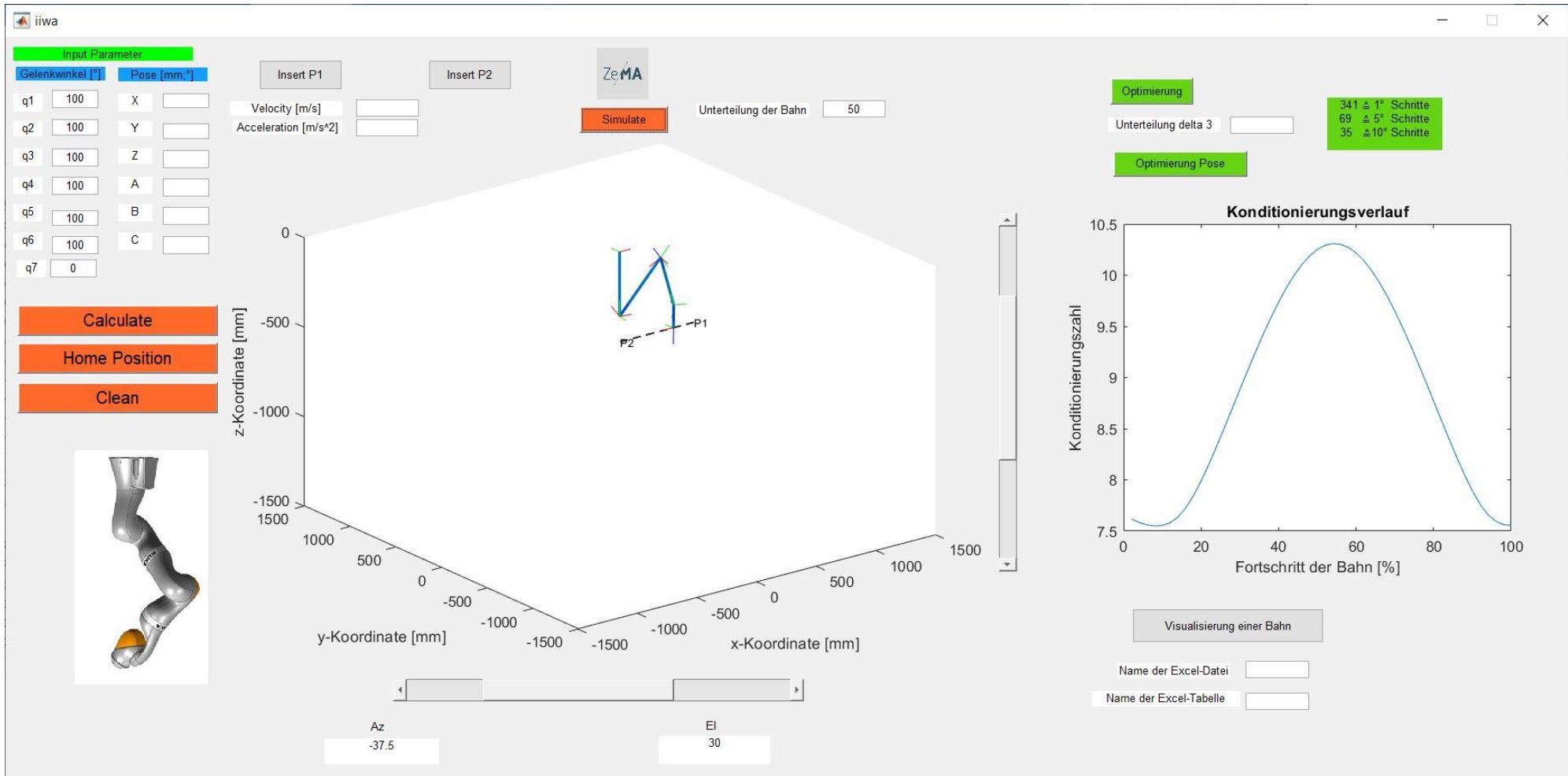
Group 2



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Graphical User Interface (GUI)



