Institute for Machine Tools and Industrial Management
TUM School of Engineering and Design
Technical University of Munich

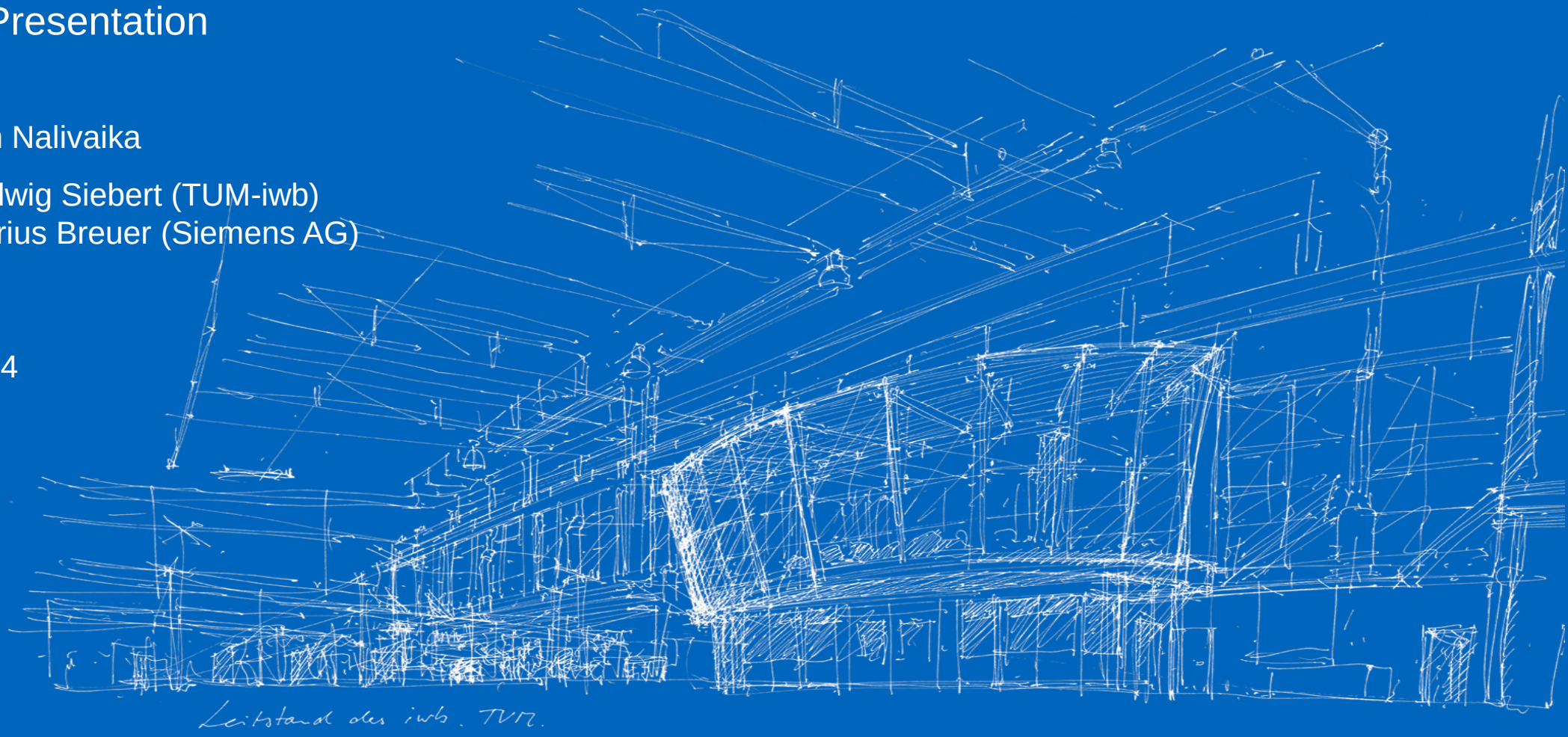
Methodical Approach for Analyzing Process Variables and Optimizing Boundary Conditions in Multi-Axis Robot Programs

Master-Thesis Presentation

Submitted by: Jan Nalivaika

Supervised by: Ludwig Siebert (TUM-iwb)
Marius Breuer (Siemens AG)

Garching 04.03.2024



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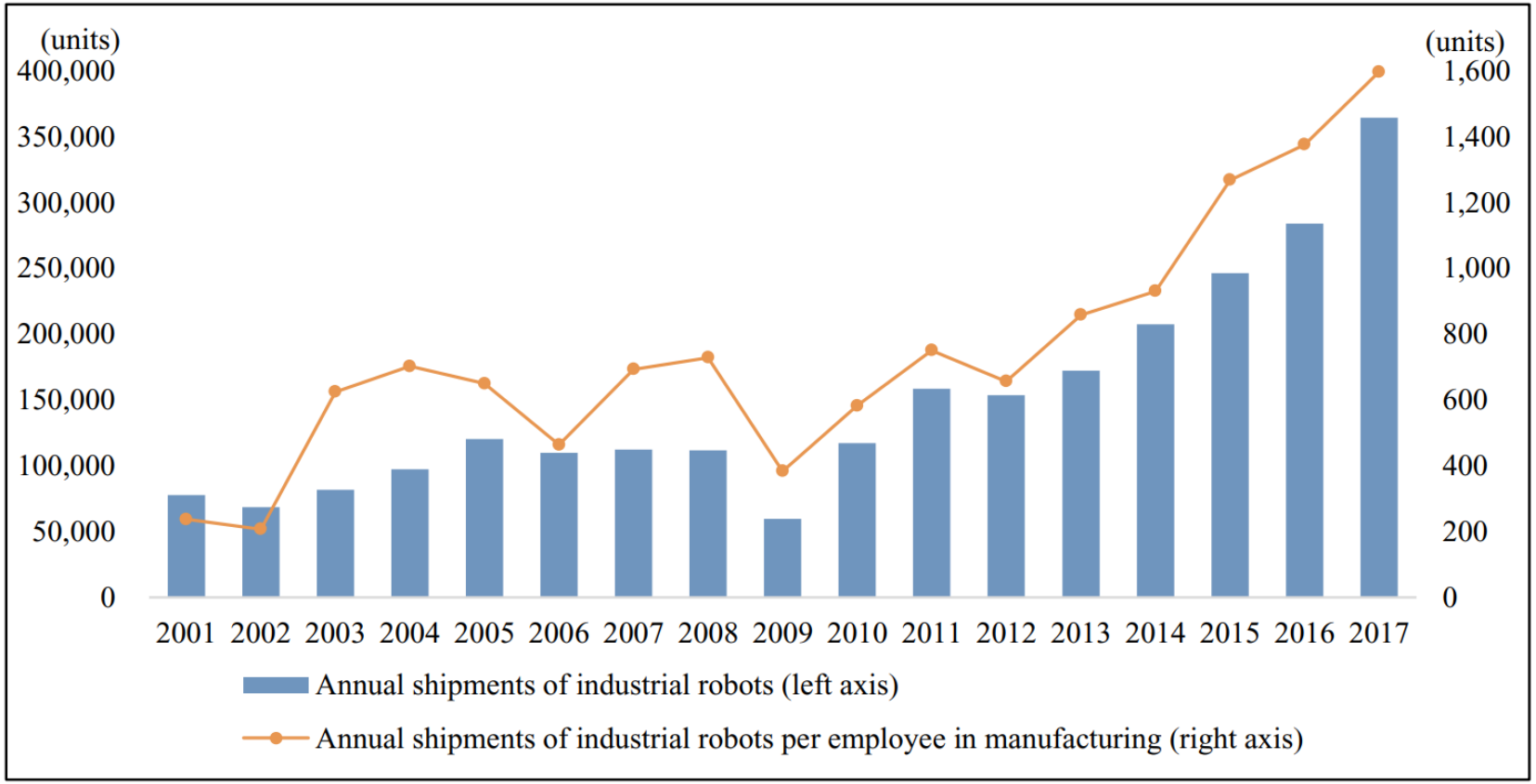
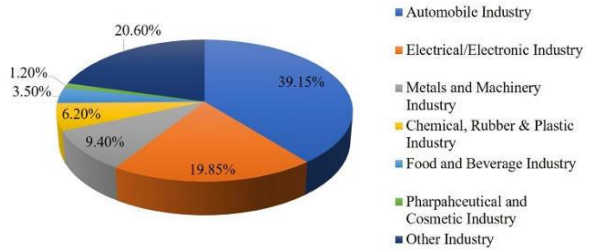
Growth of Industrial Robot Usage

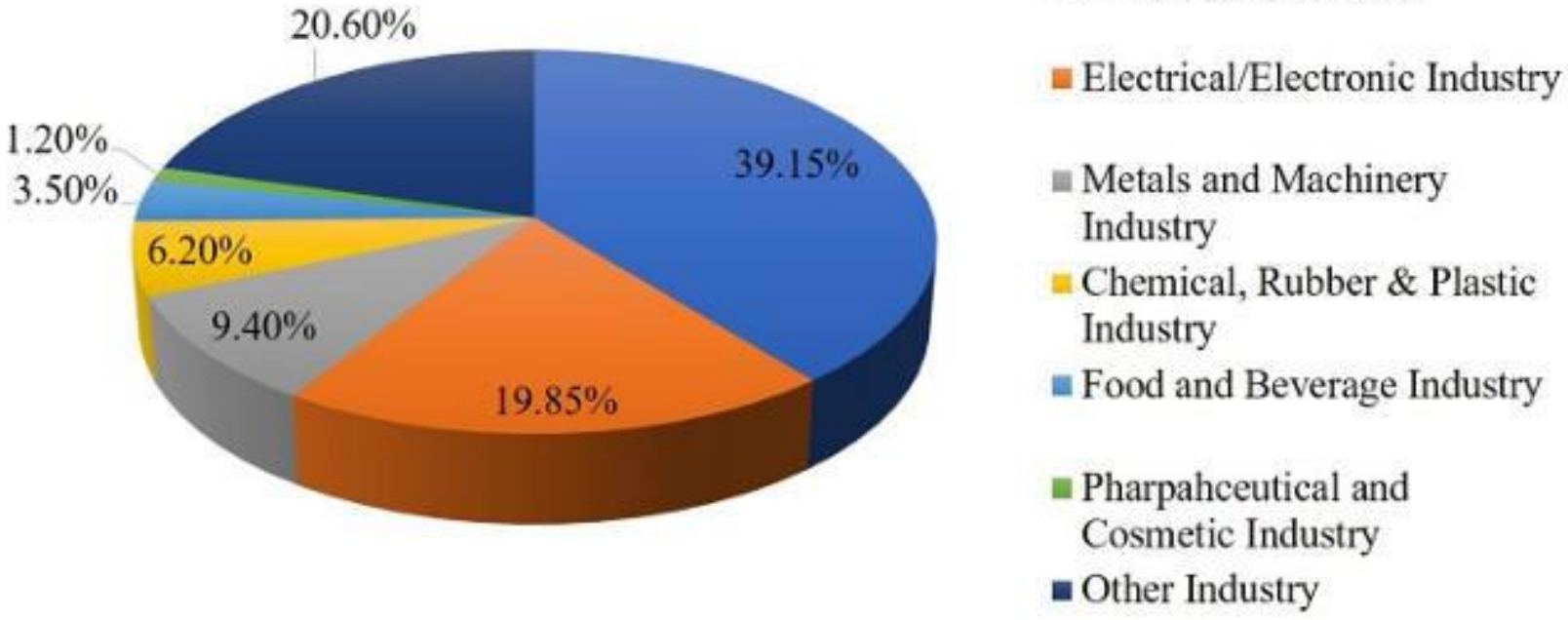
Motivation

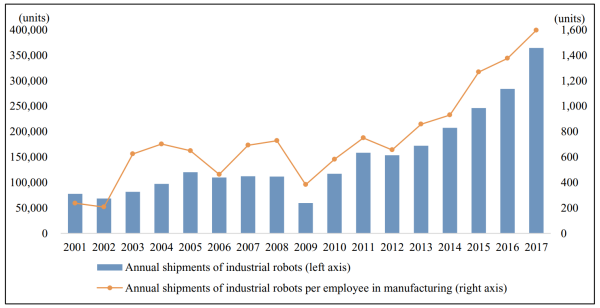




Industrial Applications of Robotics

Motivation





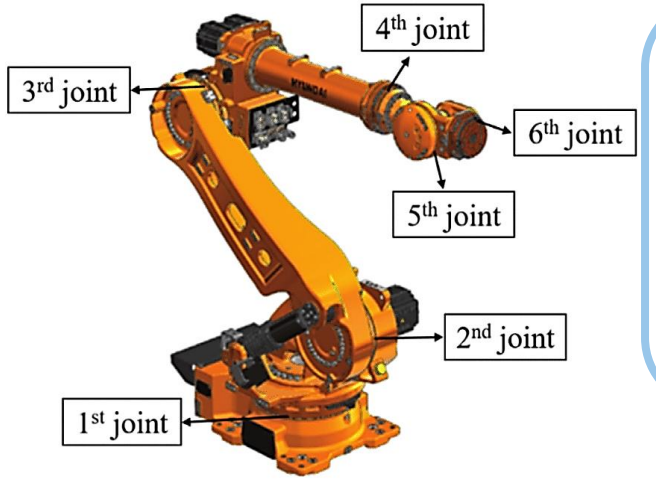
(Hwa Jung 2020)

Manufacturing Methods

Problem Formulation and Aim

In CNC milling the traversed toolpaths are usually defined in 5 DoFs.

These DoFs are:
- X,Y,Z (translation)
- A,B (rotation)



Industrial robots usually have 6 DoFs and are a great candidate for Wire Arc Additive Manufacturing (WAAM)

They can also be used for CNC machining.

A 5-DoF toolpath does not fully specify the robots configuration. While the toolpath defines the X, Y, and Z coordinates, as well as rotations A and B, rotation C is not defined and **can be chosen freely**.

The rotation C is not affecting the toolpath but the way how this toolpath is traversed. Thus, it is considered a **boundary condition**.

➔ Redundancy in the system when performing a 5-DoF task in a 6-DoF system

➔ How does the boundary condition affect the robot and how can we use the redundancy to our advantage?

Example: Traversing a Toolpath With Different C-Rotation

Problem Formulation and Aim

Rotation C = 0°

The different setting of the rotation C (rotation around the axis of the tool) significantly influences the behavior of the robot.

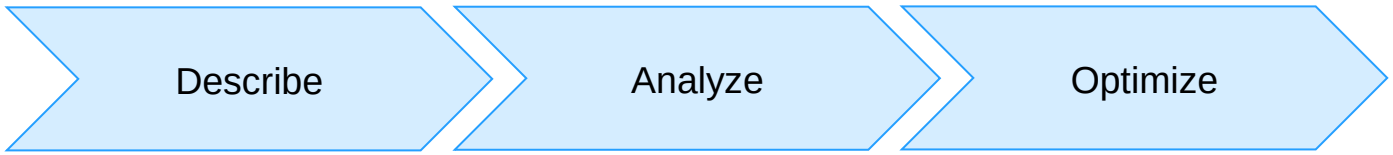
Rotation C = -30°

The influenced **process variables** are for example: Direction changes in the joints, accelerations, energy consumption, cable positioning, stiffness etc.

Shortcomings in Current Methodologies

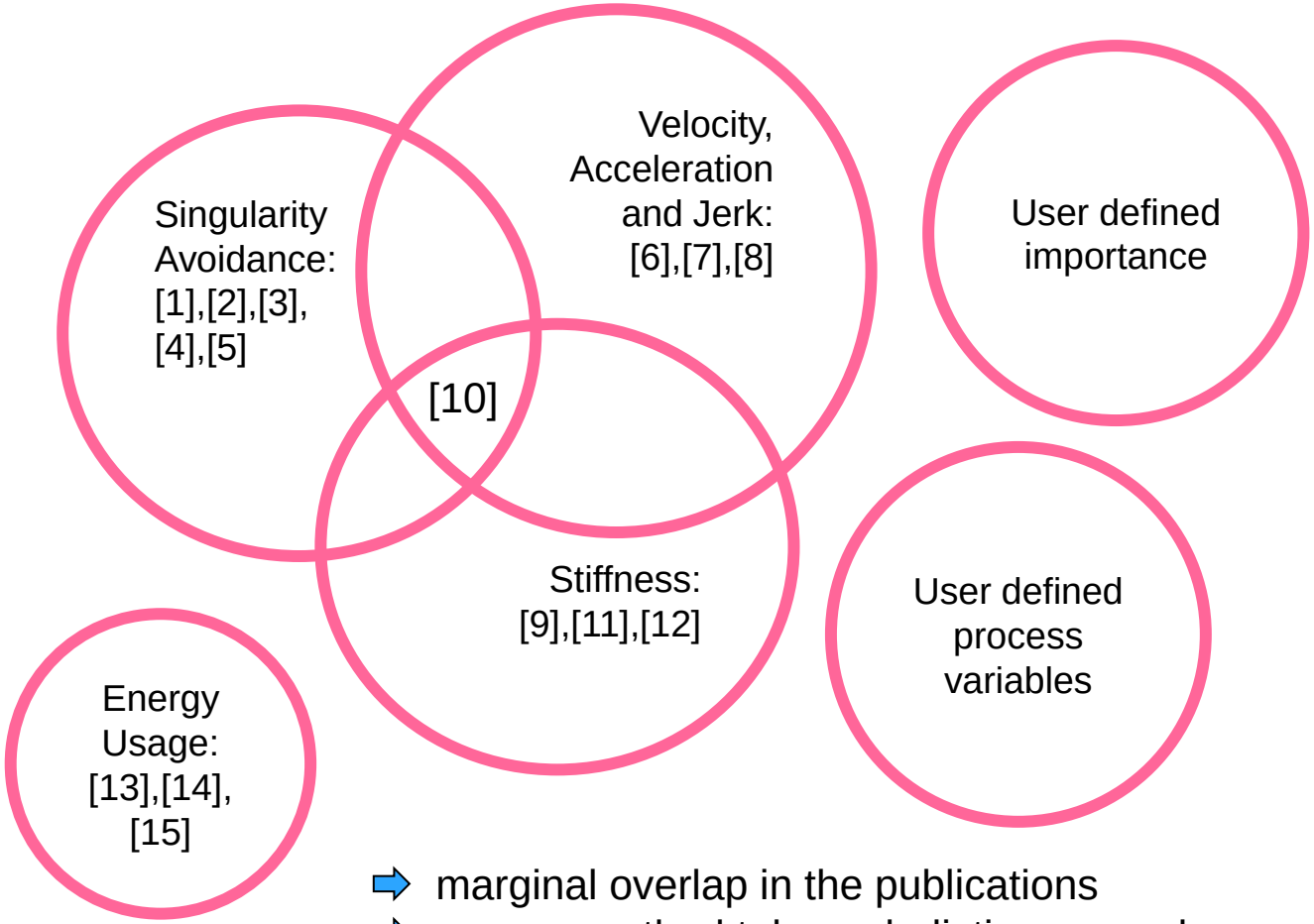
Problem Formulation and Aim

No currently published method allows the user to select specific process variables to evaluate a process	Provide a method that can work with specifically selected process variables and rate a manufacturing process
As of now, it is not possible to weigh individual process parameters and thus describe the manufacturing process as a singular scalar value	Extend the developed method with the option to add user-defined importance factor (weights) for the process variables
No available method provides a solution to optimize boundary conditions based on a user defined goal	Provide system that can optimize the boundary conditions while considering the user defined goal



Elaboration of the Research Gap

State of the Art



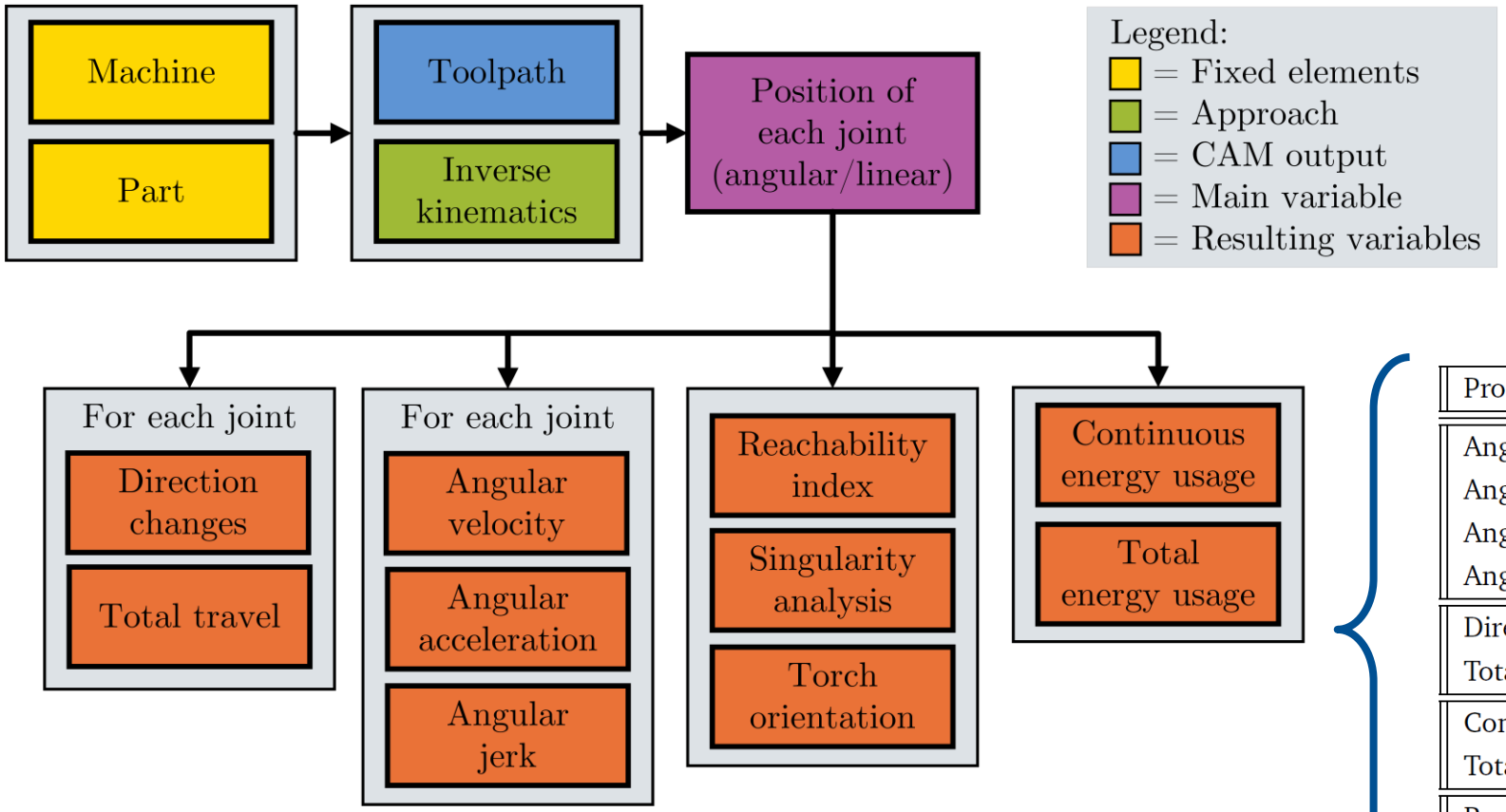
⇨ marginal overlap in the publications
⇨ now no method takes a holistic approach

[1] Singularity avoidance and aspect maintenance in redundant manipulators (R. Stevenson; B. Shirinzadeh; G. Alici 2002)
[2] Classification of singular configurations for redundant manipulators (Nazareth Bedrossian 1990)
[3] The joint-limits and singularity avoidance in robotic welding (Liguo Huo, Luc Baron 2008)
[4] Wrist singularity avoidance with a robot end-effector adding an oblique, redundant axis (Paul_Milenkovic 2021)
[5] Kinematics and Singularity Analysis of a 7-DOF Redundant Manipulator (Xiaohua Shi, Yu Guo, Xuechan Chen, Ziming Chen, and Zhiwei Yang 2021)
[6] Planning Jerk-Optimized Trajectory With Discrete Time Constraints for Redundant Robots (Chengkai Dai; Sylvain Lefebvre; Kai-Ming Yu; Jo M. P. Geraedts; Charlie C. L. Wang 2020)
[7] Time-Jerk Optimal Trajectory Planning for a 7-DOF Redundant Robot Using the Sequential Quadratic Programming Method (Li Jiang, Shaotian Lu, Yikun Gu & Jingdong Zhao 2017)
[8] On the Effect of the End-effector Point Trajectory on the Joint Jerk of the Redundant Manipulators (Xuan Bien Duong 2021)
[9] Review of Industrial Robot Stiffness Identification and Modelling (Kai Wu, Jiaquan Li, Huan Zhao, Yong Zhong 2021)
[10] Stiffness-based Pose Optimization of an Industrial Robot for Five-axis Milling (Gang Xiong, Ye Ding, Limin Zhu 2019)
[11] Optimization of redundant degree of freedom in robotic milling considering chatter stability (Linwei Wang, Yu Liu, Ye Yu, Jinyu Zhang & Bin Shu 2022)
[12] Pose optimization in robotic machining using static and dynamic stiffness models (Toni Cvitanic, Vinh Nguyen, Shreyes N. Melkote 2020)
[13] Energy Efficient Usage of Industrial Robots for Machining Processes (Eckart Uhlmann, Sascha Reinkober, Tobias Hollerbach 2016)
[14] Energy Optimization of Functionally Redundant Robots through Motion Design (Boscariol, Paolo, Roberto Caracciolo, Dario Richiedei, and Alberto Trevisani. 2020)
[15] Optimization of energy consumption in industrial robots, a review (Mohsen Soori, Behrooz Arezoo, Roza Dastres 2015)

No method gives the user the possibility to weigh the individual process variables in relation to each other and optimize the setting of redundant DoFs towards a user-defined goal.