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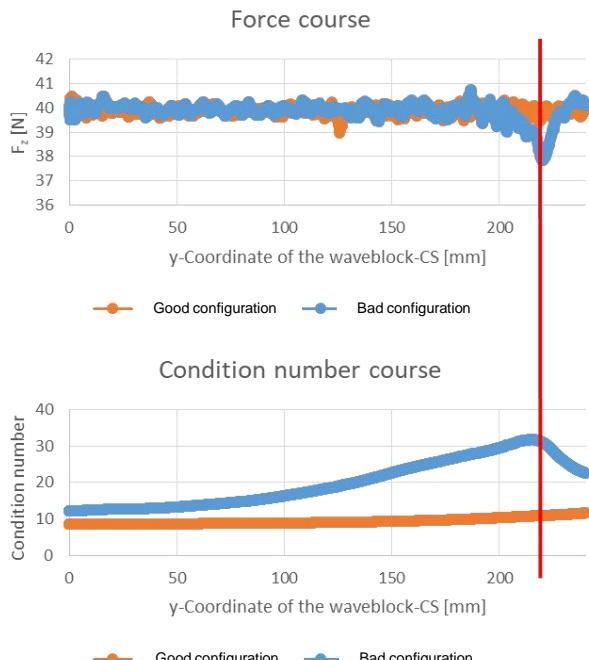
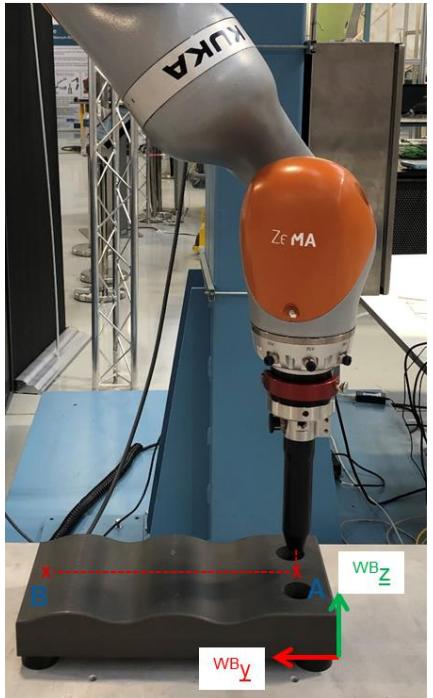
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Validation of the solution approach



- Utilization of the kinematic redundancy of the Kuka LBR iiwa
- Variation of the configuration while maintaining the pose
→ Adjusting the joint angle $\delta_{3,2}$



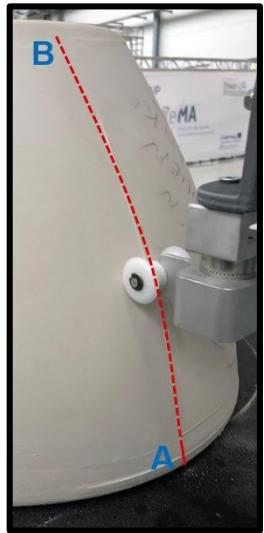
Adjusting the joint angle $\delta_{3,2}$



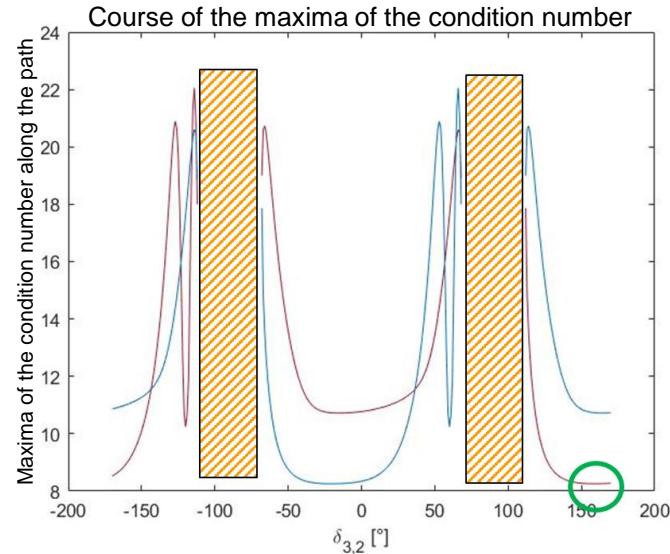
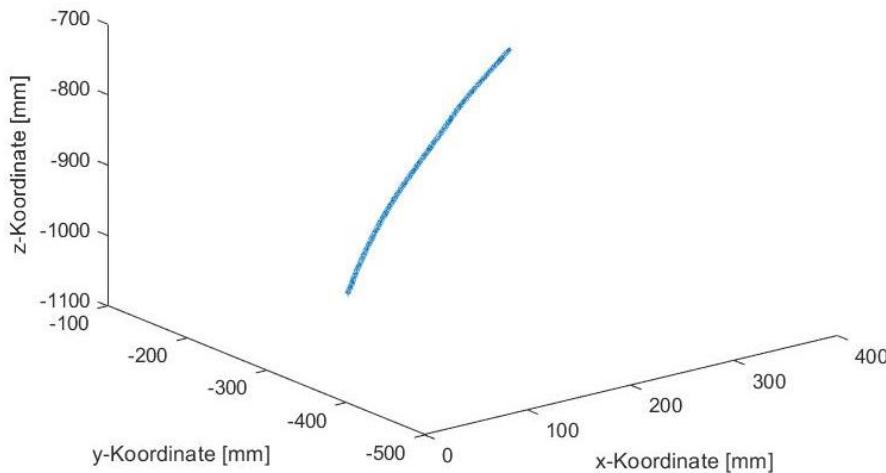
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Optimization process 3D ceramic part

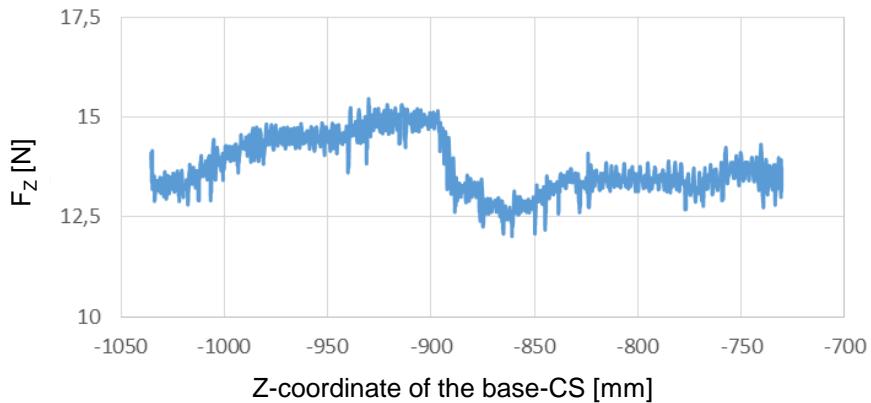


1. Tracing the contour with the prototype tool
2. Read in the point cloud of the object in MatLab
3. Optimization and identification of the best configuration
4. Implementation of an offset in a dynamic environment
5. Execution of the grinding process (deburring)