Extraction of Process Variables

Methodology

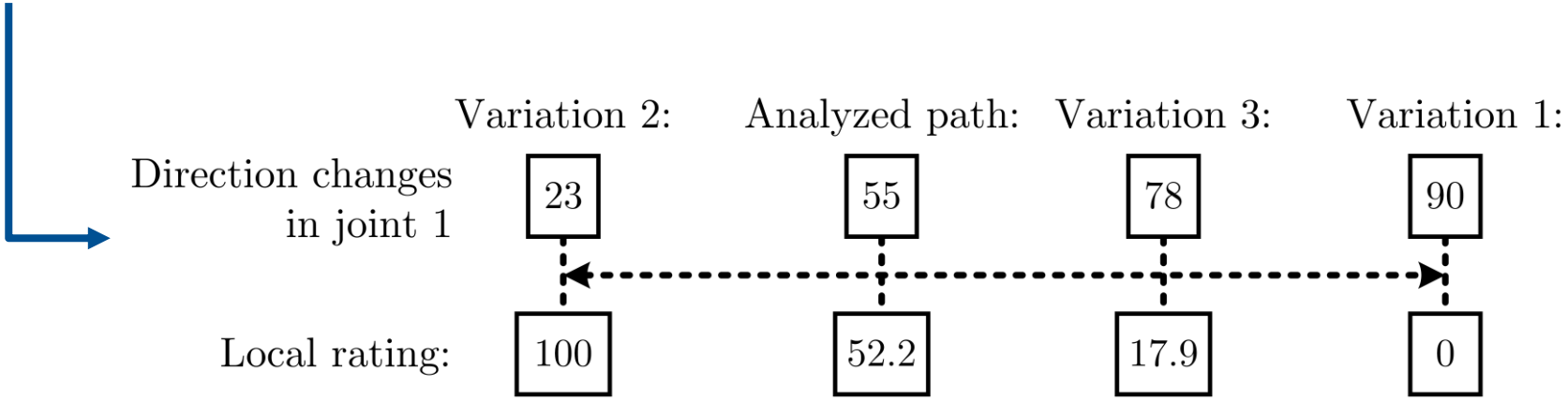


Process variables	Numerical form
Angular position of each joint	Time-series
Angular velocity of each joint	Time-series
Angular acceleration of each joint	Time-series
Angular jerk of each joint	Time-series
Direction changes of each joint	Scalar value
Total travel of each joint	Scalar value
Continuous energy usage	Time-series
Total energy usage	Scalar value
Reachability index	Binary value / Time-series
Singularity Analysis	Scalar value / Time-series
Torch orientation	Time-series

Incorporation of User Defined Importance Factors

Methodology

Process variable	Local rating	Importance factor	Local score
Process variable Nr. 1	74	0.5	37
Process variable Nr. 2	34	0.1	3.4
Process variable Nr. 3	65	0.1	6.5
Process variable Nr. 4	22	0.3	6.6
Global score			53.5

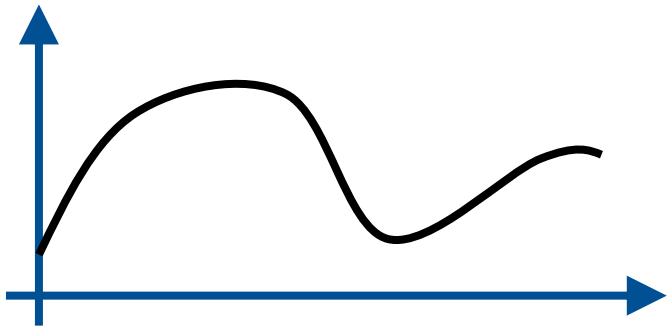


Transforming Time-Series Data into Scalar Values

Methodology

Time-series data:

- Velocity
- Acceleration
- Jerk
- …



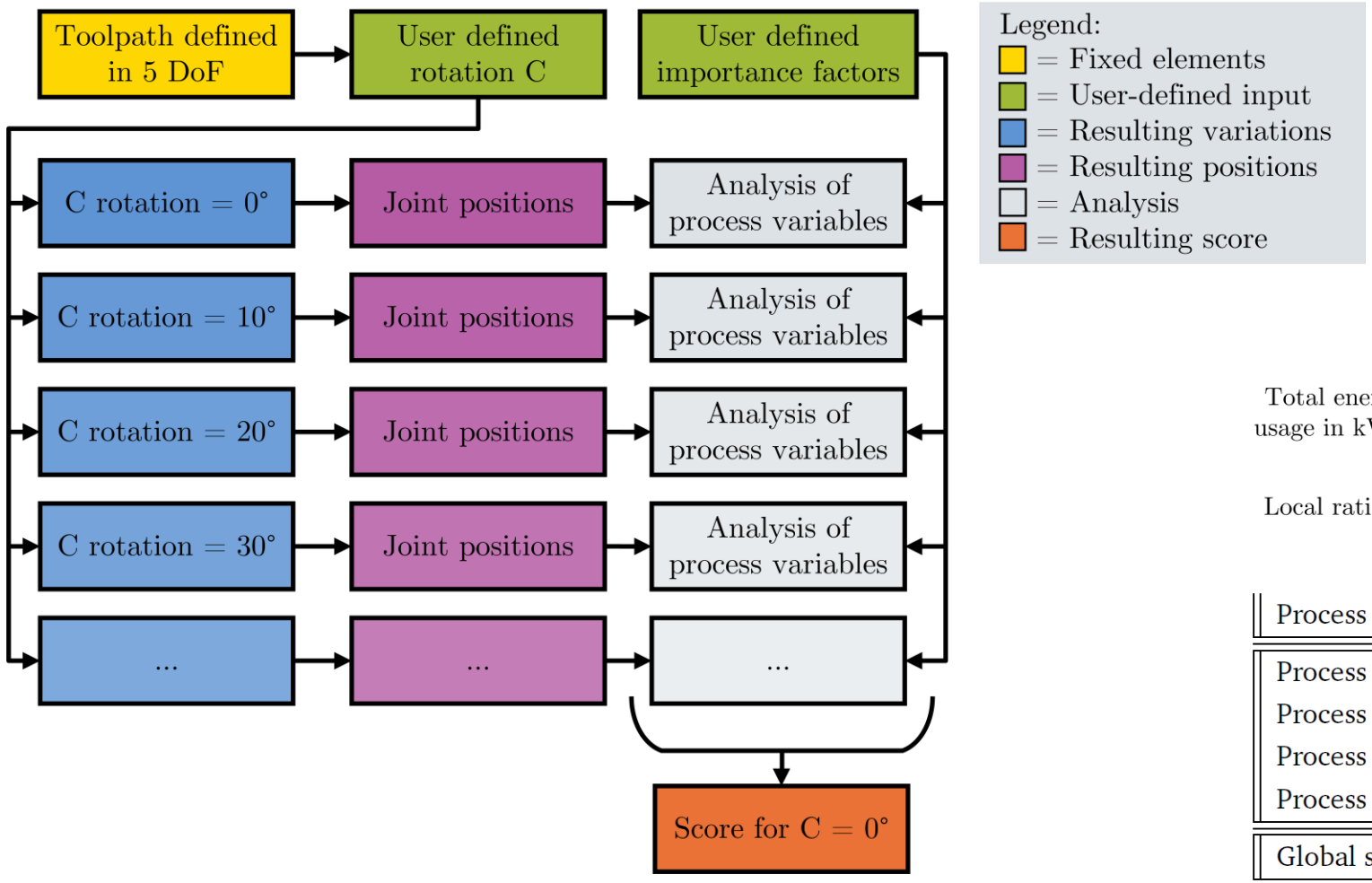
Optional procedures:

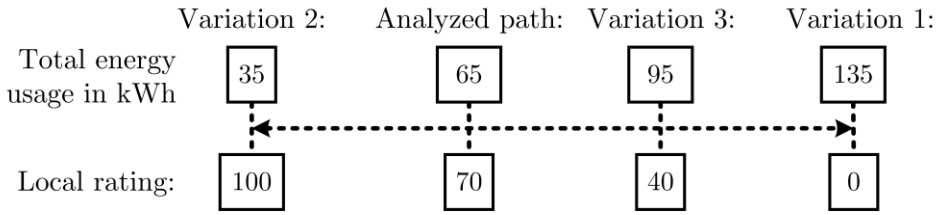
- Squaring and aggregation
- Cubing and aggregation
- Definition of thresholds
- Machine learning

Process variables	Local rating	Importance factors	Local score
Velocity in joints 1-6	45	0.1	4.5
Accelerations in joint 2	90	0.8	72
Accelerations in joint 1 and 3-6	15	0.1	1.5
Jerk in joints 1-6	4	0	0
Global Score			78

General Process Analysis

Methodology





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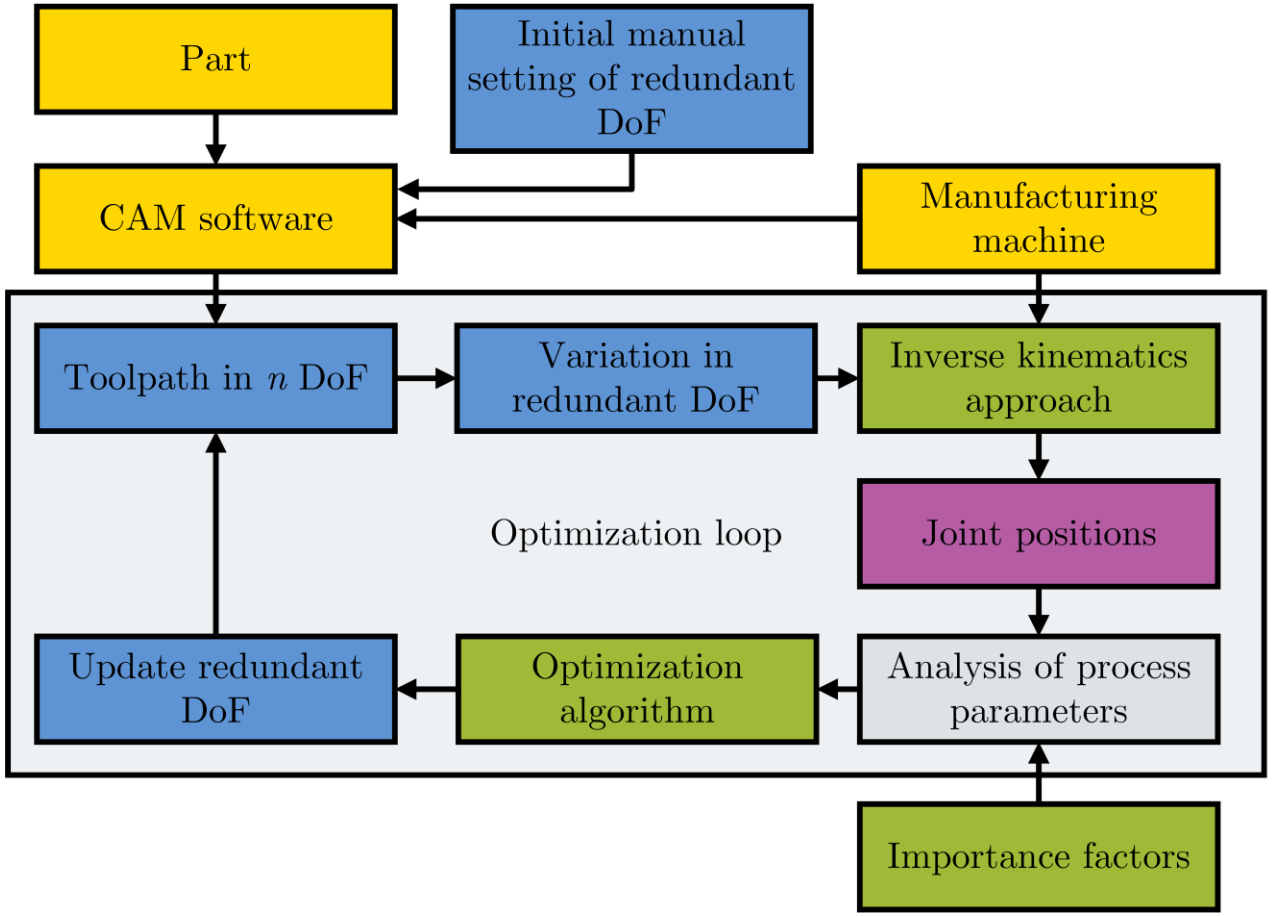
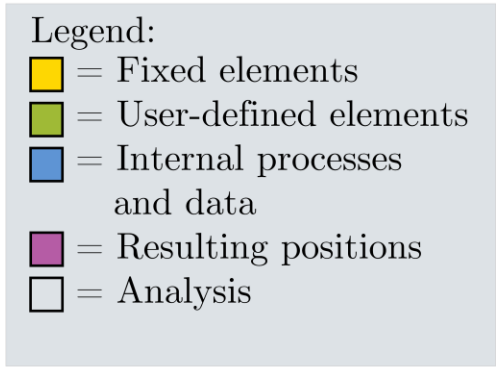
Boundary Condition Optimization

Methodology



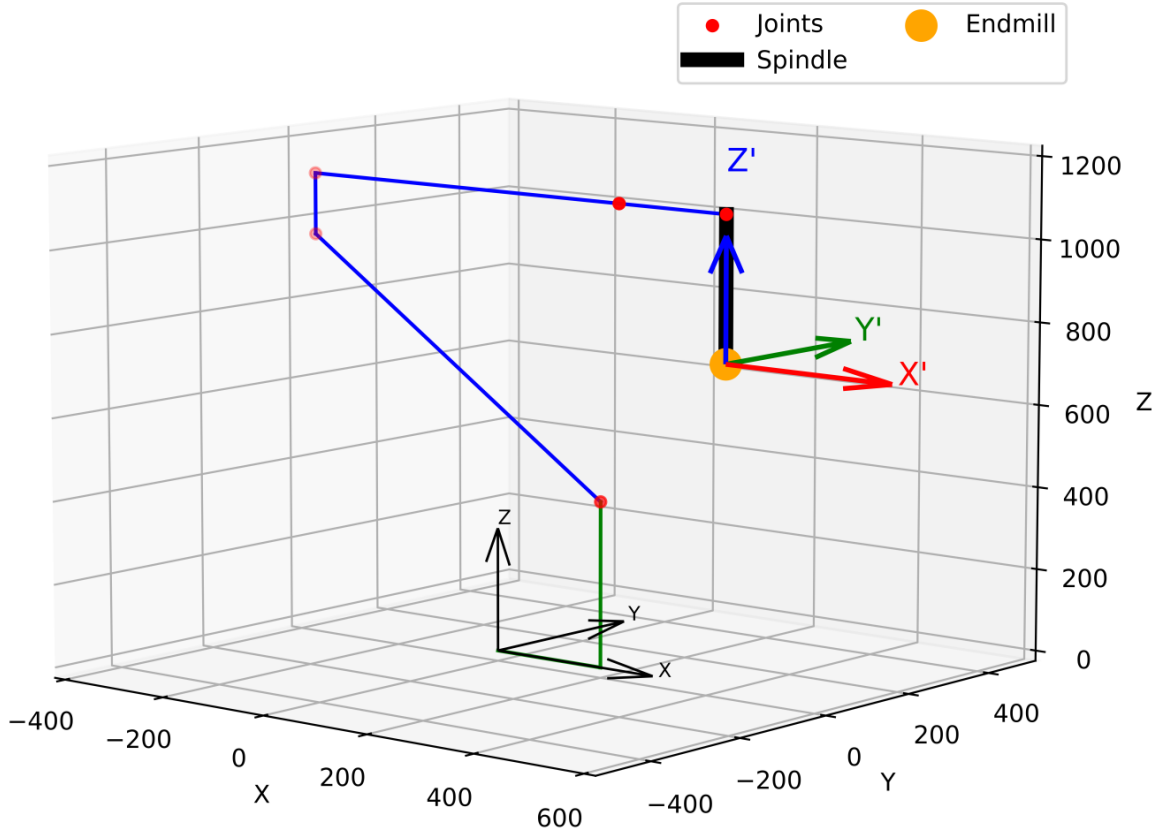


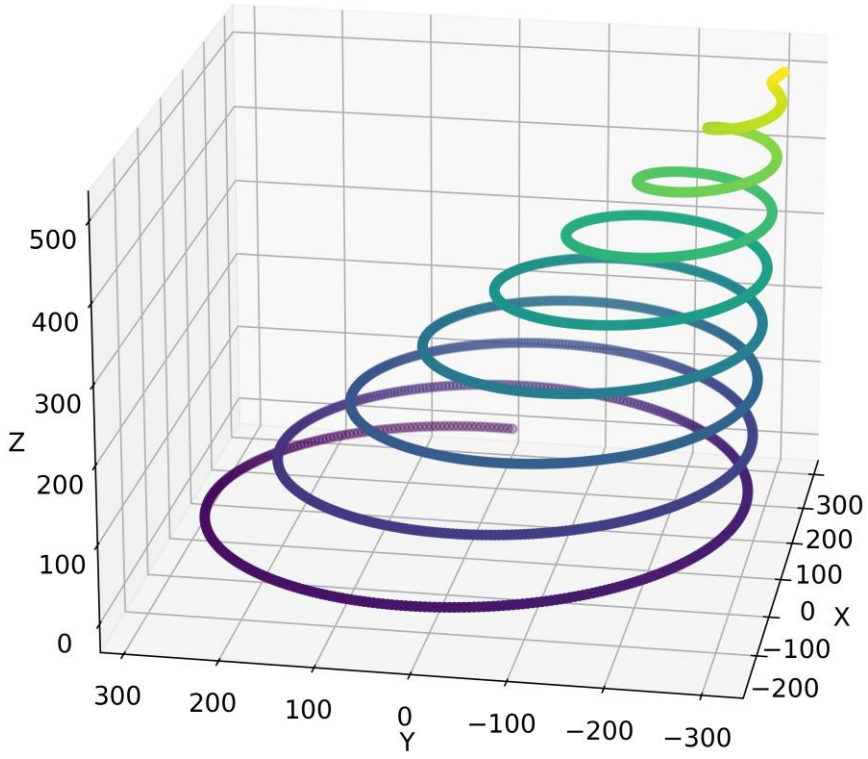
Possible optimization algorithms:

- Evolutionary algorithm
- Genetic algorithms
- Particle swarm optimization
- Ant colony optimization
- Differential evolution
- Harmony search