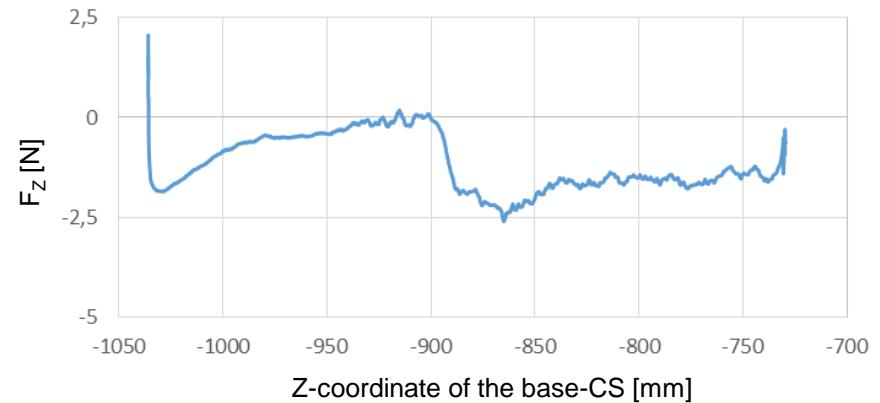


Validation of the offset in a dynamic environment

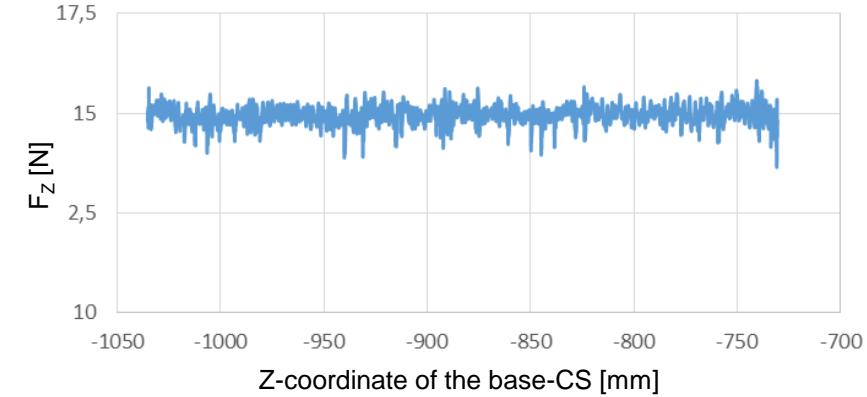
Force curve incl. the offset



Force curve offset



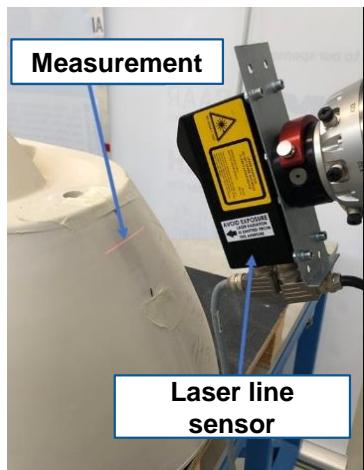
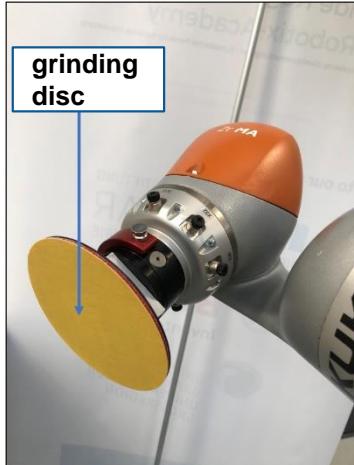
Force curve after deduction of the offset