Modeled Robot and Analyzed Toolpath

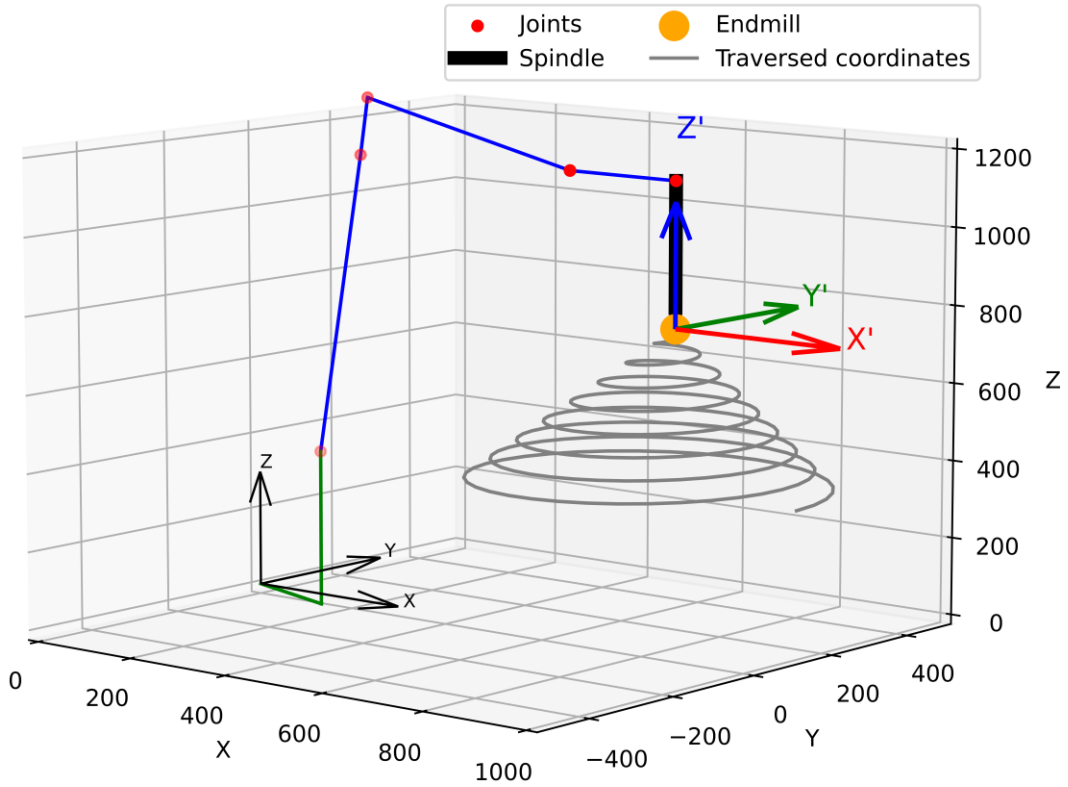
Implementation and Results

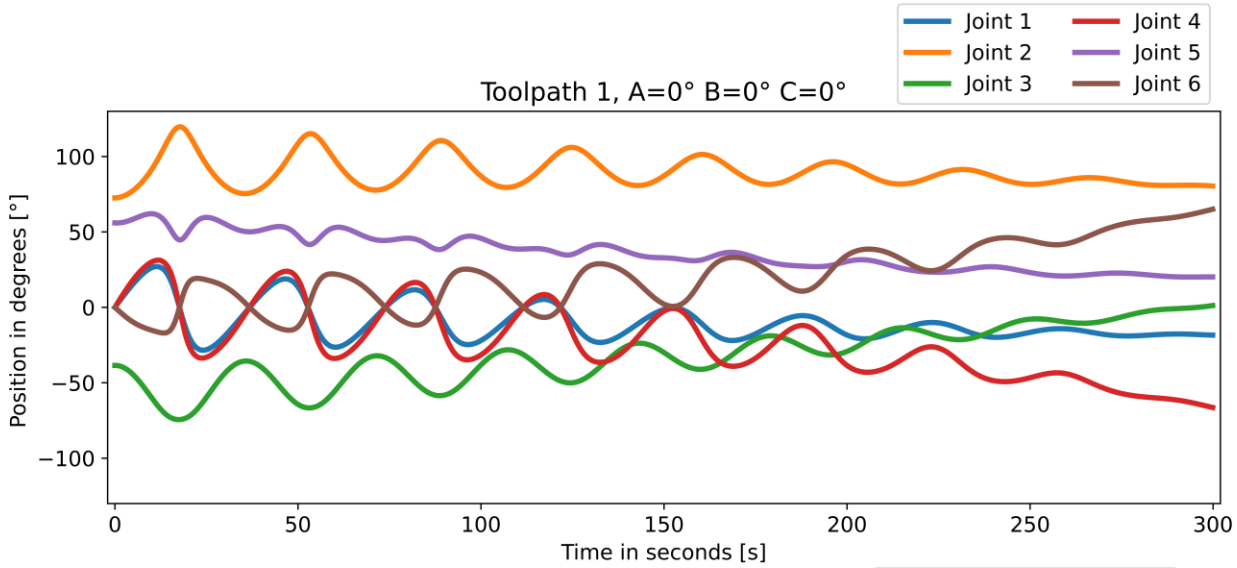


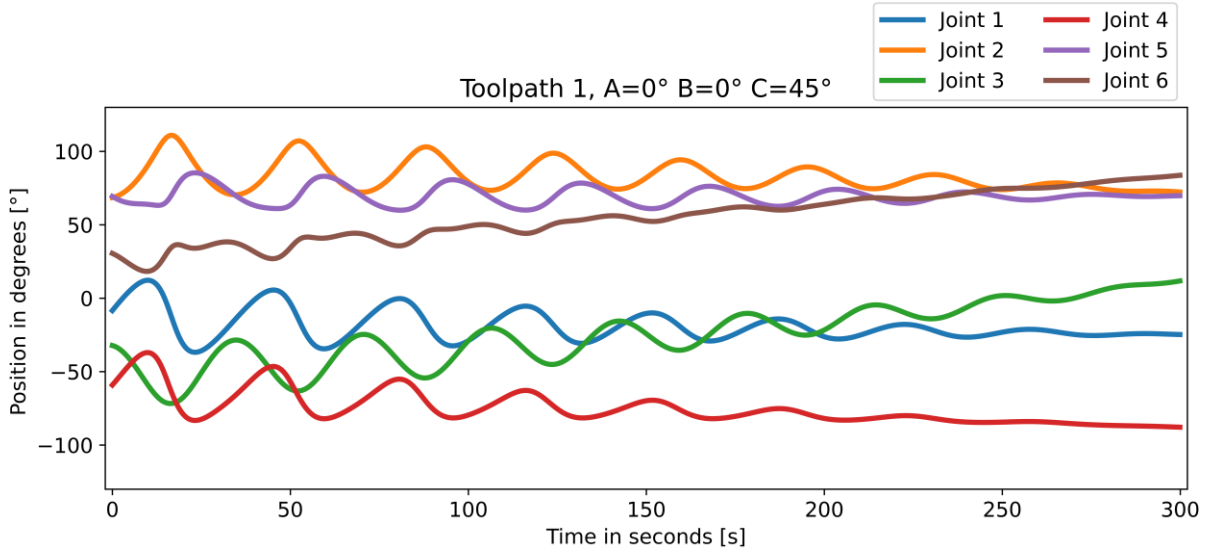


Extracting Joint Positions

Implementation and Results



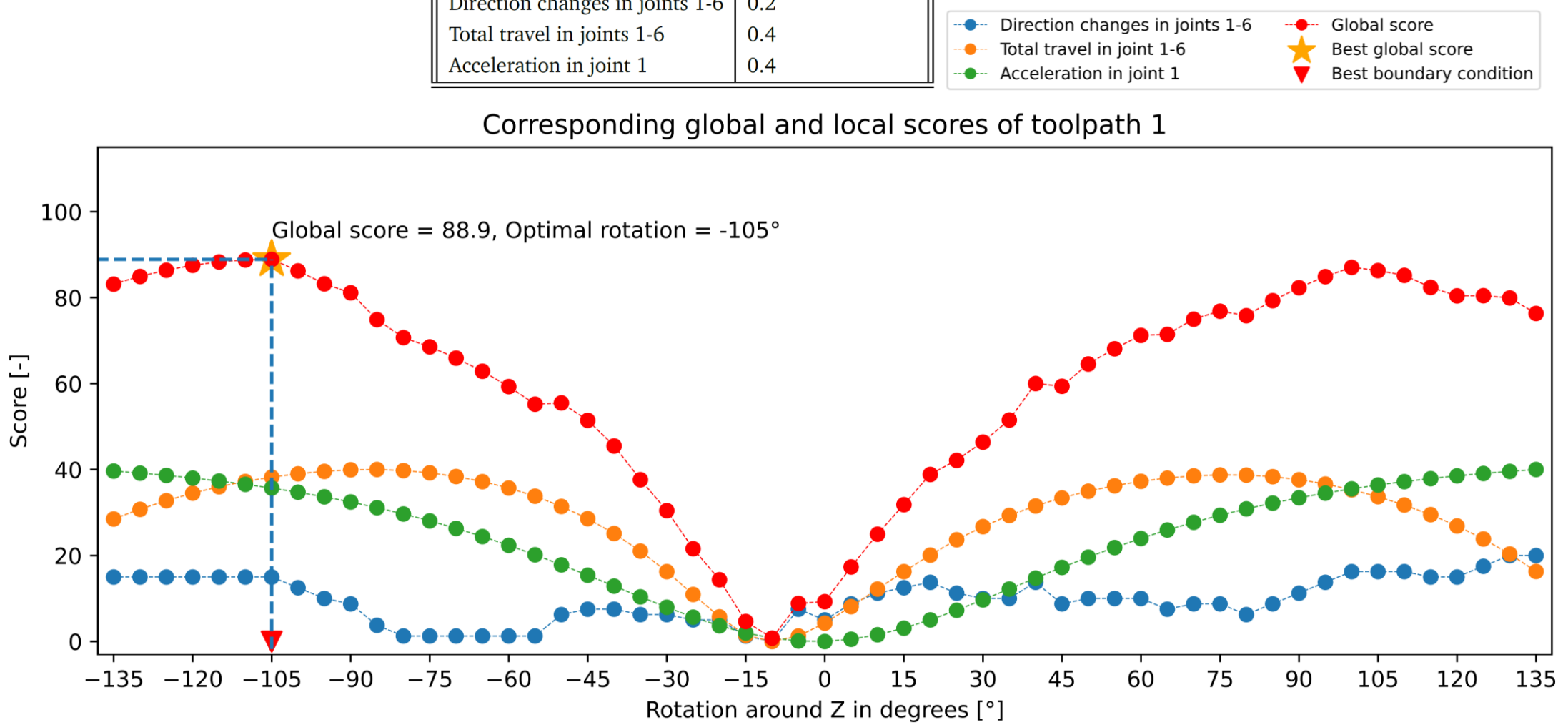




Local and Global Score

Implementation and Results

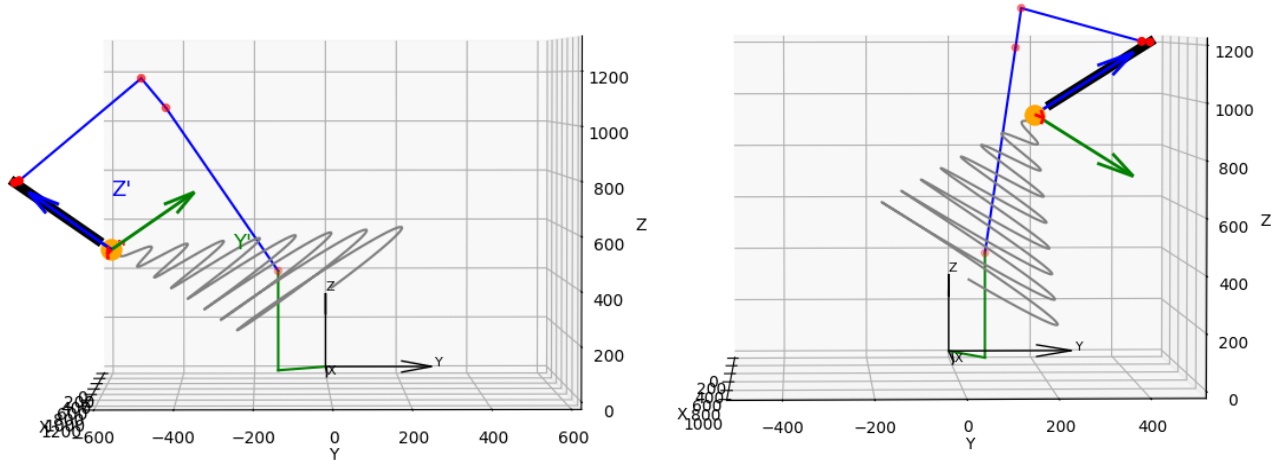
Process variables	Importance factors
Direction changes in joints 1-6	0.2
Total travel in joints 1-6	0.4
Acceleration in joint 1	0.4



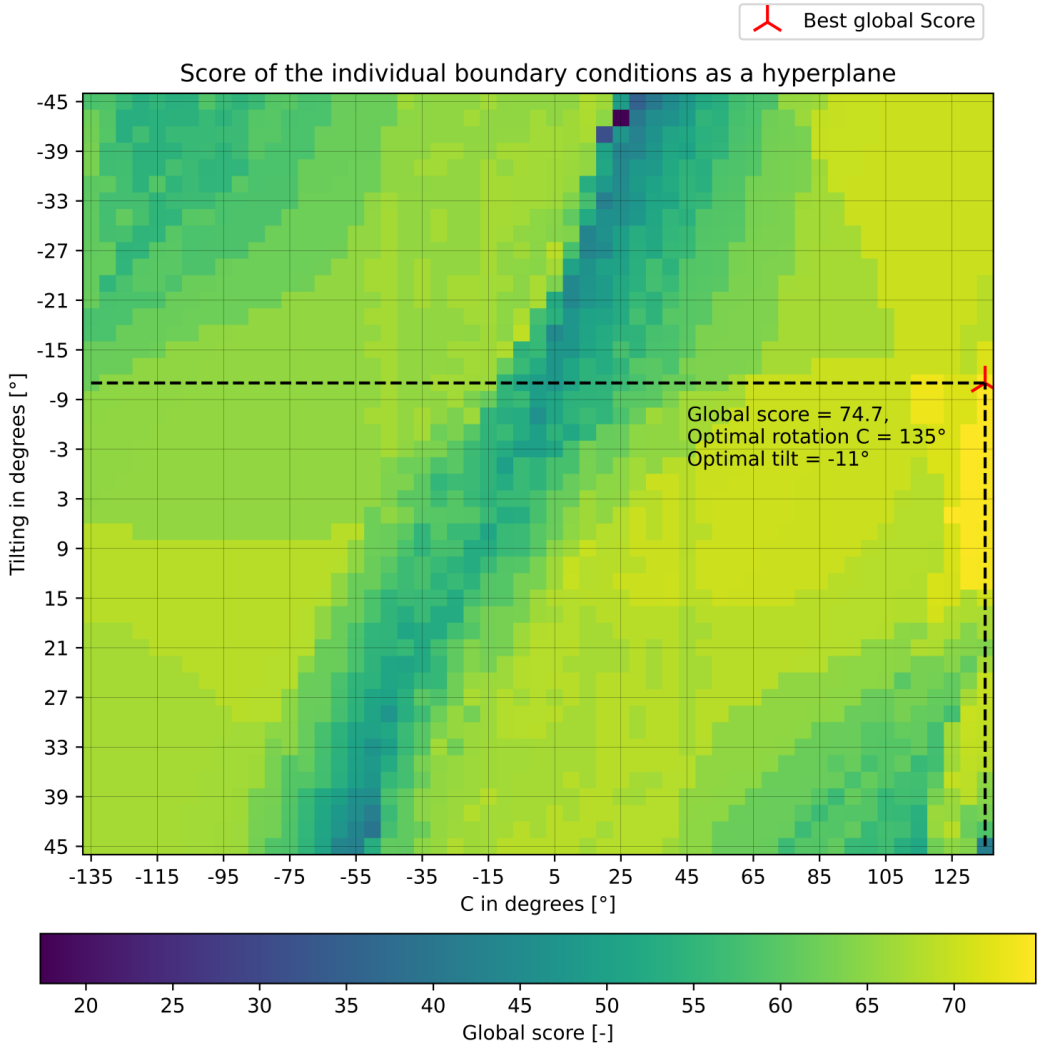
Addition of a Second Redundant DoF in Form of a Rotary-Tilt-Table

Implementation and Results

Two redundant DoFs: 1) Rotation C (tool symmetry axis)
2) Tilting of the base-plate

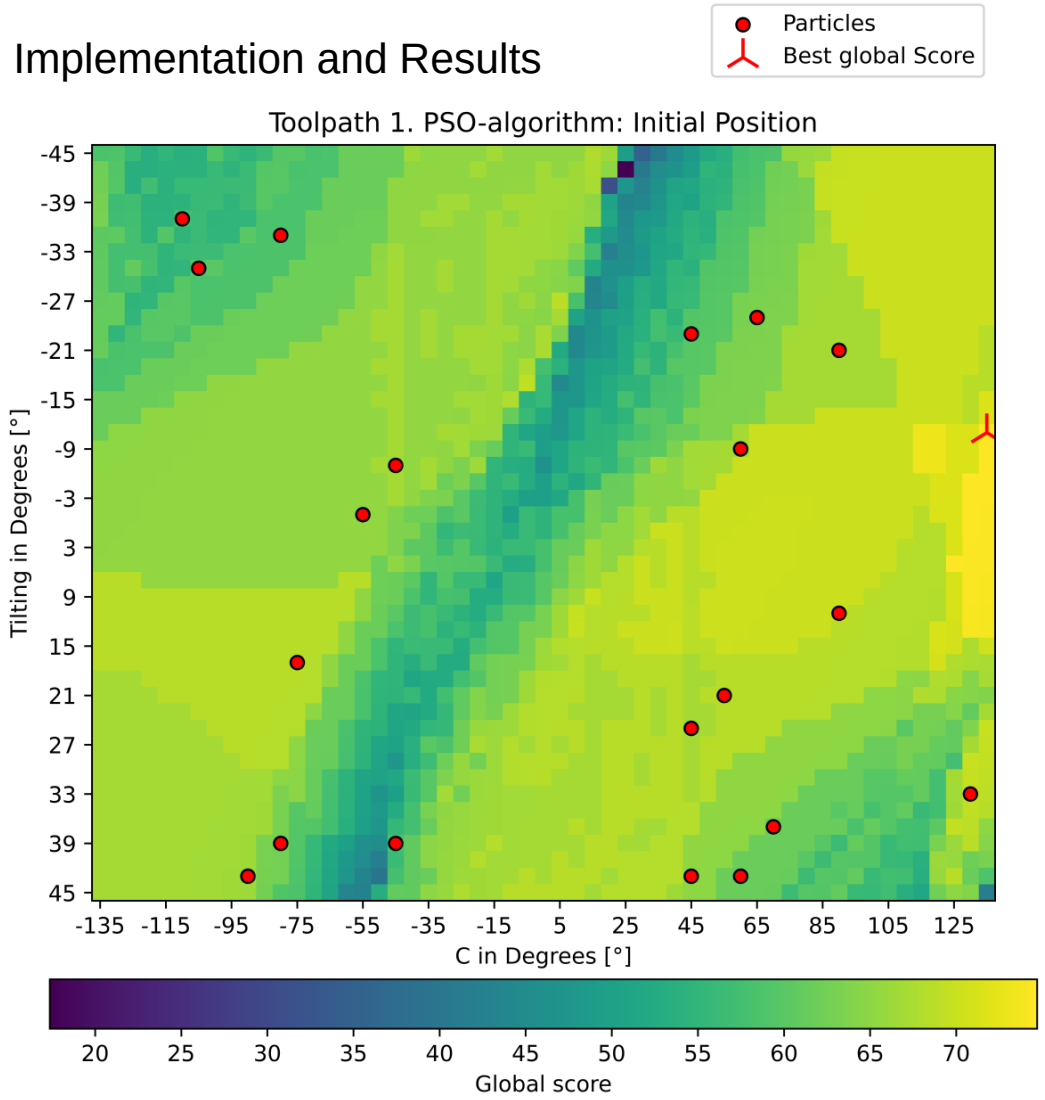


Process variables	Importance factors
Direction changes in joints 2+3+5	0.3
Direction changes in joints 1	0.25
Acceleration in joint 4	0.25
Velocity in joint 6	0.2