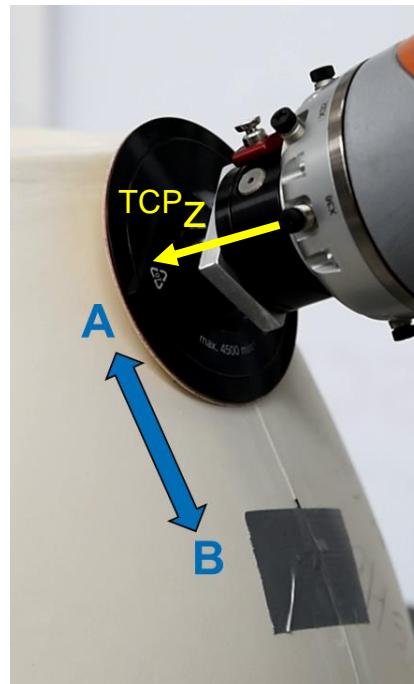
$F_{\text{soil}} = 15 \text{ N}$

Execution of the grinding tests

Setup of the test

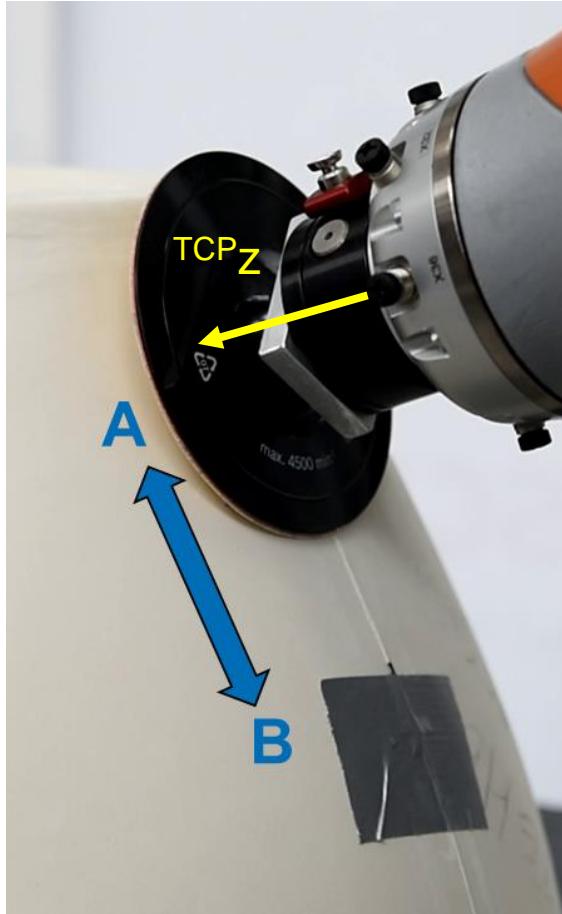


- Prototype tool with grinding plate and grinding disc on the flange of the KUKA LBR iiwa
- Abrasion through defined contact with the component
- Measurement of the burr by laser line sensor
Quantification of the abrasion



Execution of the grinding tests

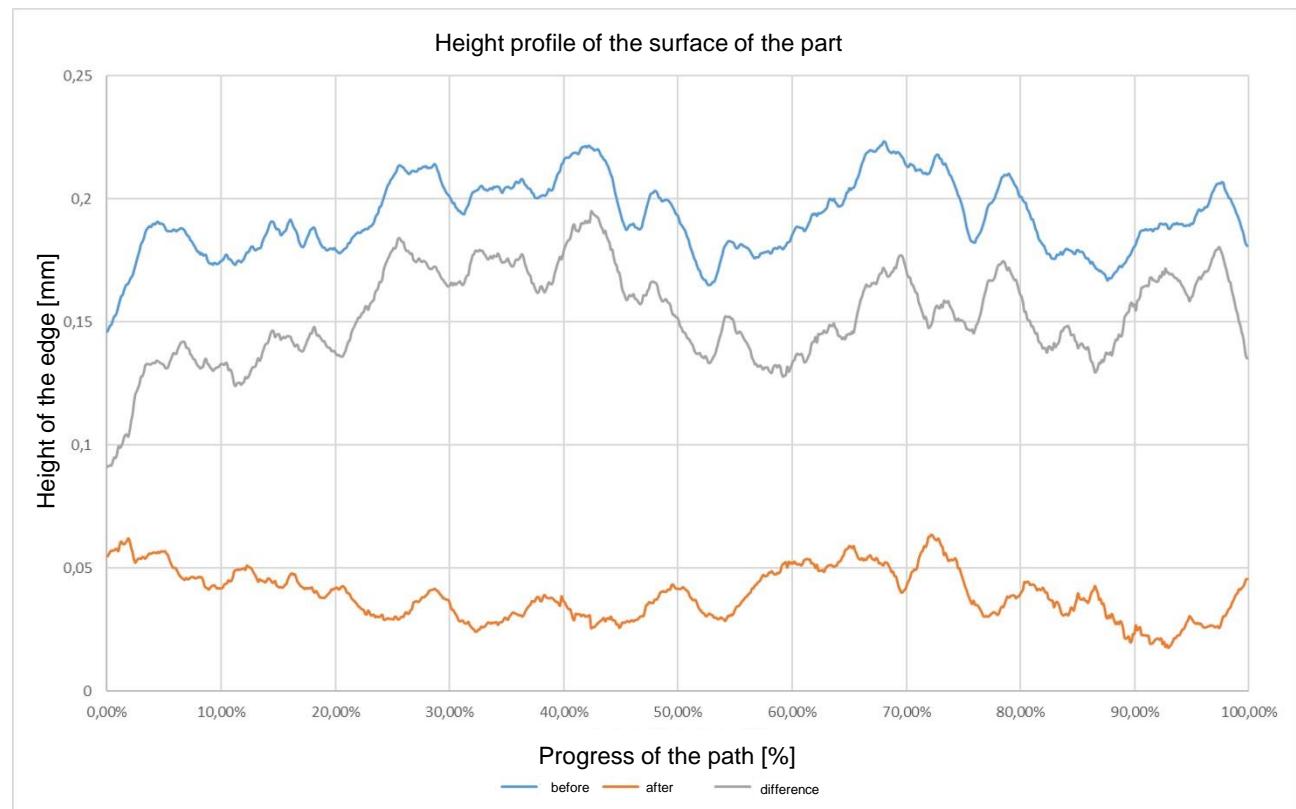
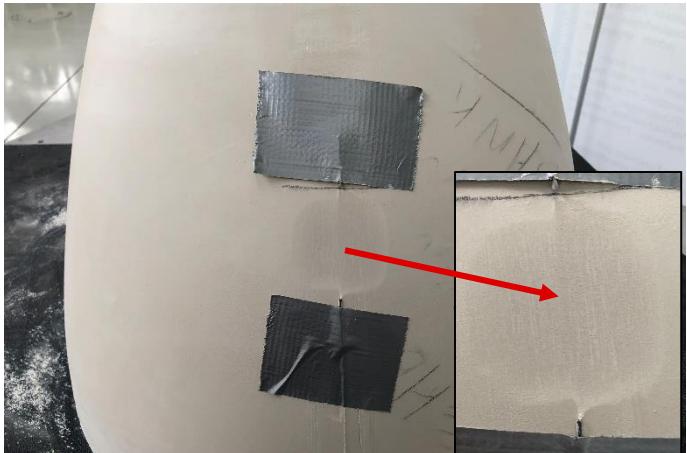
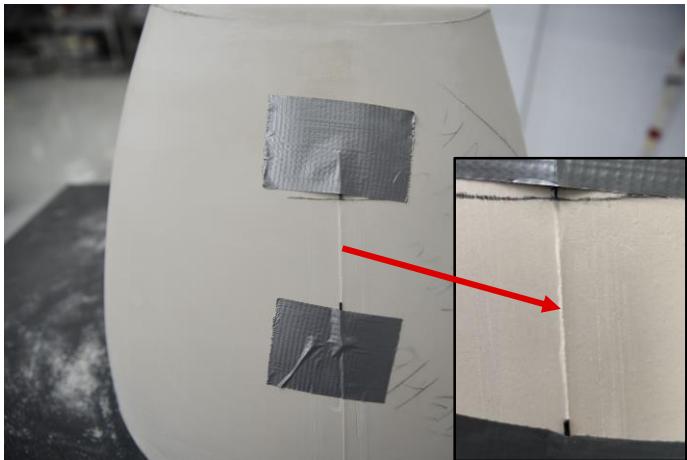
Robot application



- Programming of the robot incl. defined interaction with the part → Force control (here: 10 N)
- Specification of a normal force in the direction of the z-axis of the TCP or flange coordinate system during the grinding process
- Optimization of the configuration of the robot using the MatLab tool
- Implementation of a offset to improve the accuracy of the determined external forces and torques
- Cyclic grinding
- Cartesian speed: 25 mm/s