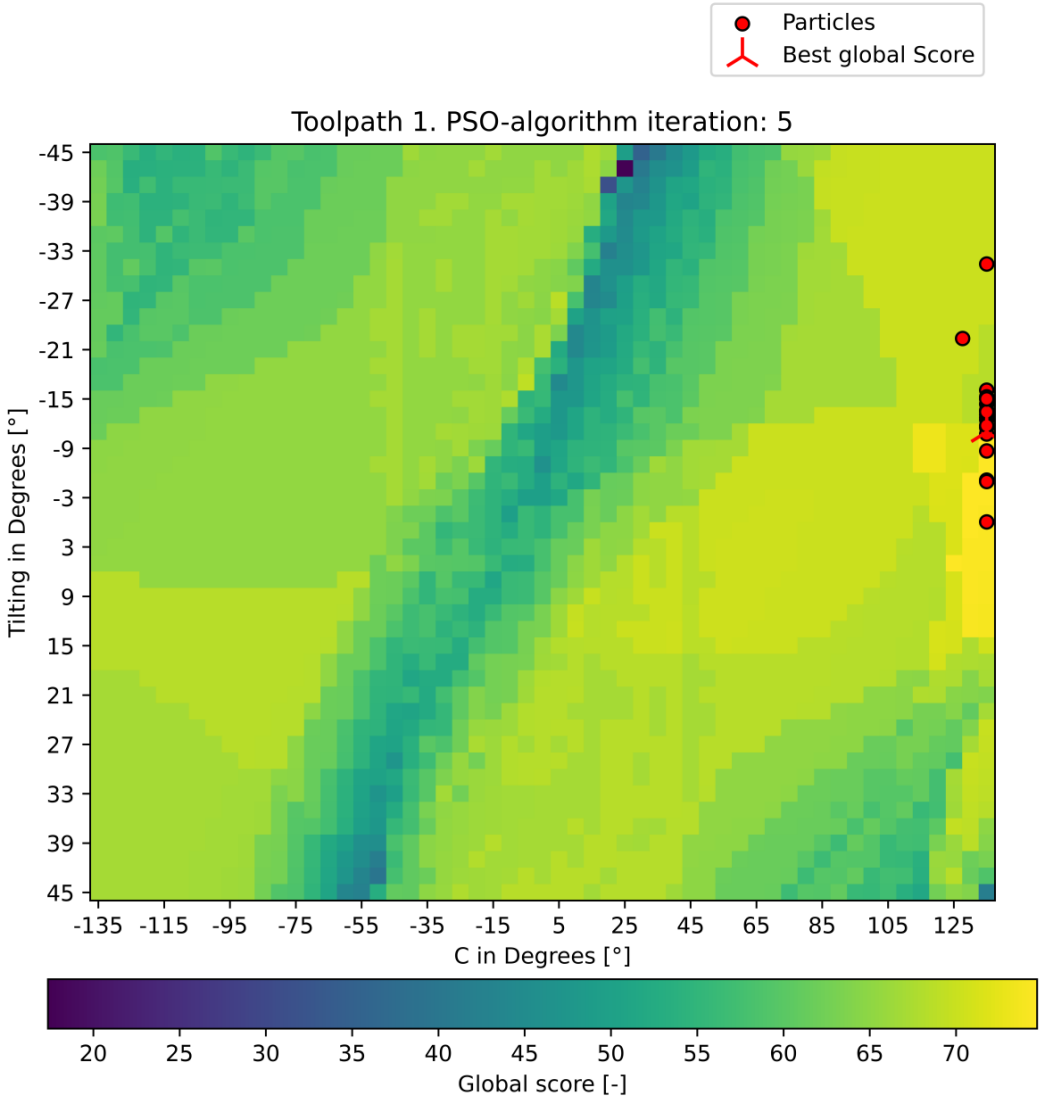


Implementation of a PSO-Algorithm

Implementation and Results

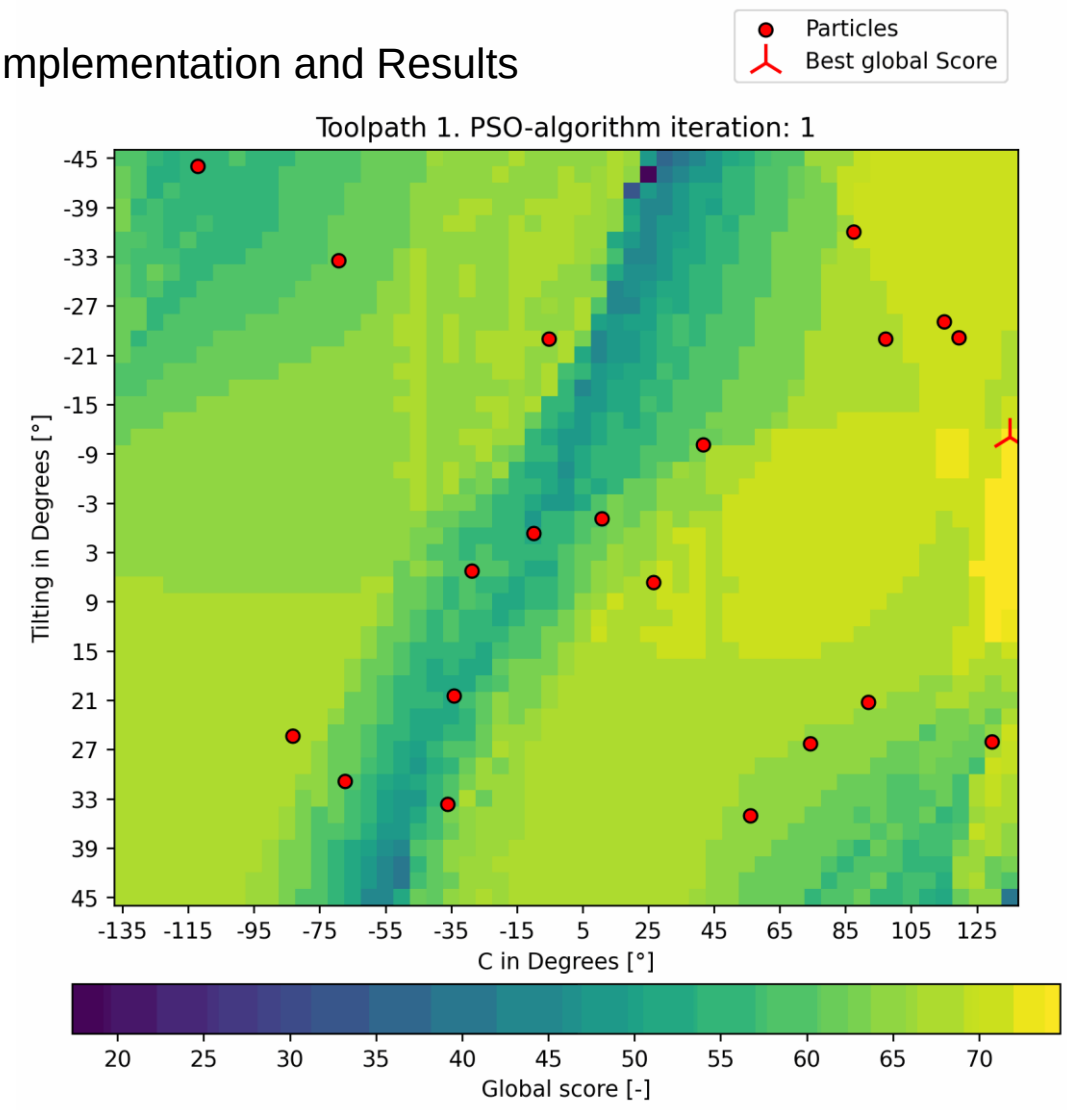


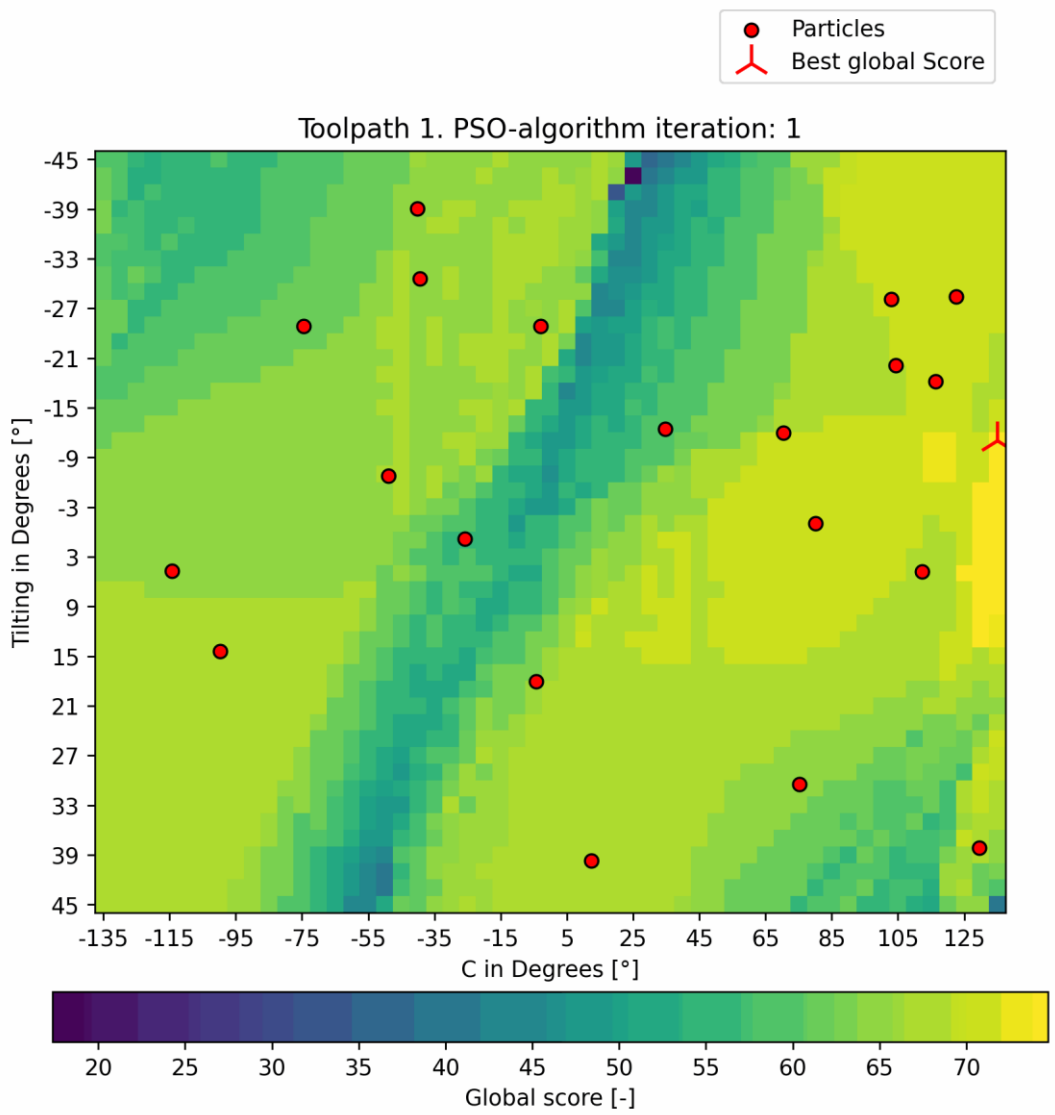
5 Iterations



Visualization of the PSO-Algorithm

Implementation and Results





Valid Proof Of Concept

Summary and Outlook

- The validation provides a solid proof-of-concept for the proposed methodology.
- It is shown that the redundant DoFs can offer significant potential for improvement in the robot’s movement.
- A PSO-algorithm is reasonable choice for finding the optimal boundary condition for two redundant DoF.
- The method's adaptability allows for wide application to a broad spectrum of robotic systems
- Additional factors need to be considered for detailed validation, such as longer production G-codes and complex multi-axis operations with more than two redundant DoFs.

Outlook:

- A combination with CAM-software can significantly reduce computation time
- Implementation of stiffens analysis
- Piecewise optimization of the toolpath instead of whole toolpath

Contact

Jan Nalivaika

Student at Siemens

☎ +49 163 7180148
✉ nalivaika@outlook.de

Ludwig Siebert

Supervisor at TUM

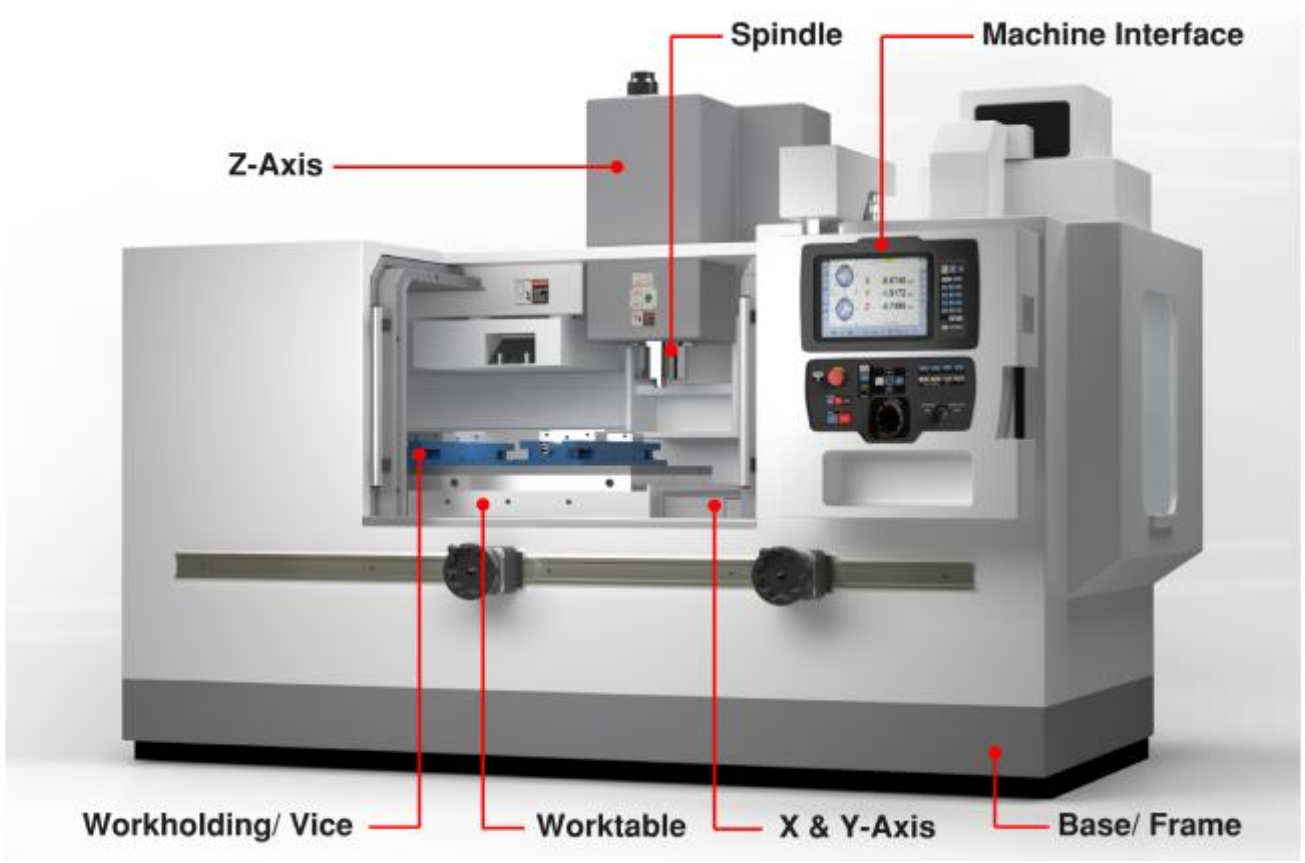
☎ +49 89 289 15578
✉ ludwig.siebert@iwb.tum.de

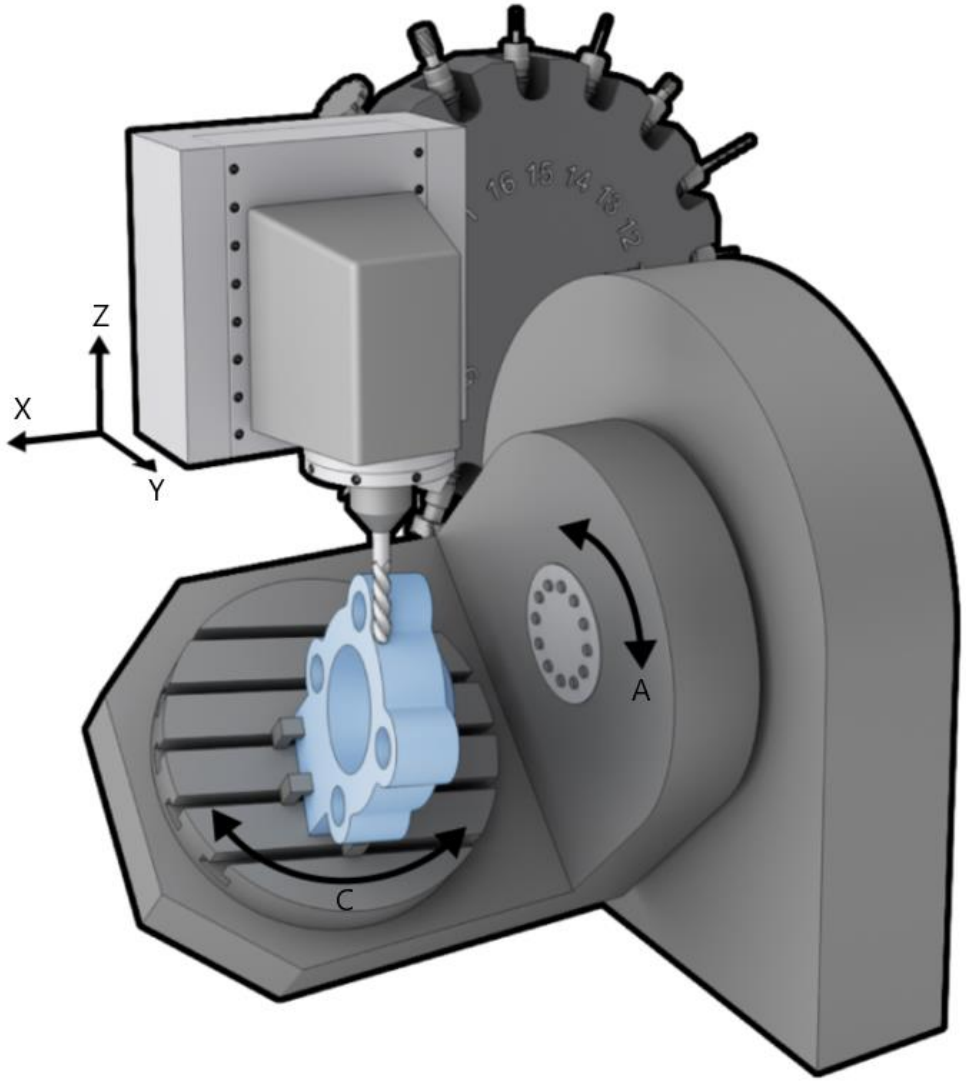
Marius Breuer

Supervisor at Siemens

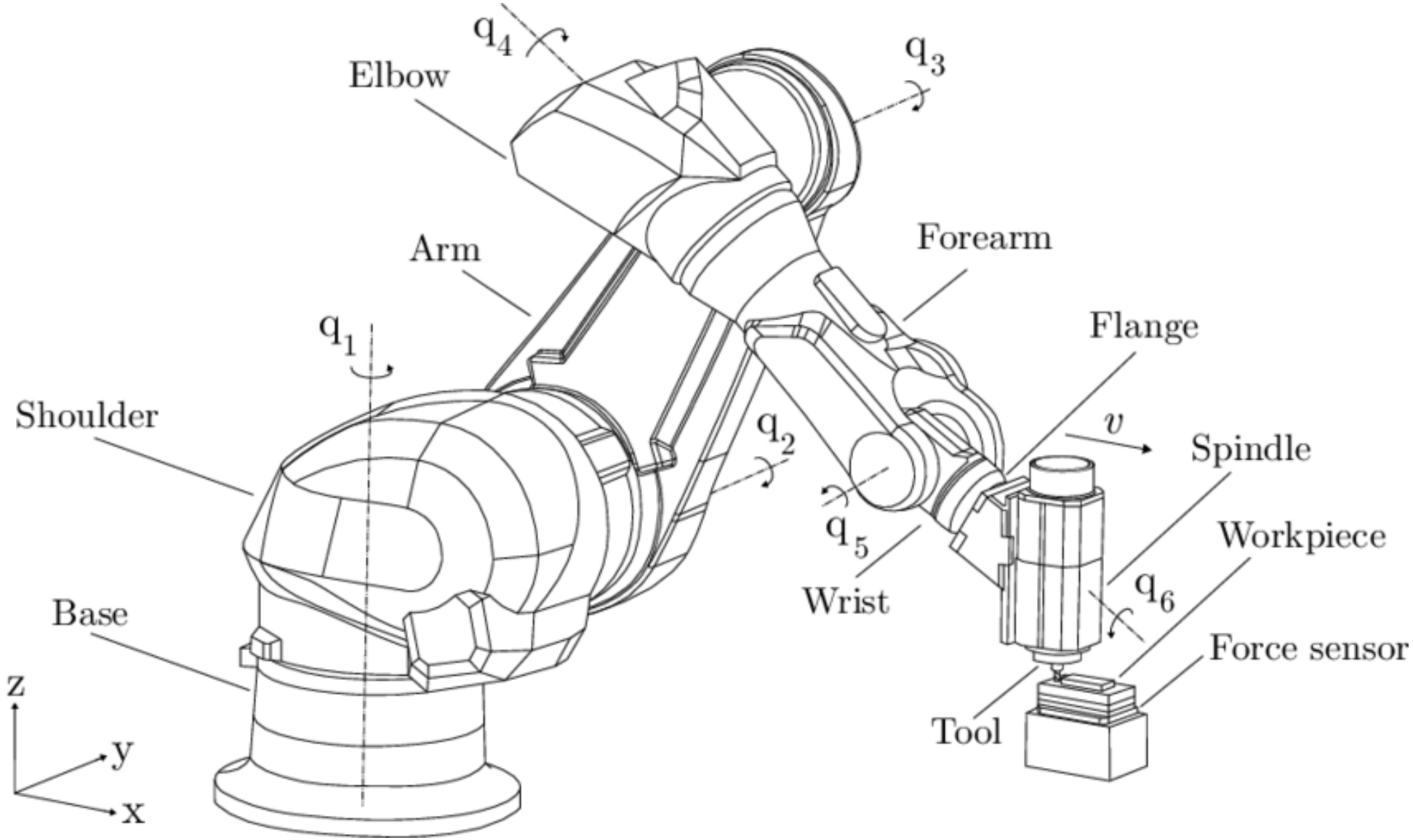
☎ +49 172 8396287
✉ marius.breuer@siemens.com