Execution of the grinding tests

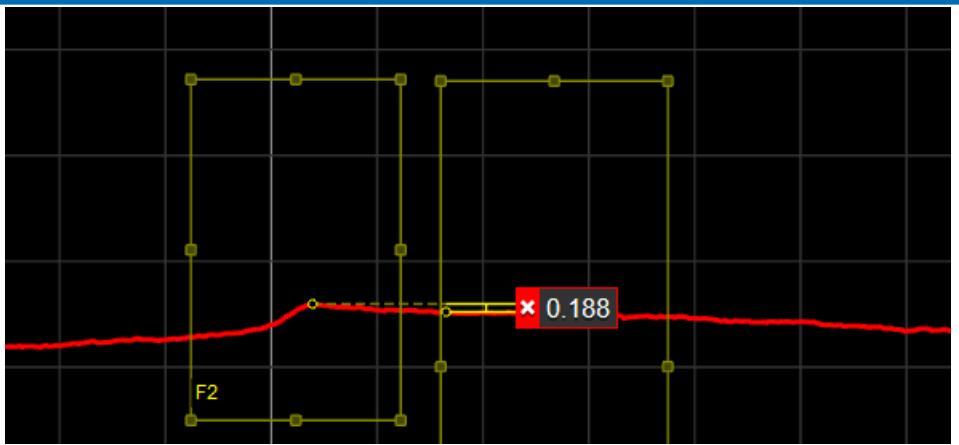
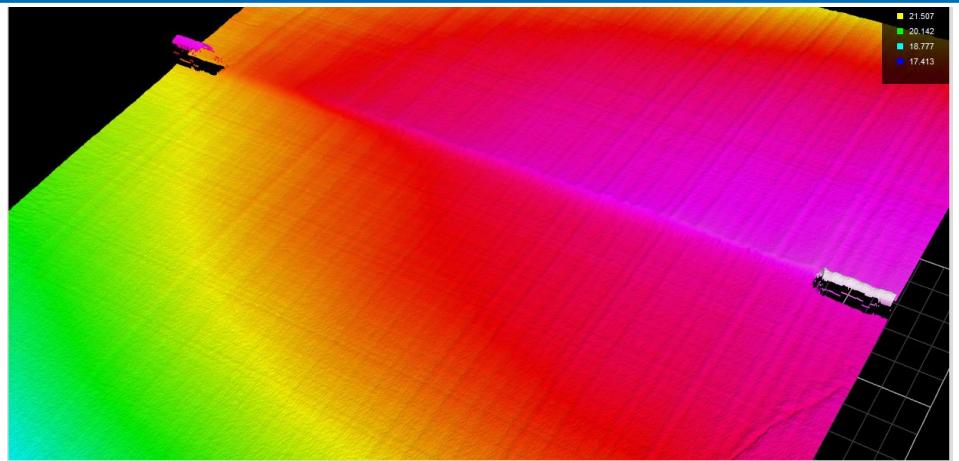
Comparison before vs. after



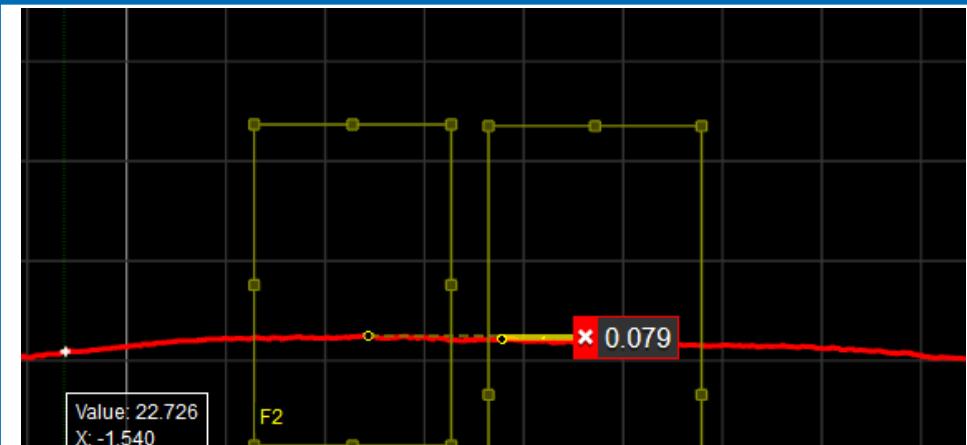
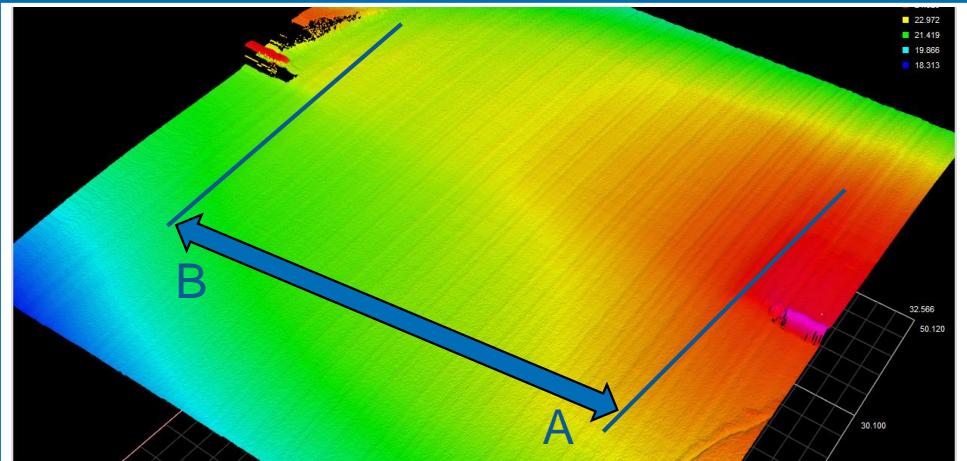
Execution of the grinding tests