CNC machines

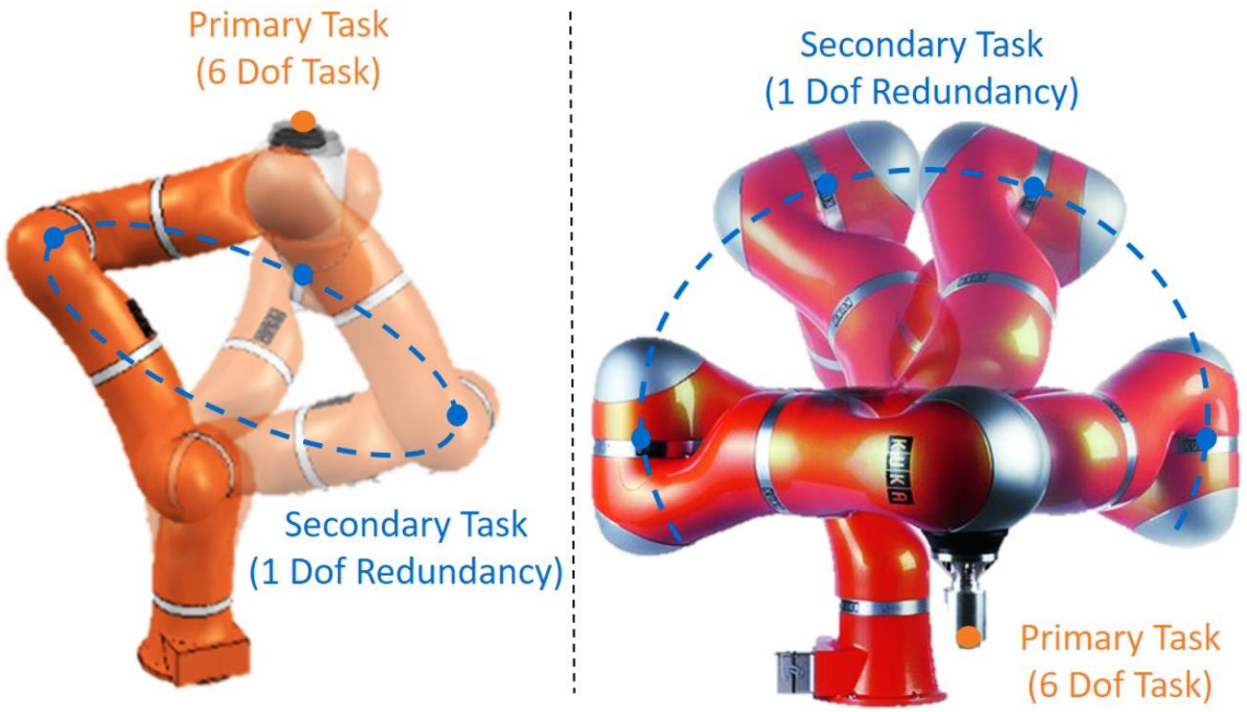




Industrial Robot

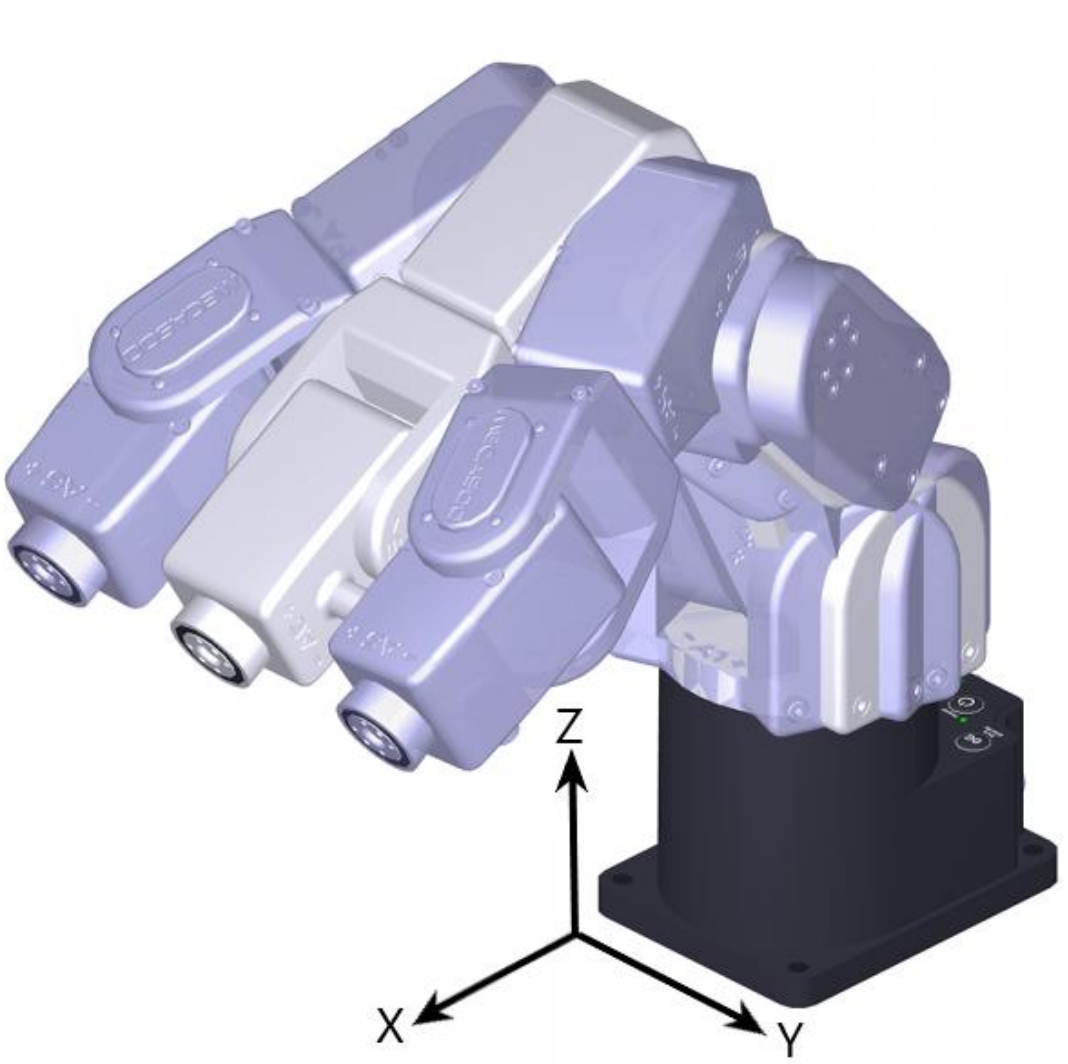


Manufacturing Systems with Redundant DoFs

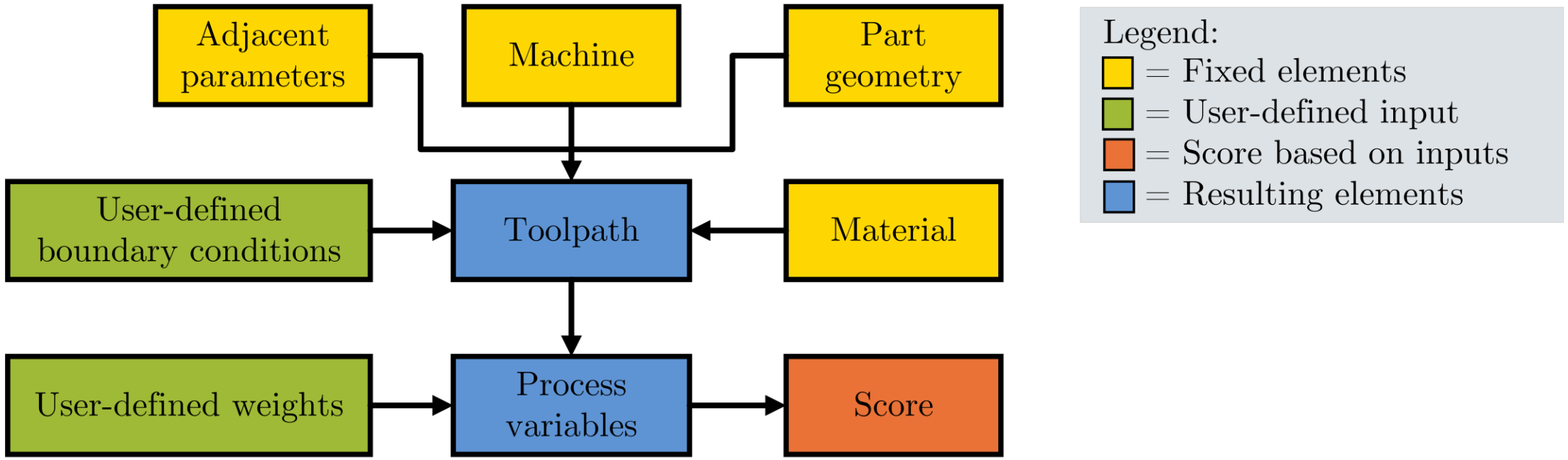


7 Dof Robot (KUKA LWR)

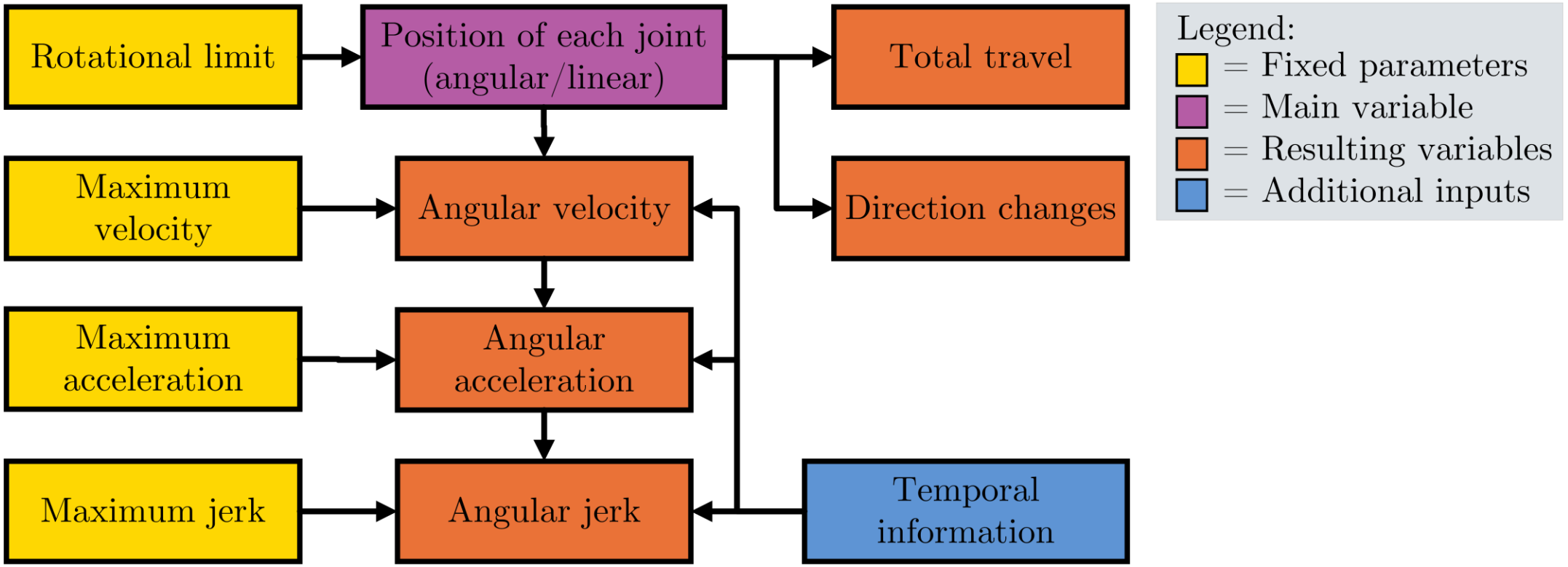
Singularity



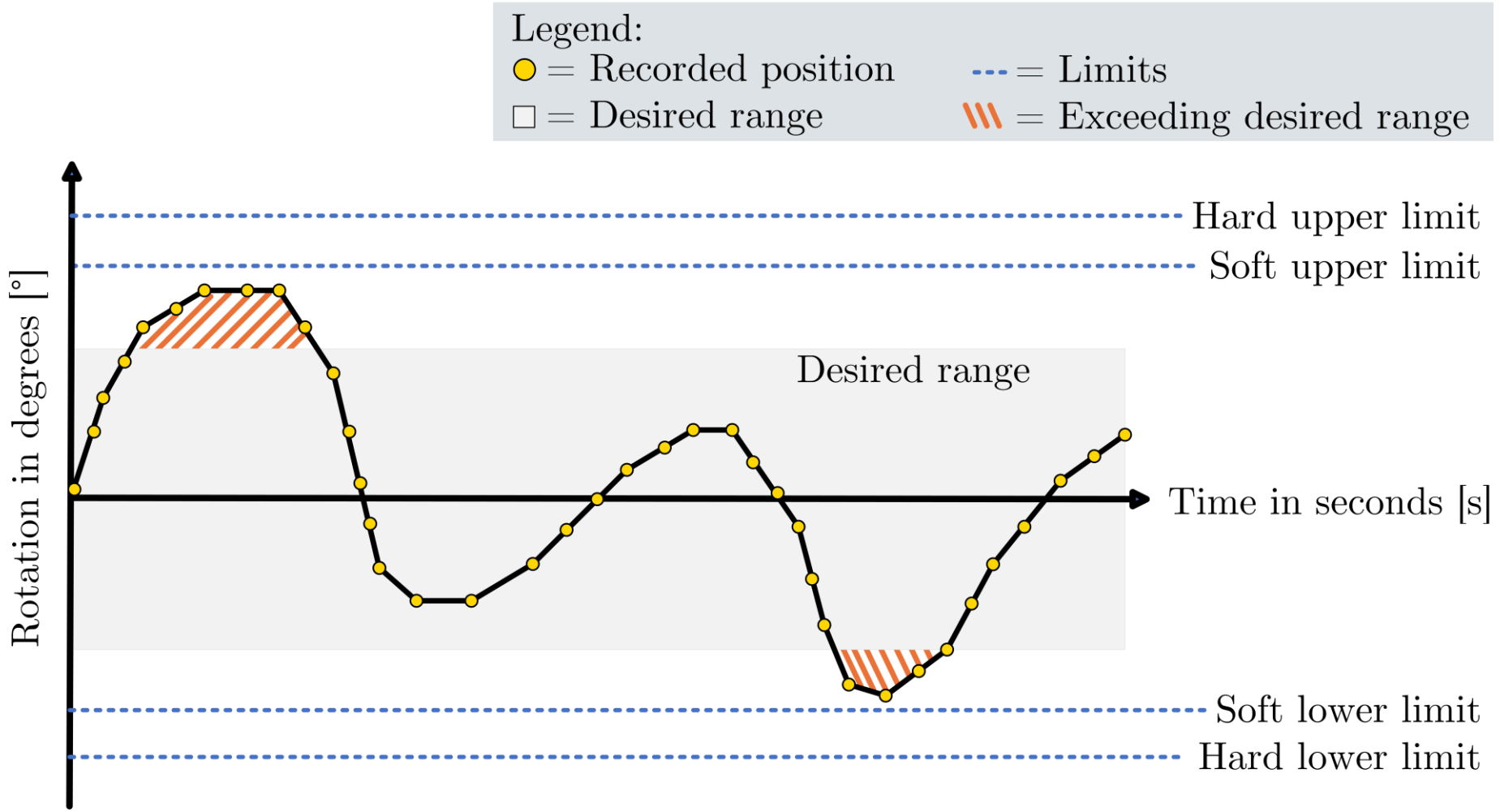
Interdependence of various parameters and elements



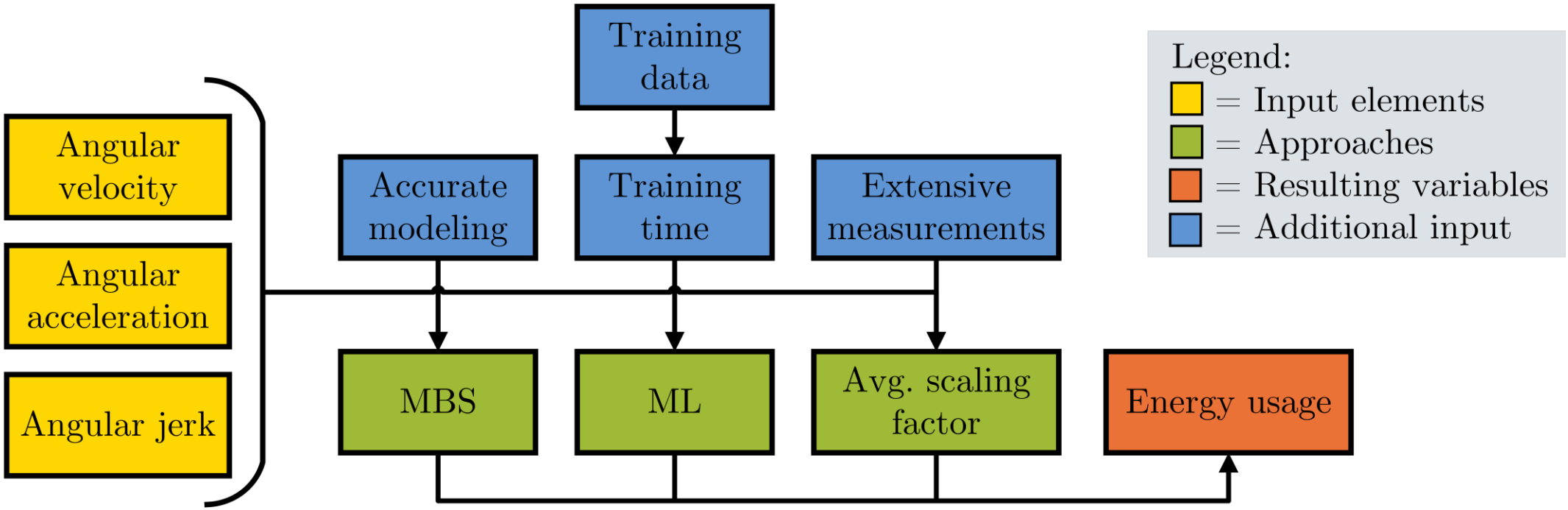
Additional information for angular position of each joint



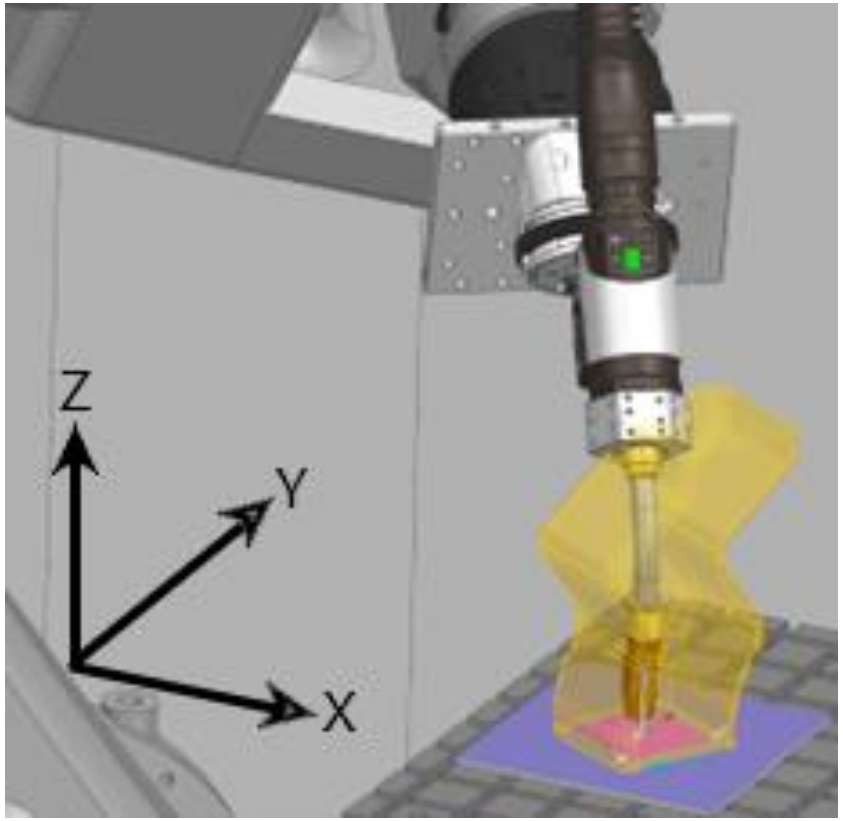
Hard and soft limits with desired range

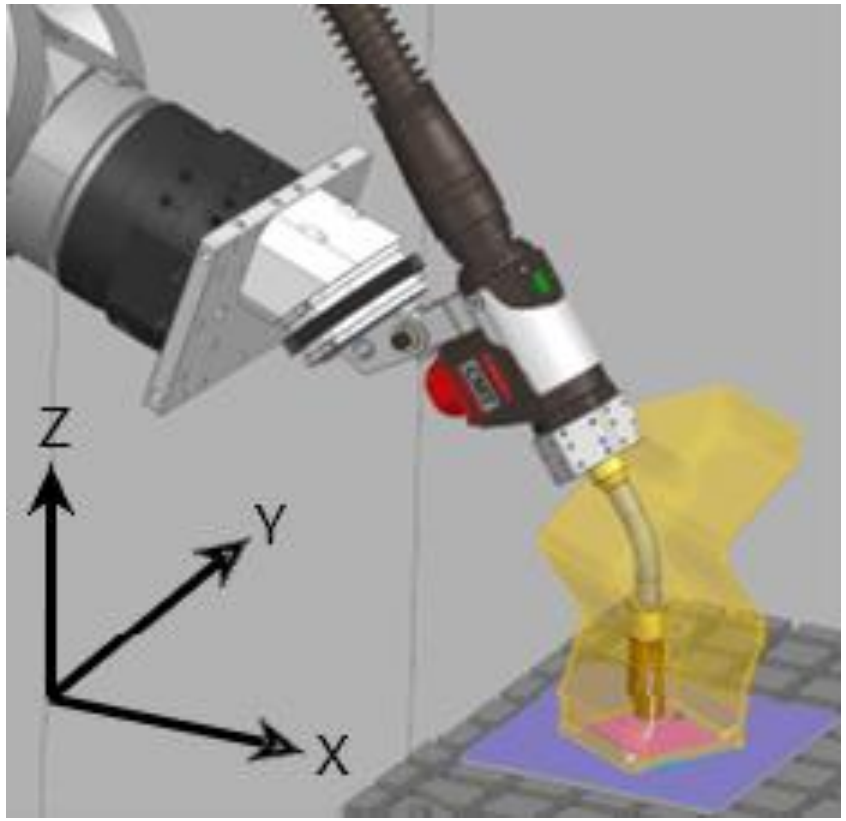


Exemplary methods for energy usage calculations



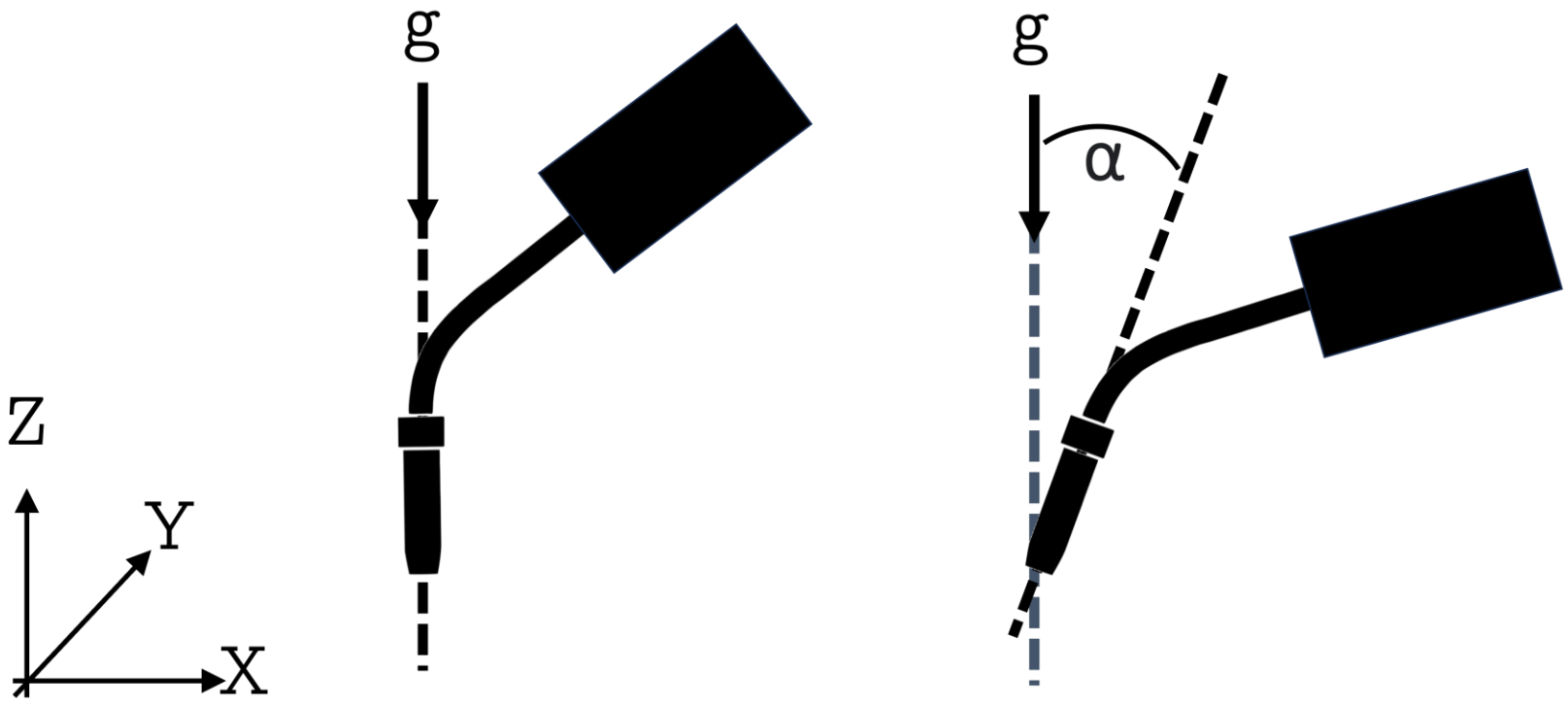
Rotation around the C-Axis of a welding torch



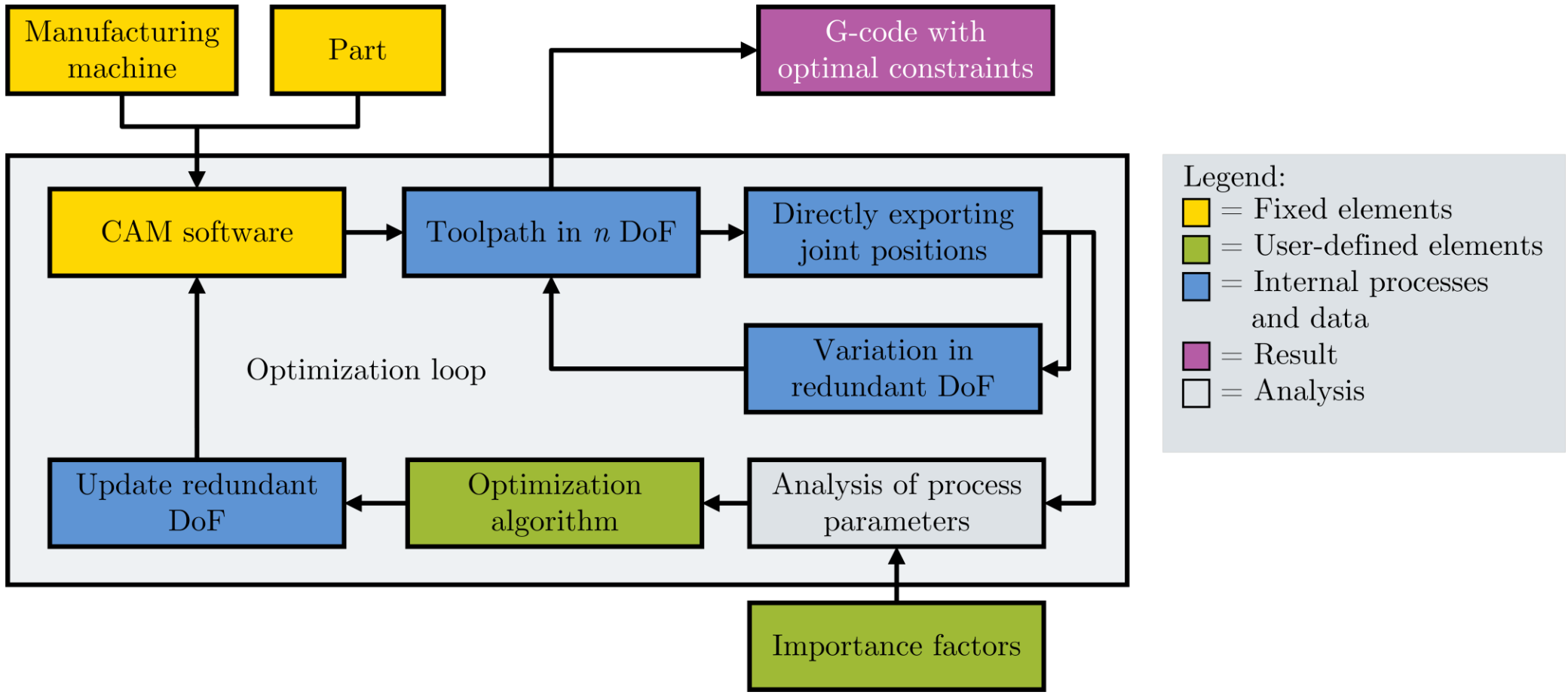


Torch Orientation

Example of optimal and non-optimal tilt in the welding torch

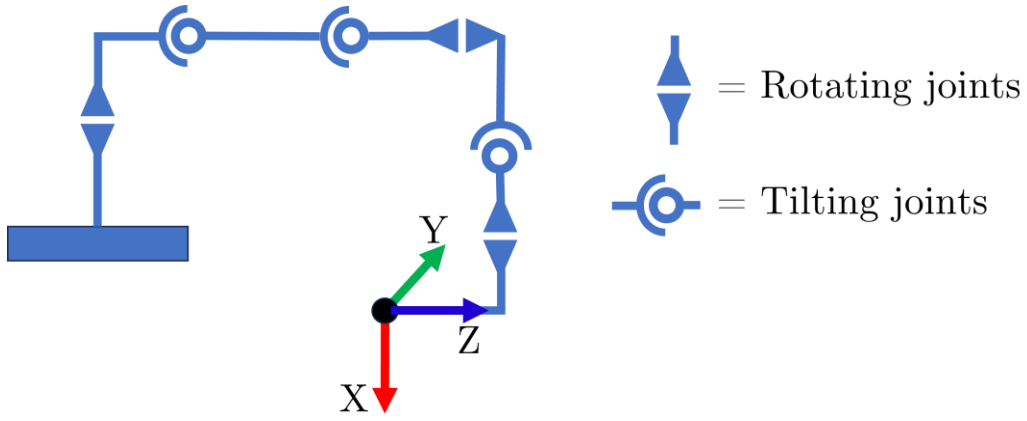


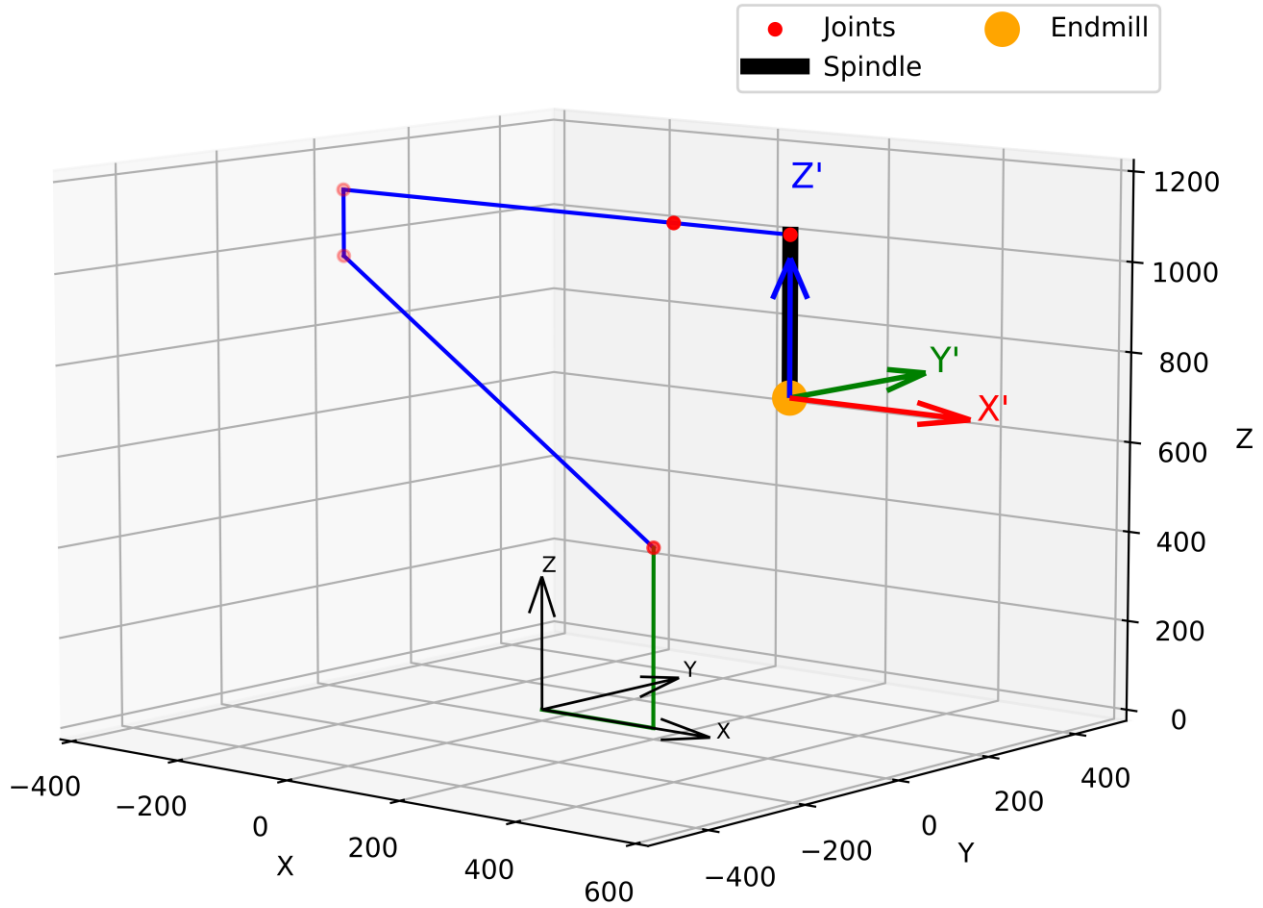
Optimization Loop With CAM Software in the Loop



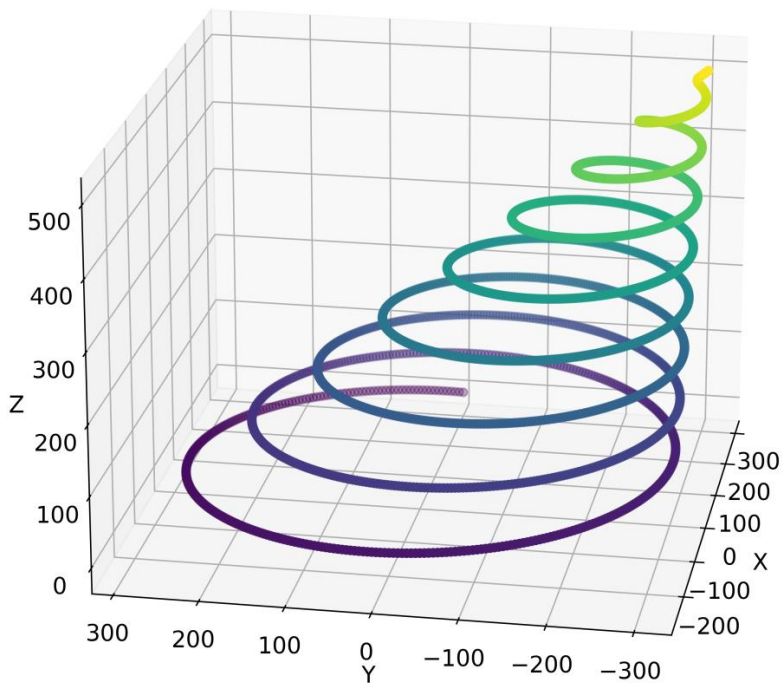
Modeled Robot

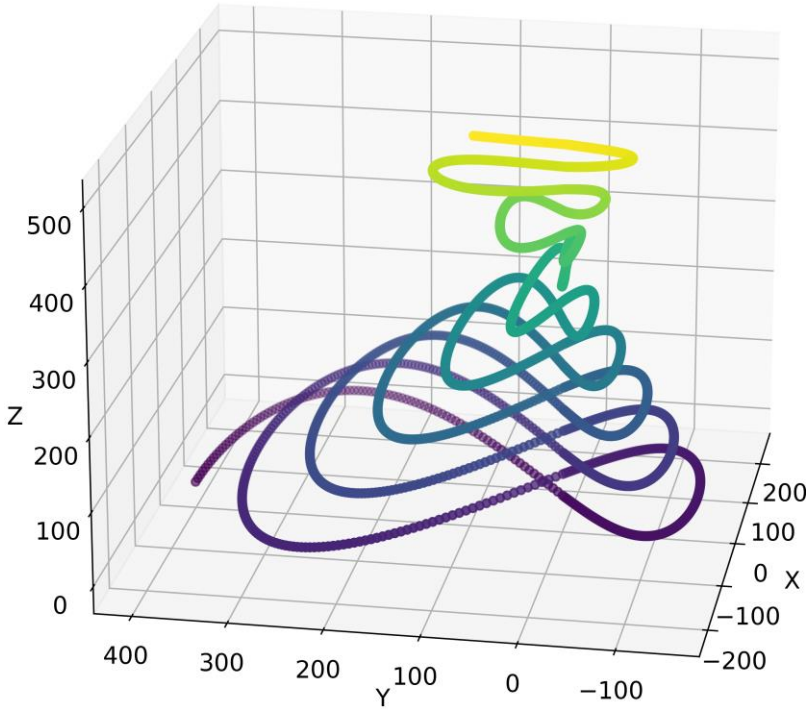
Parameters	Values
a in [mm]	[200, 800, 150, 0, 0, 0]
alpha in [°]	[90, 0, 90, -90, 90, 0]
d in [mm]	[400 0, 0, 600, 0, 200]