Comparison before vs. after 3D & 2D

before



after



Agenda

- 1 Introduction and State of the art
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- 3 Development of a solution approach
- 4 Validation of the solution approach
- 5 Conclusion
- 6 Literature

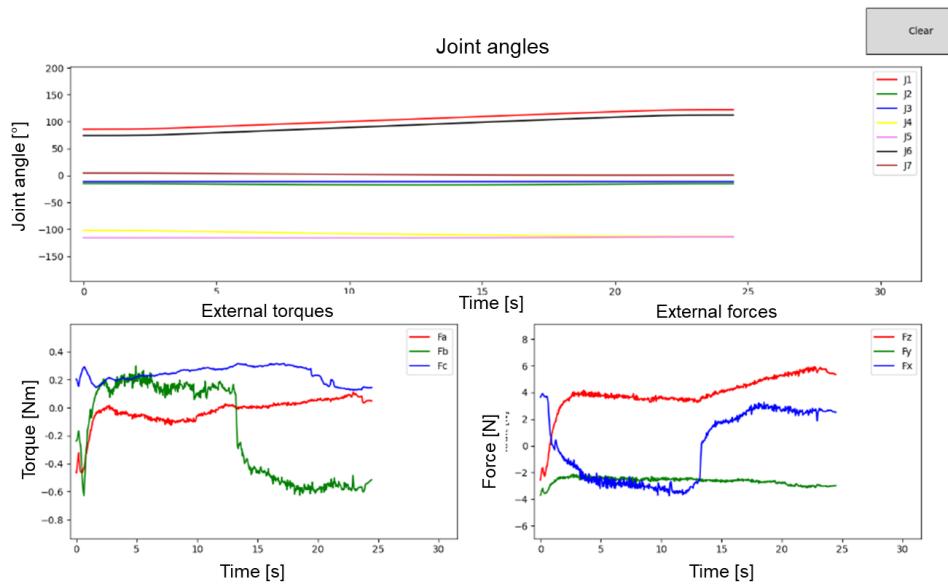
Conclusion

- The use of sensitive robot systems opens up new fields of application in the context of assembly and production technology
- Optimization procedure for a sensitive 7-DoF robot with integrated torque sensors was presented
- Increase of the accuracy of the determined external forces and torques
- Improvement of force controlled movements
- Software tool in MatLab in the form of a graphical user interface (GUI) that can be used by the operator
- Proof of the added value of the developed process by applying it to a typical assembly
- Monitoring of external forces and torques possible

Outlook and future work



- Process development including measuring strategy or inspection concept of the grinding process
- Tool development
- Evaluation of contact forces and moments
 - Possibility to evaluate the grinding process?
 - conventional and unconventional approaches conceivable



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Thank you for your attention!