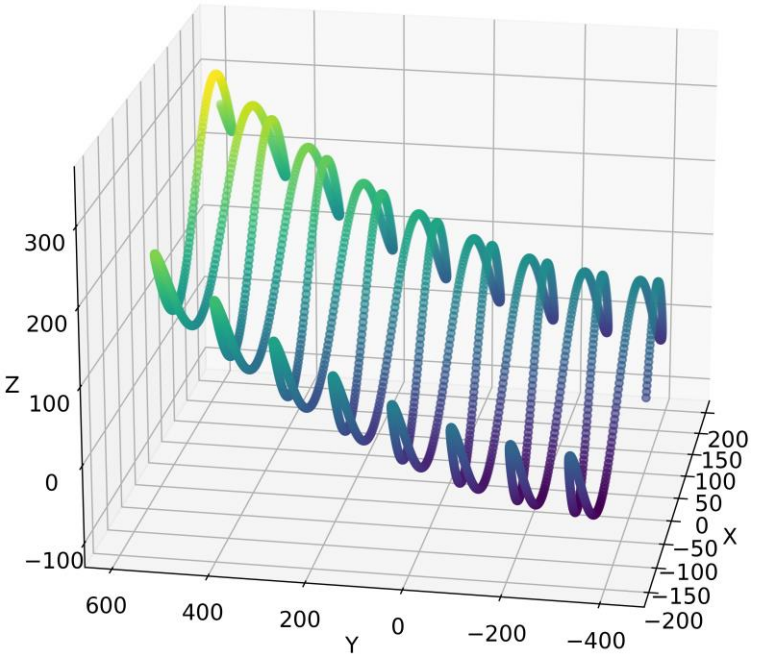




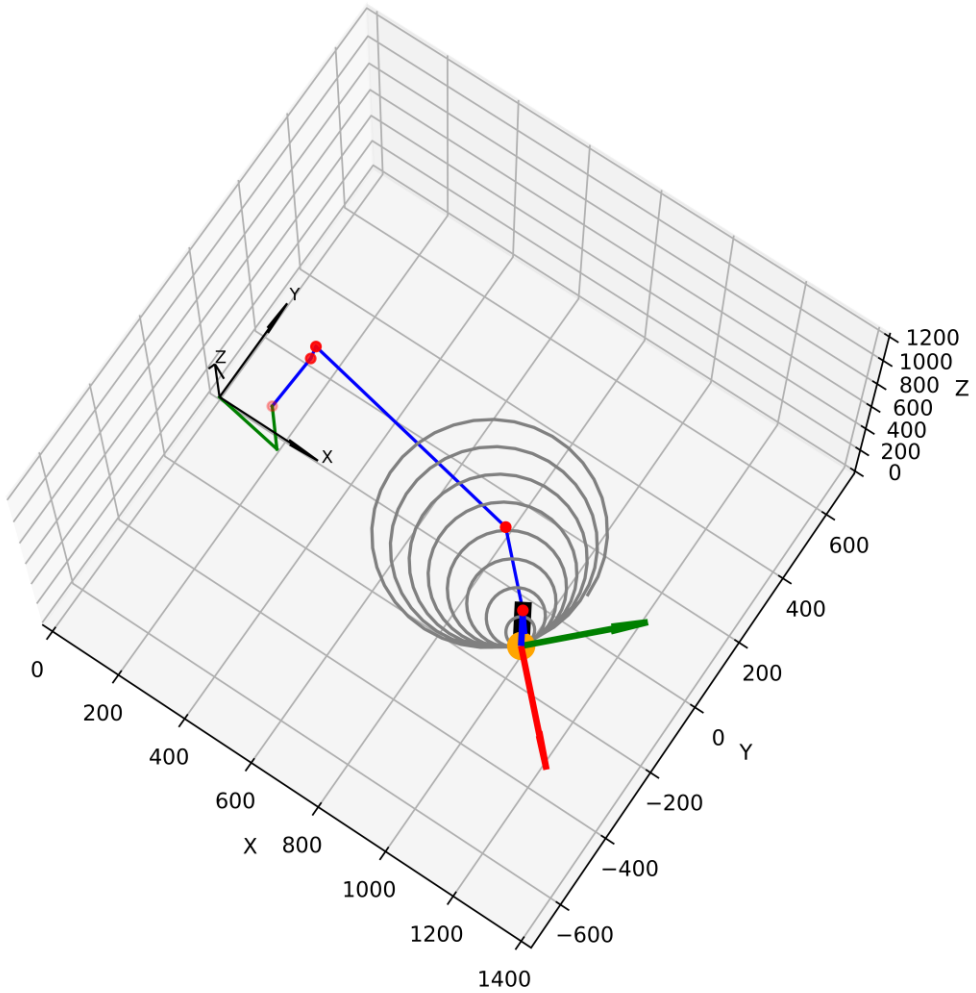
Modeling a Basic Toolpath

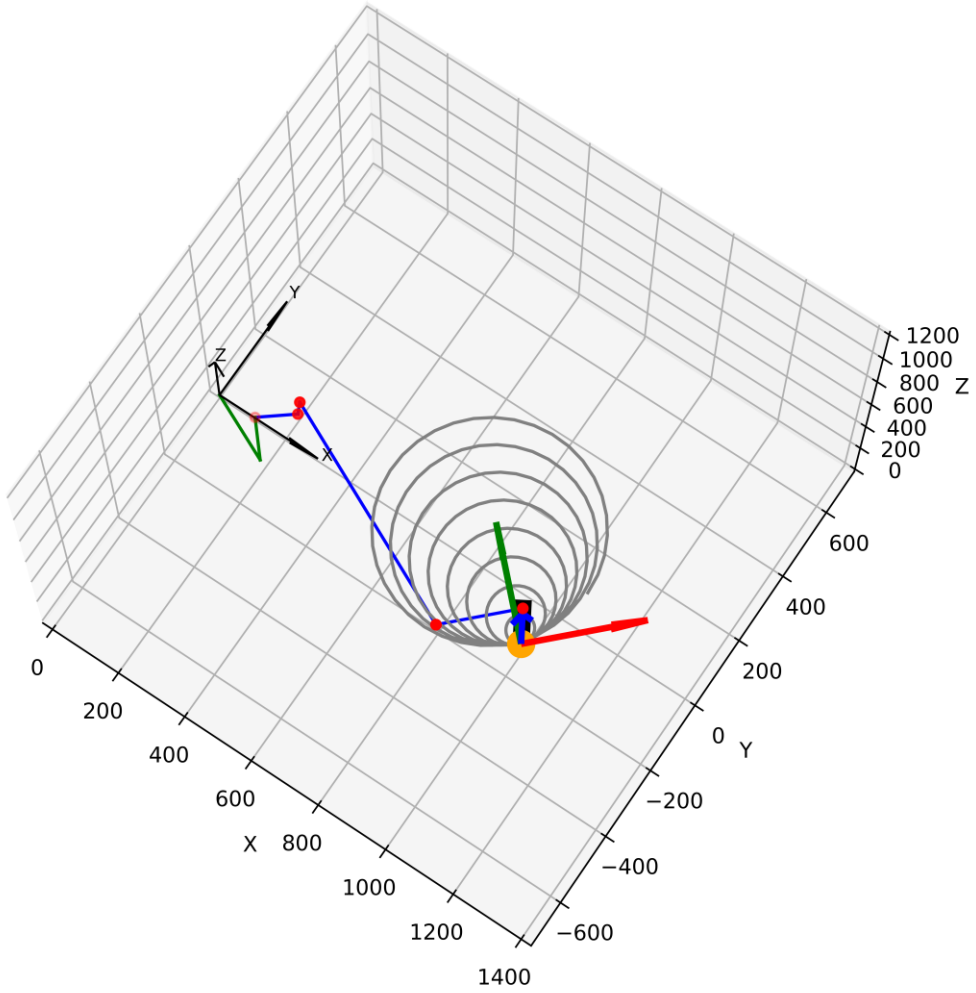




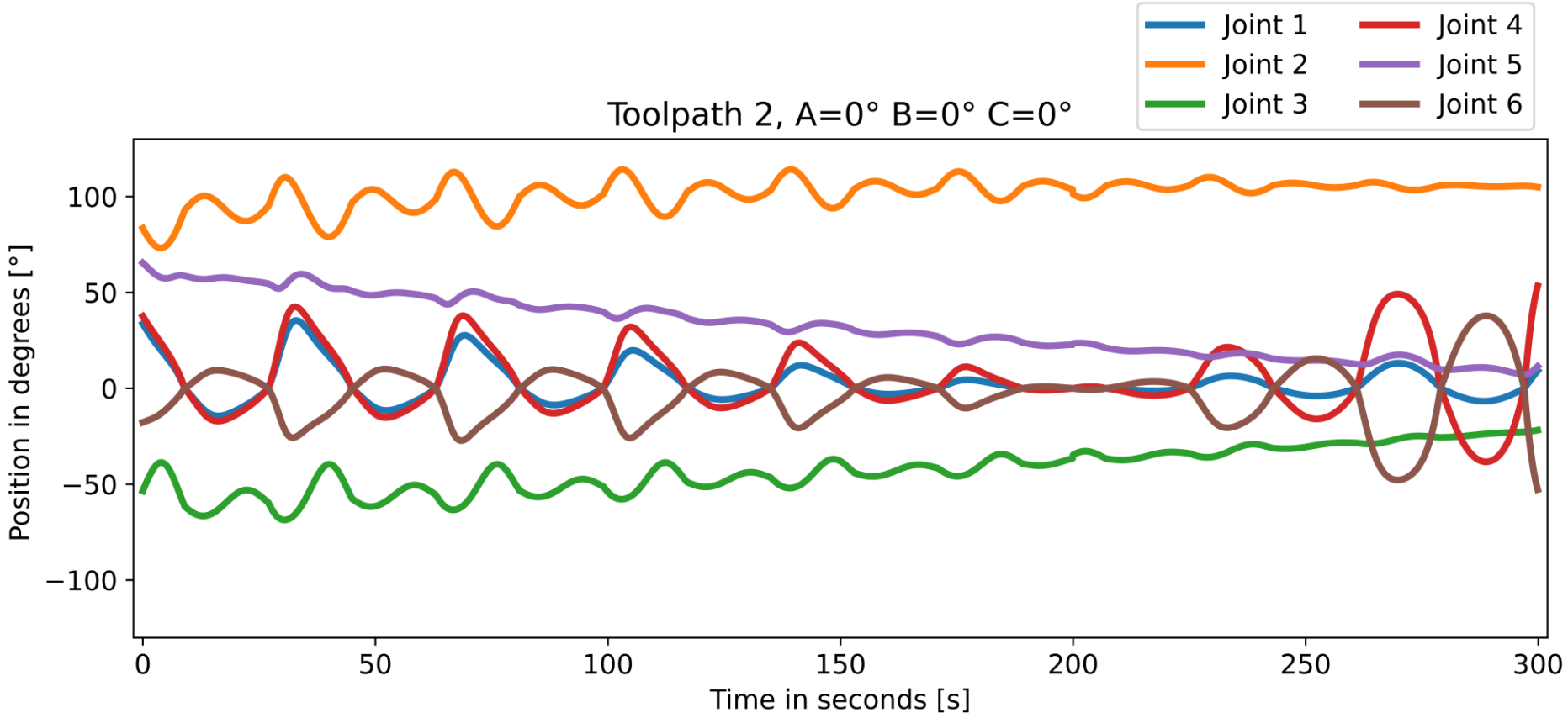


Rotation around the Z-axis for toolpath 1

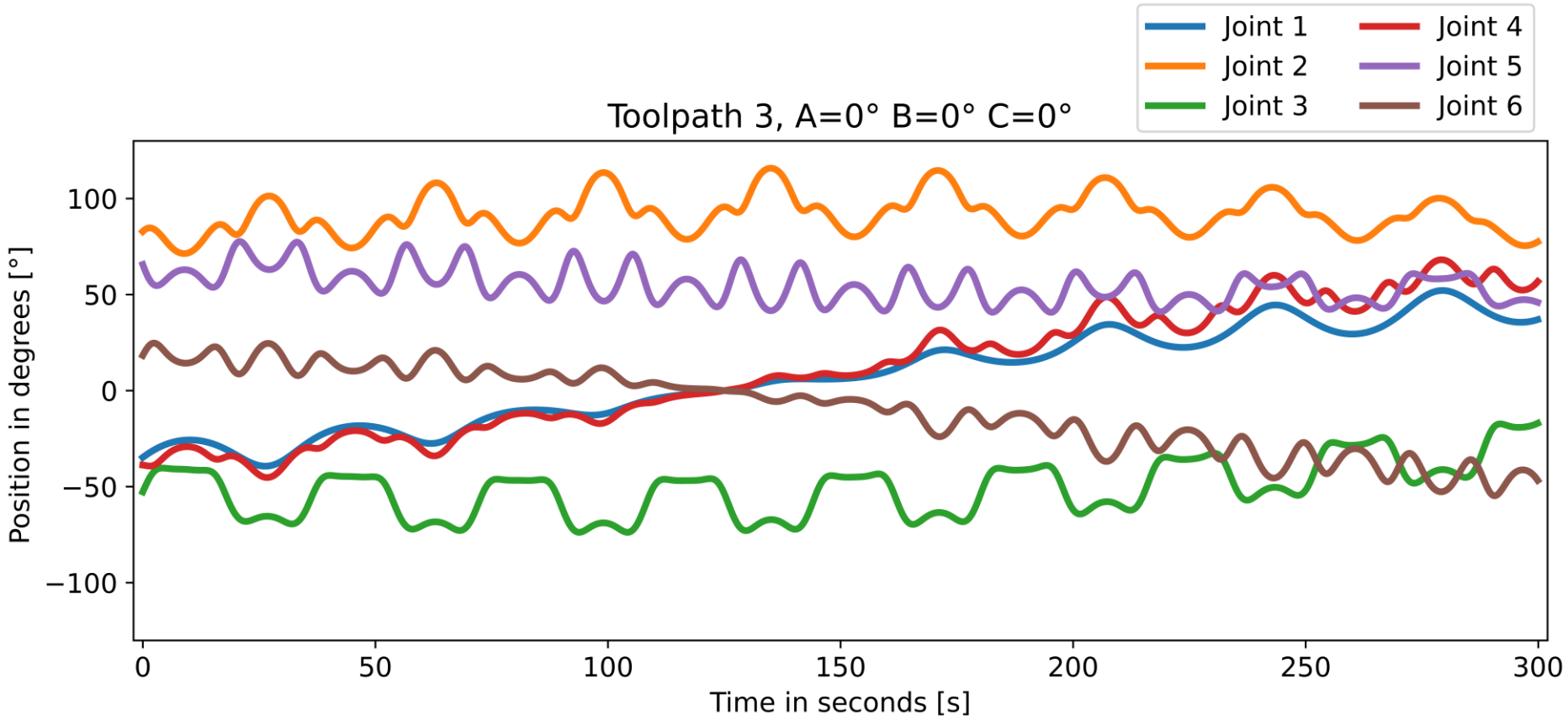




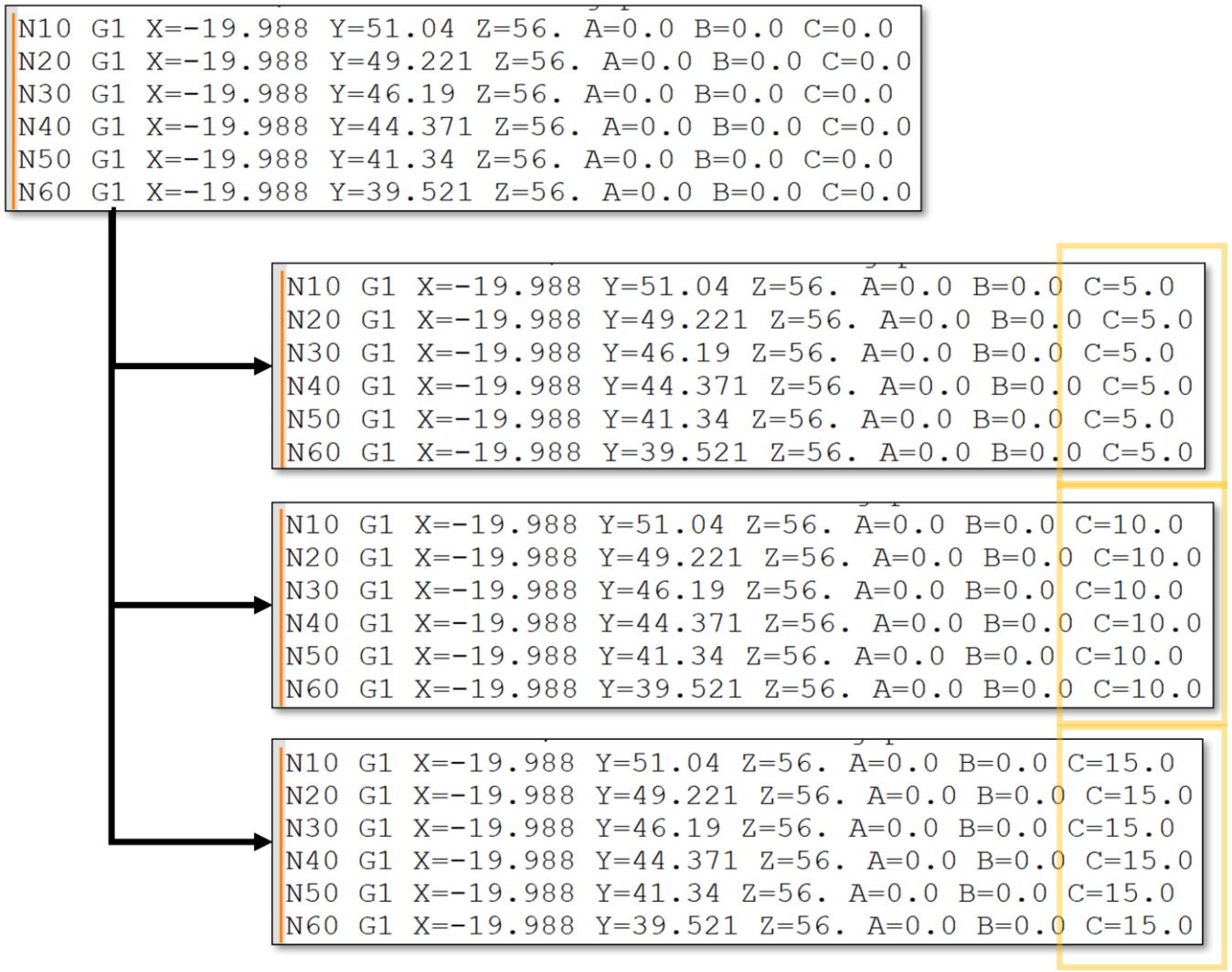
Toolpath 2


Toolpath 2, A=0° B=0° C=0°
Joint 1
Joint 2
Joint 3
Joint 4
Joint 5
Joint 6
Position in degrees [°]
100
50
0
−50
−100
0
50
100
150
200
250
300
Time in seconds [s]

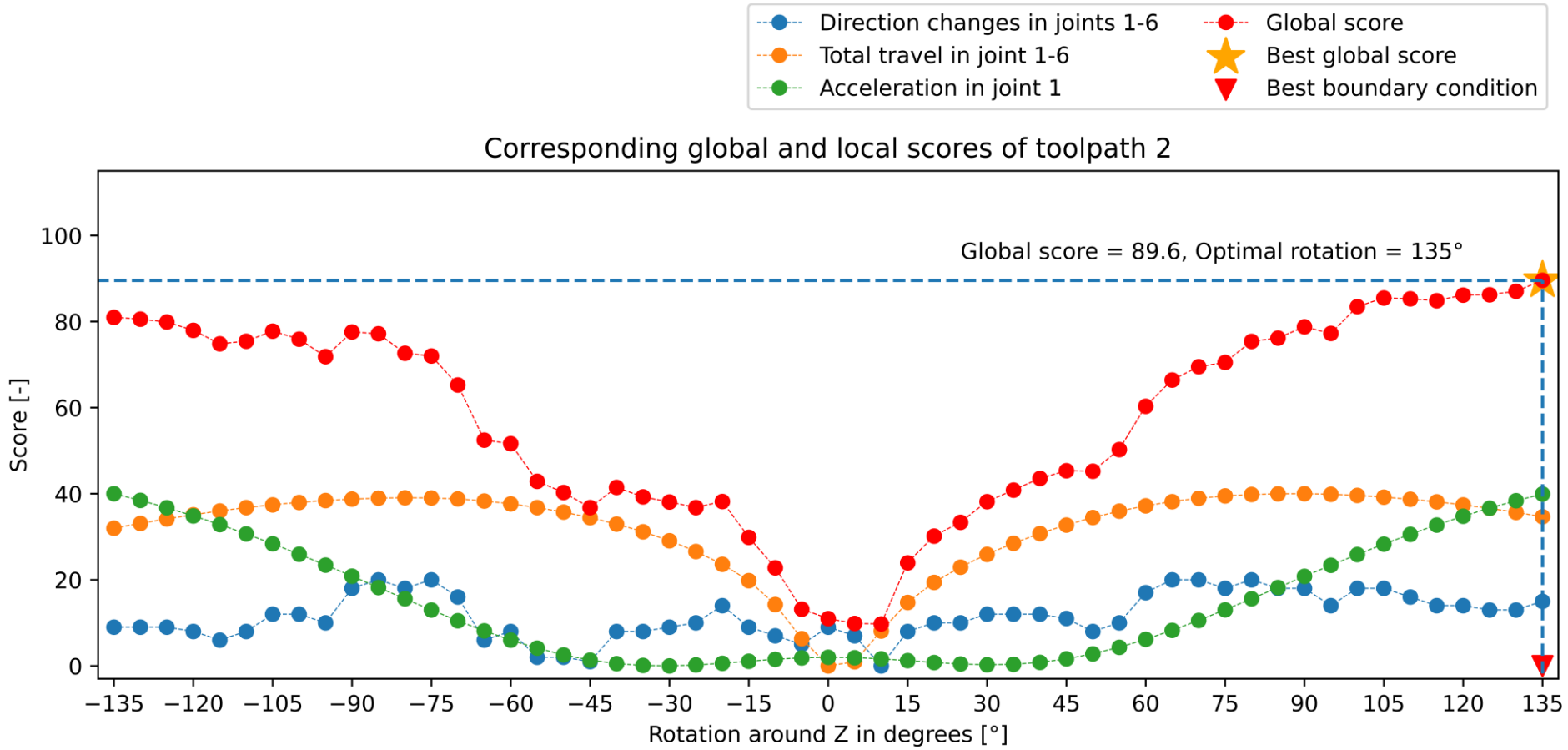
Toolpath 3


Joint 1
Joint 2
Joint 3
Joint 4
Joint 5
Joint 6
Toolpath 3, A=0° B=0° C=0°
Position in degrees [°]
100
50
0
−50
−100
0
50
100
150
200
250
300
Time in seconds [s]

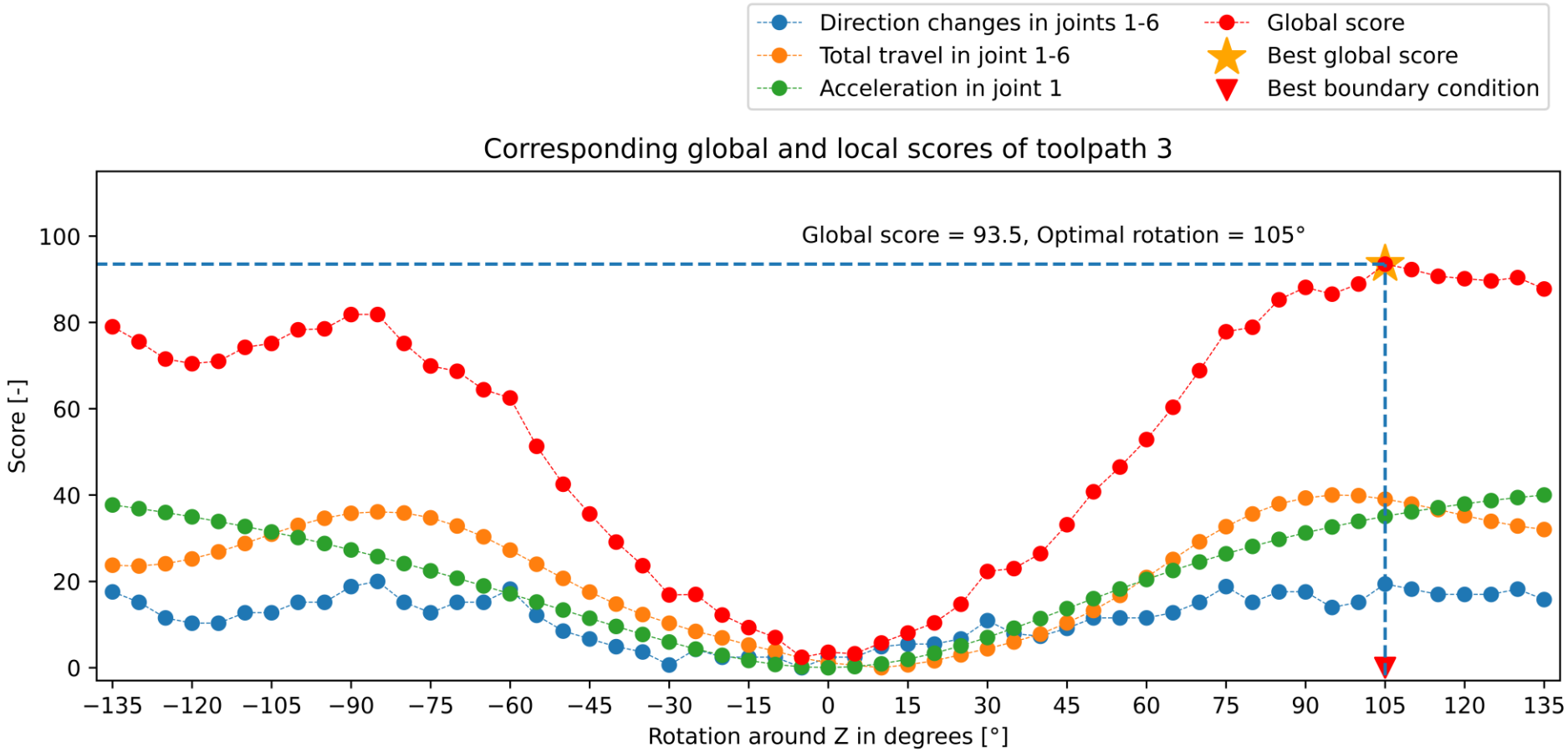
G-code Variation

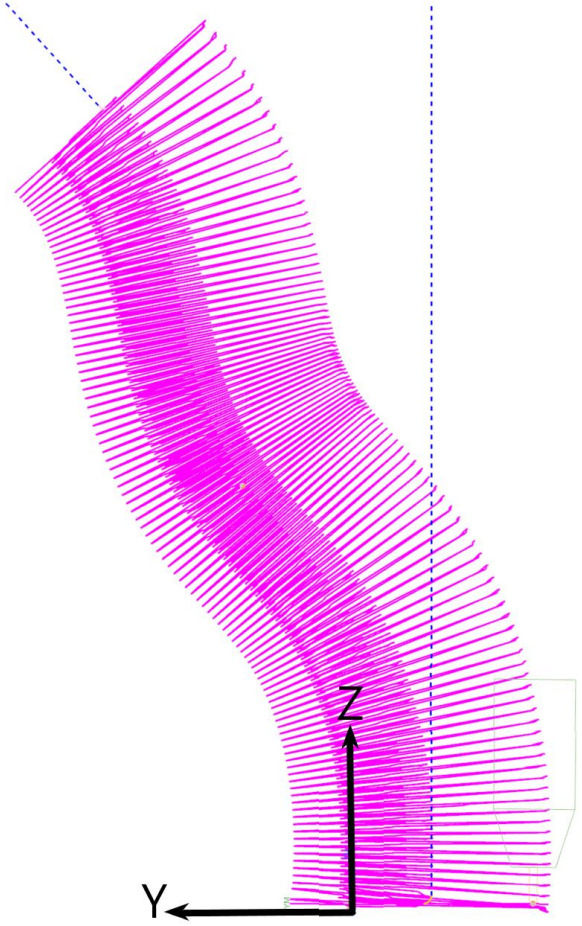


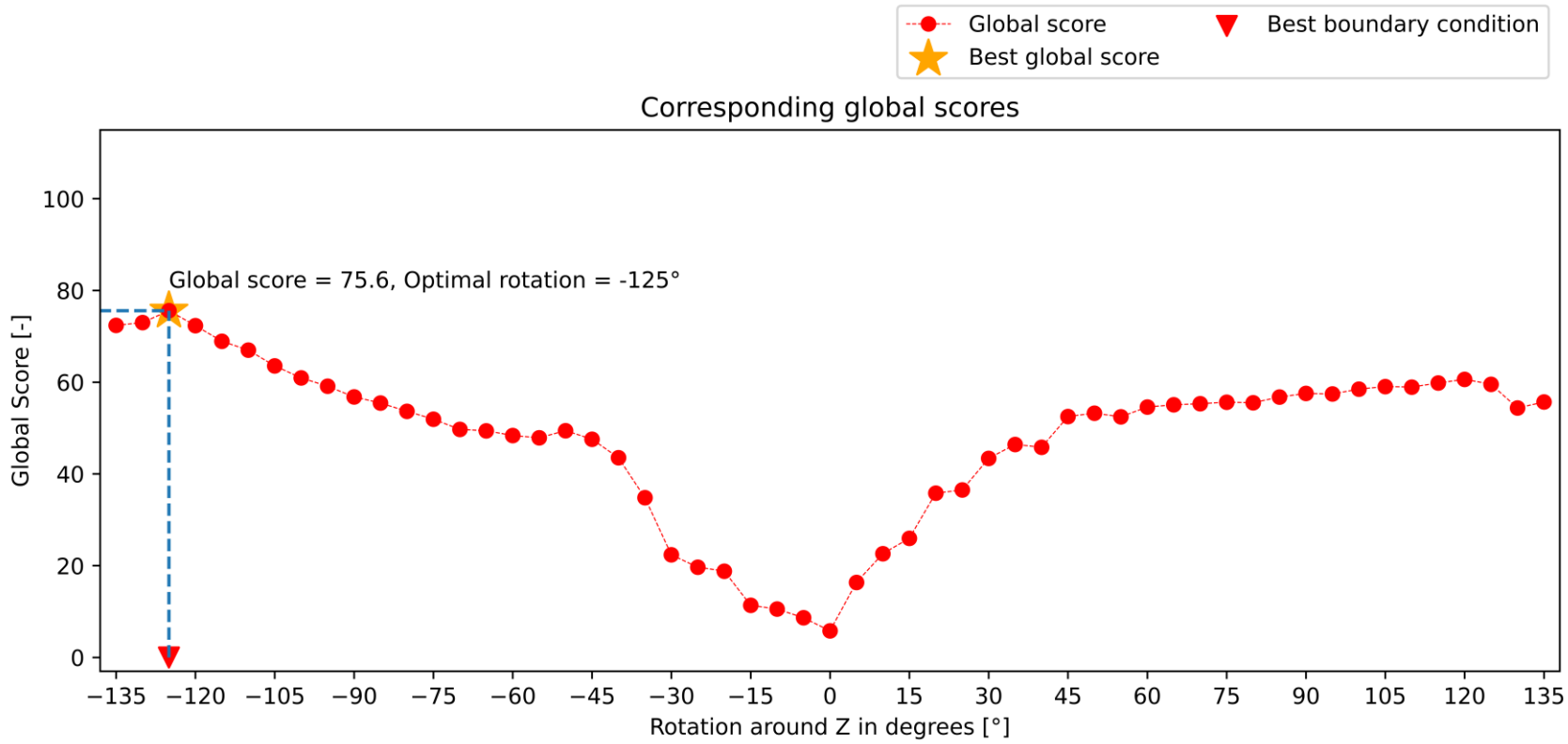
Toolpath 2 and Score



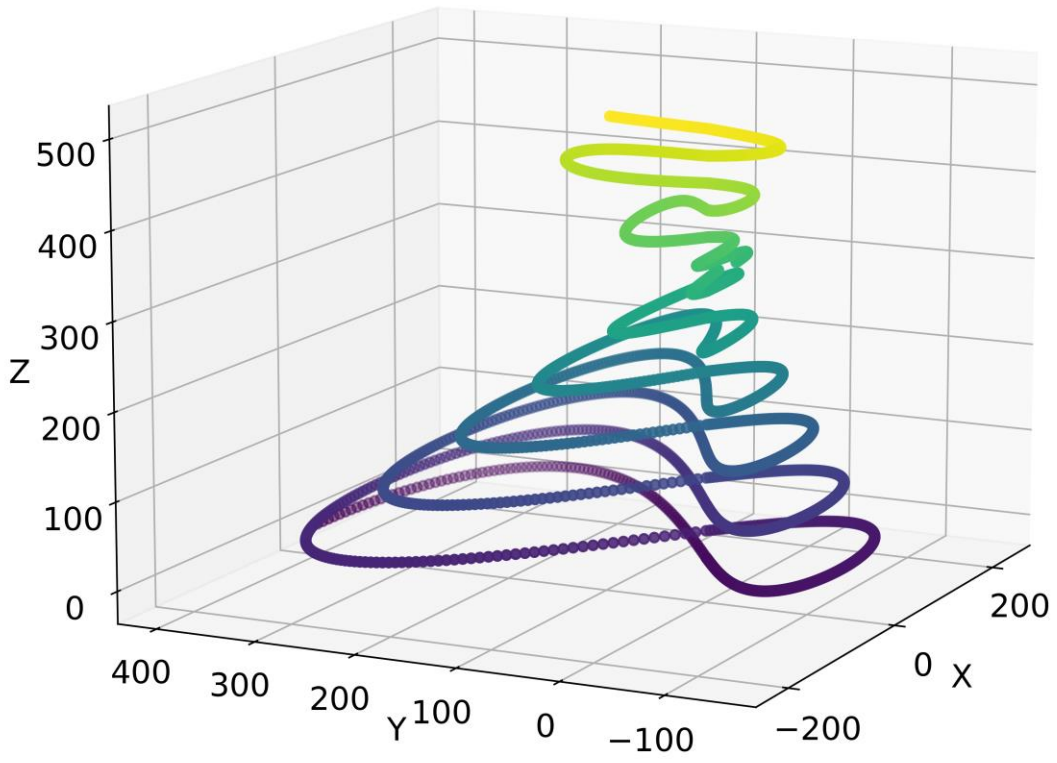
Toolpath 3 and Score

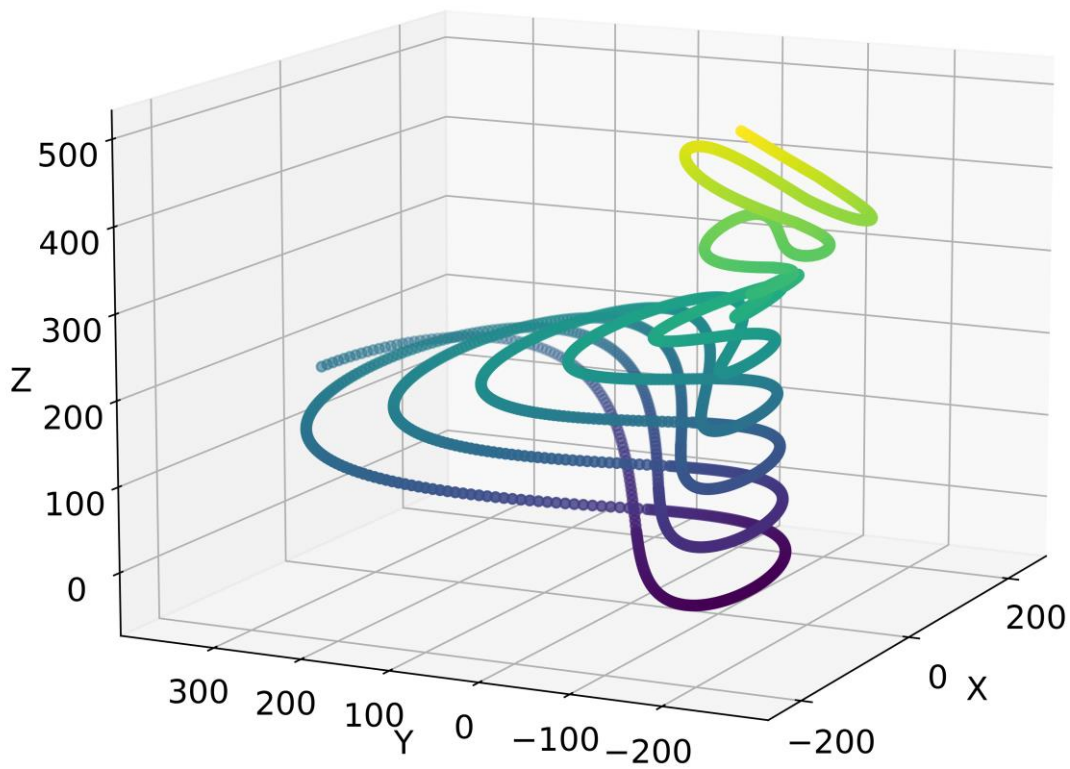



Z
Y

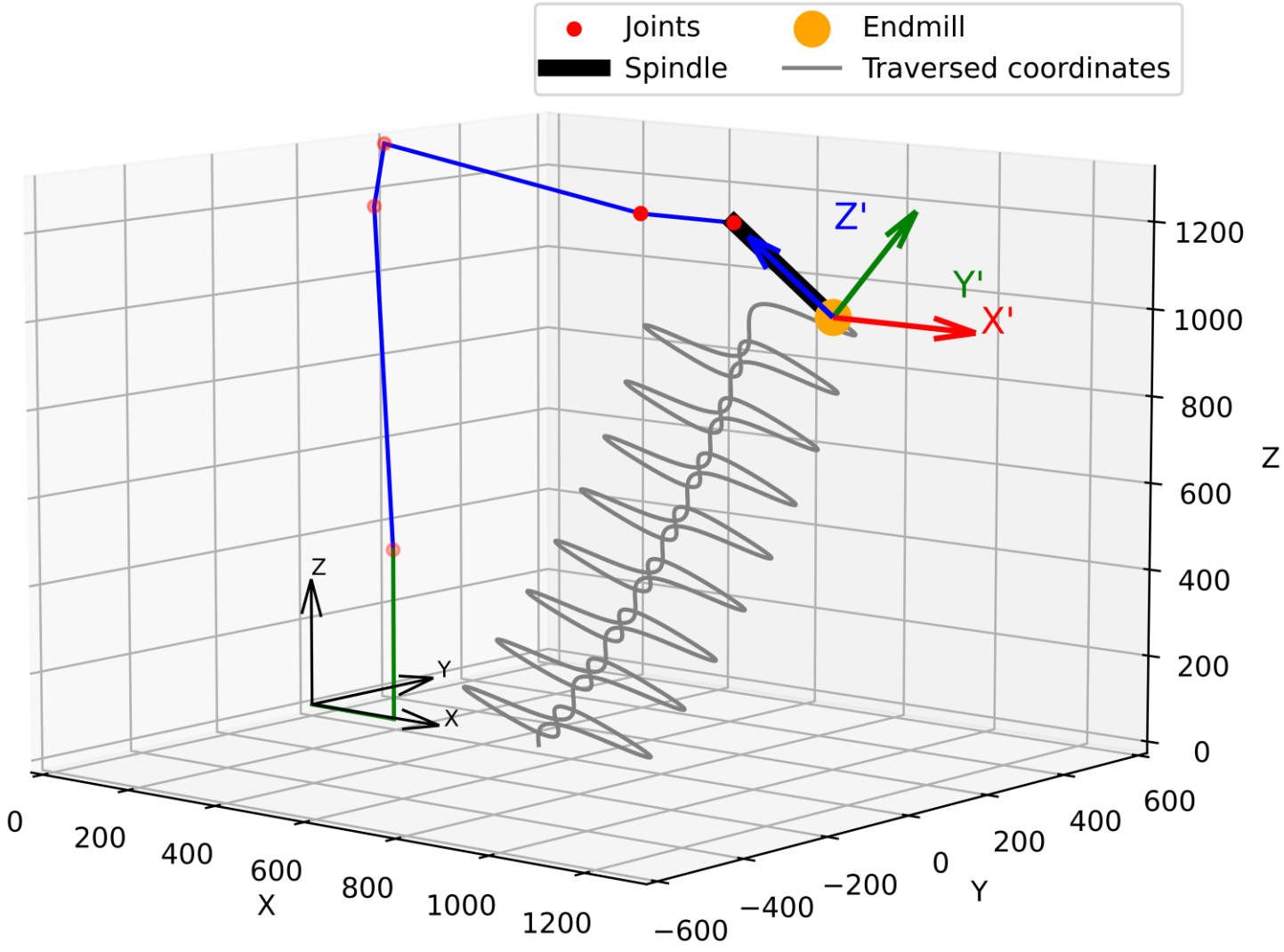

Global score
Best global score
Best boundary condition
Corresponding global scores
Global score = 75.6, Optimal rotation = -125°
Global Score [-]
Rotation around Z in degrees [°]
100
80
60
40
20
0
−135
−120
−105
−90
−75
−60
−45
−30
−15
0
15
30
45
60
75
90
105
120
135

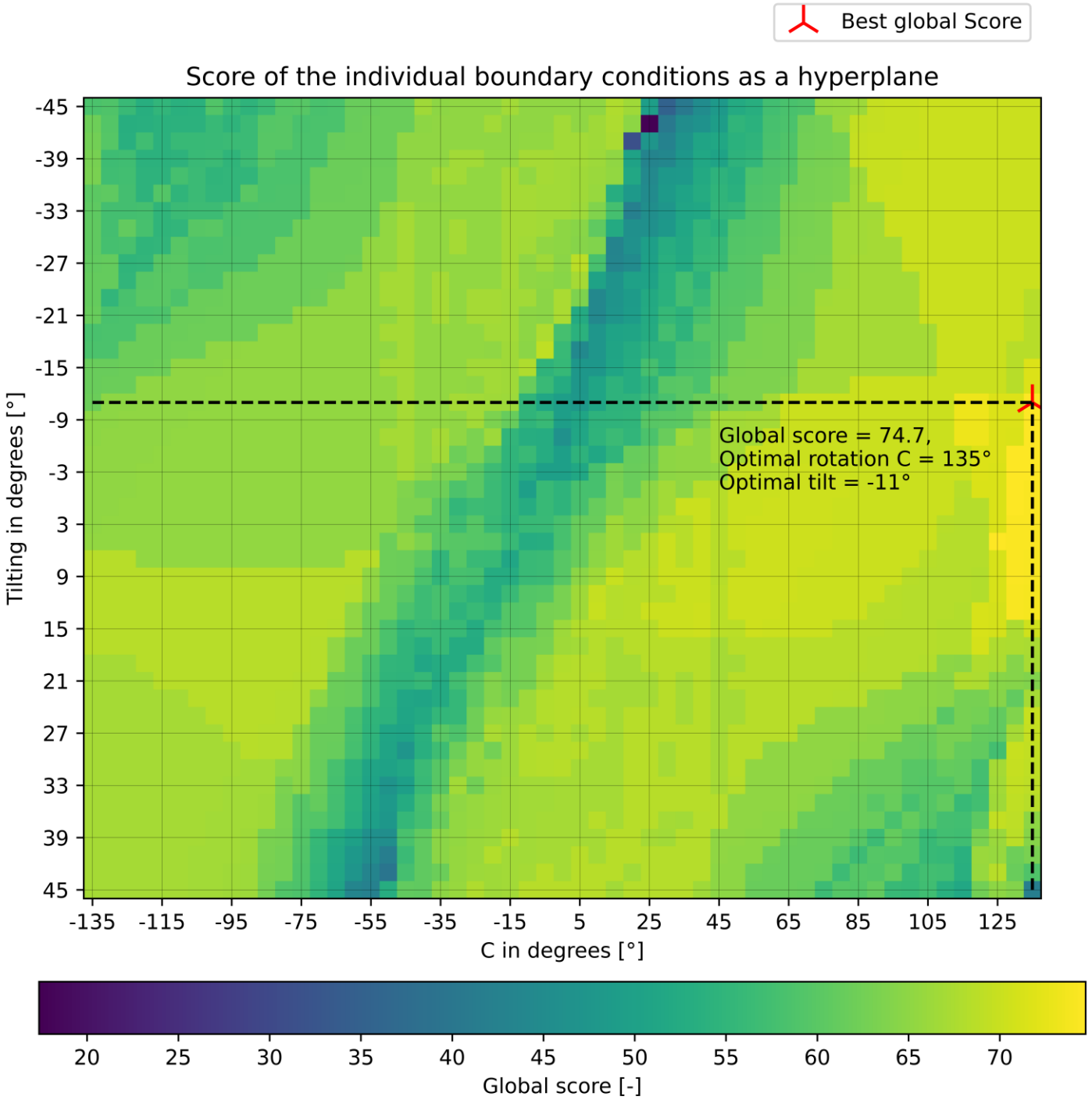
Rotation toolpath 2

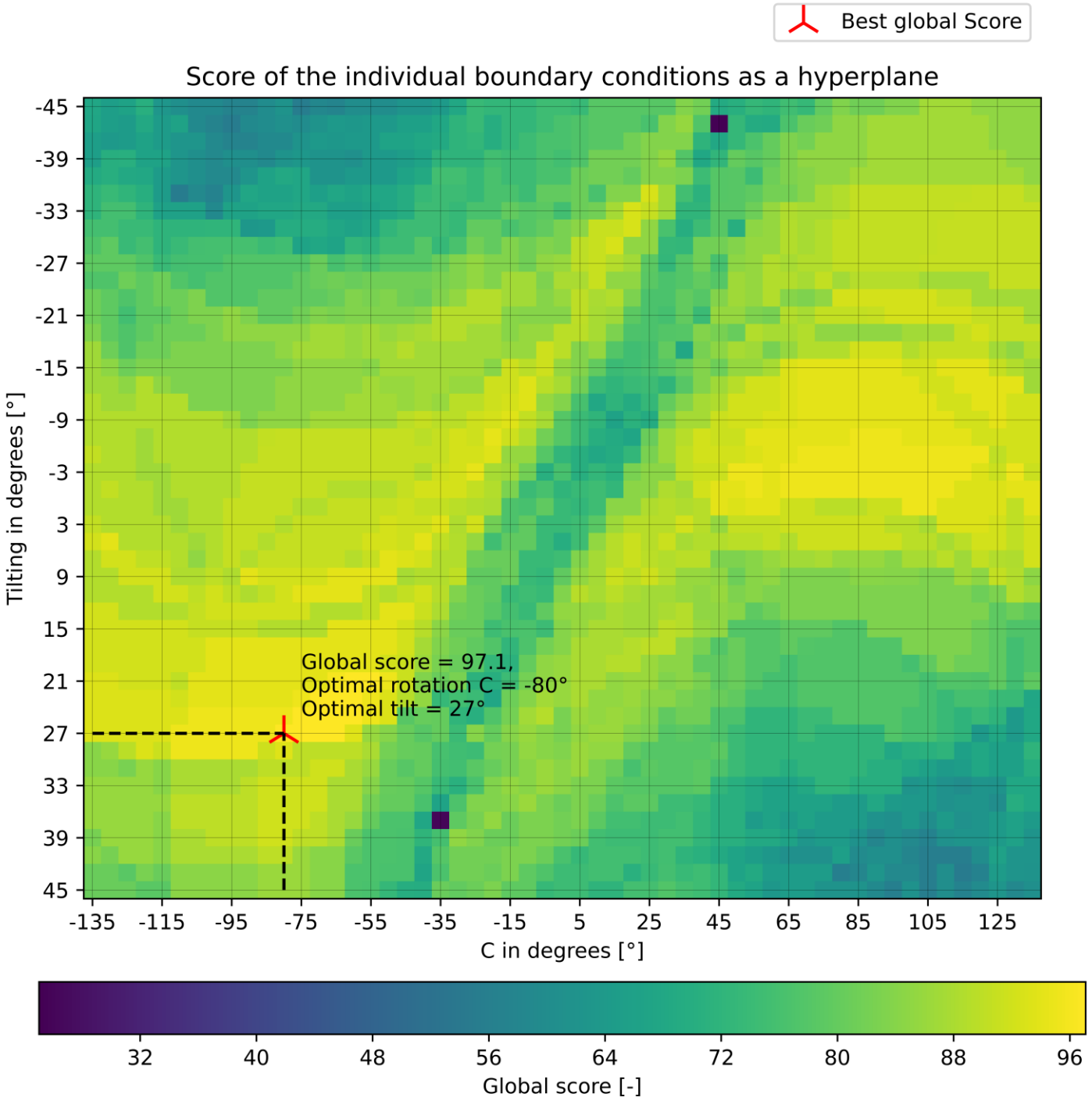


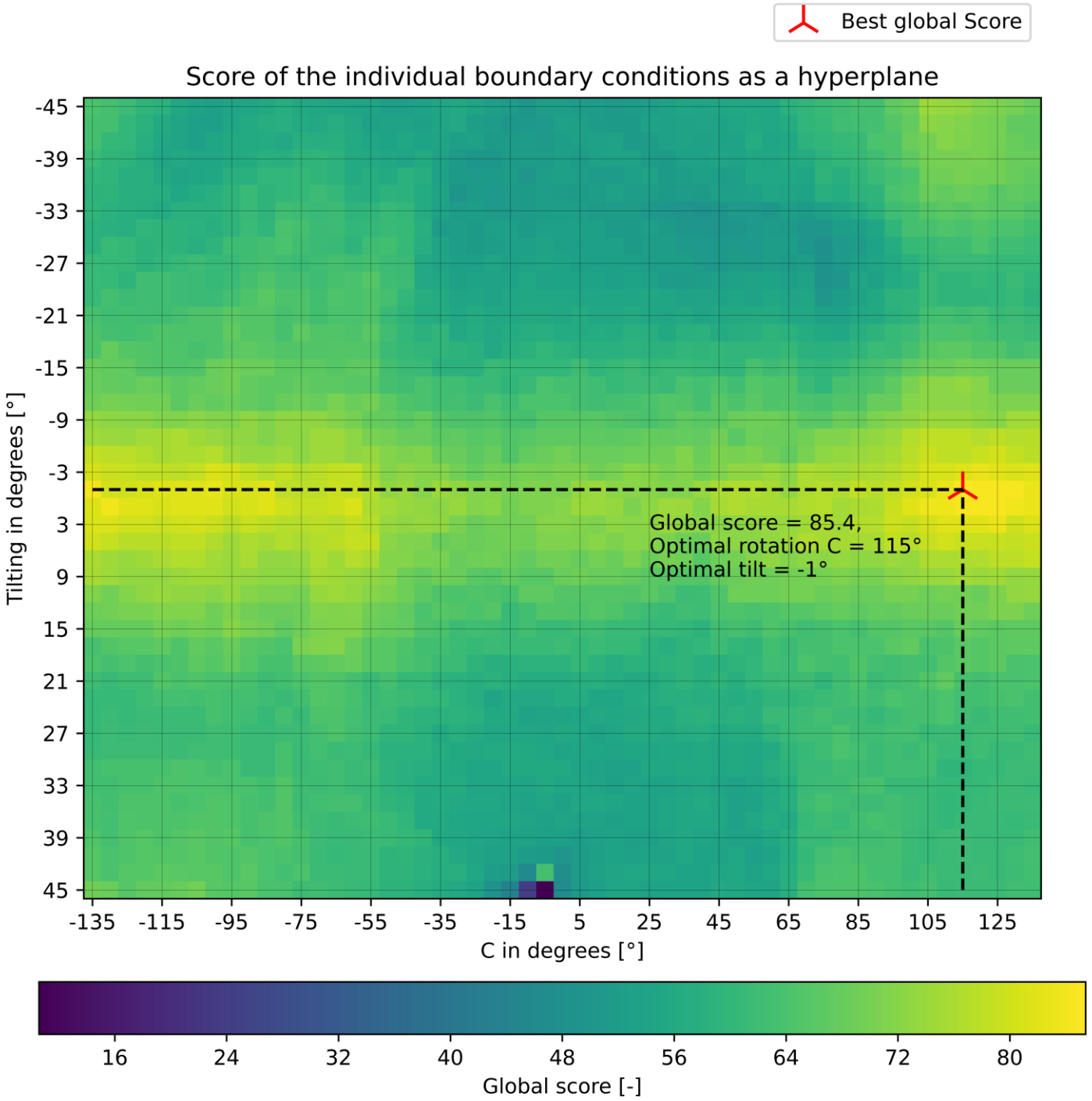


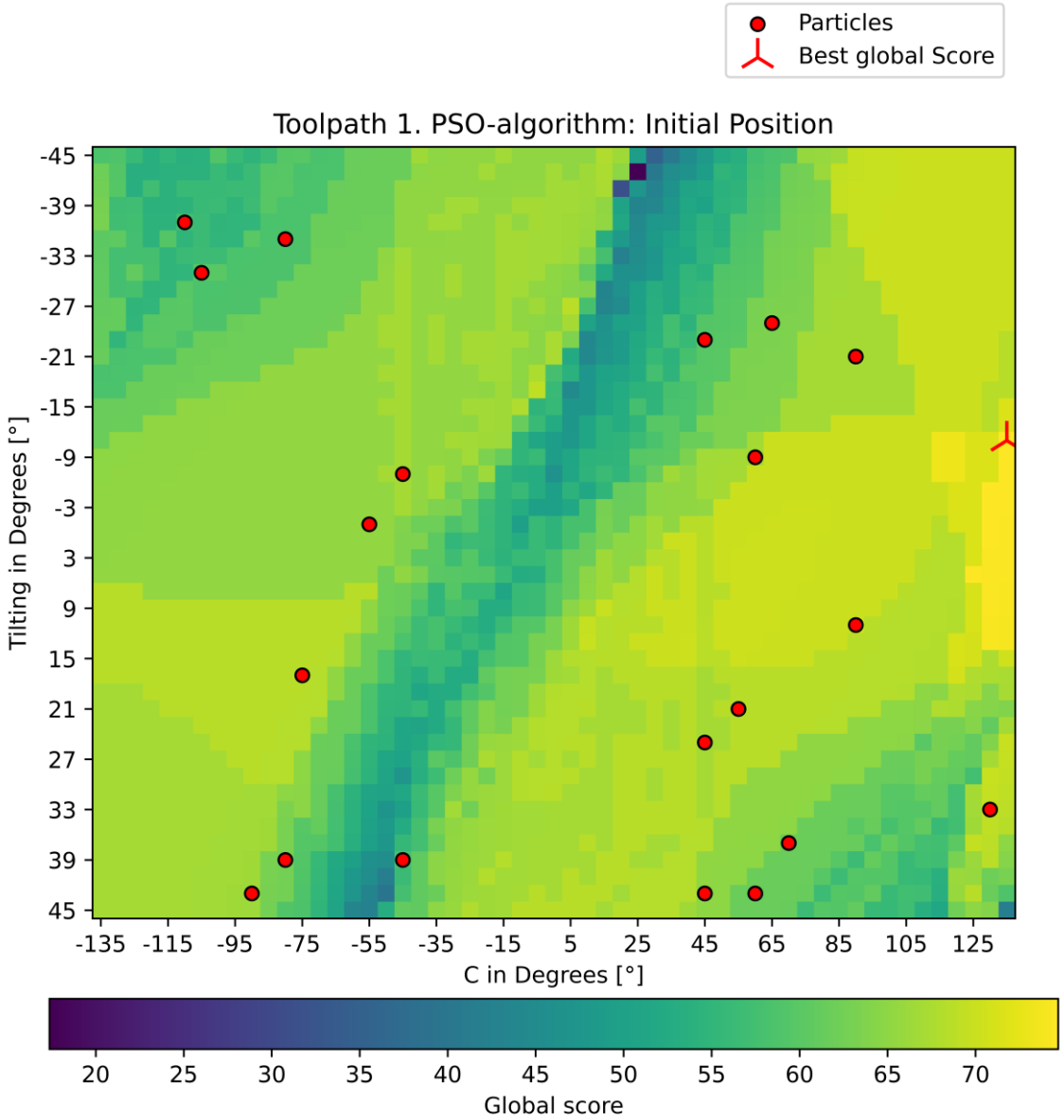
Toolpath 3

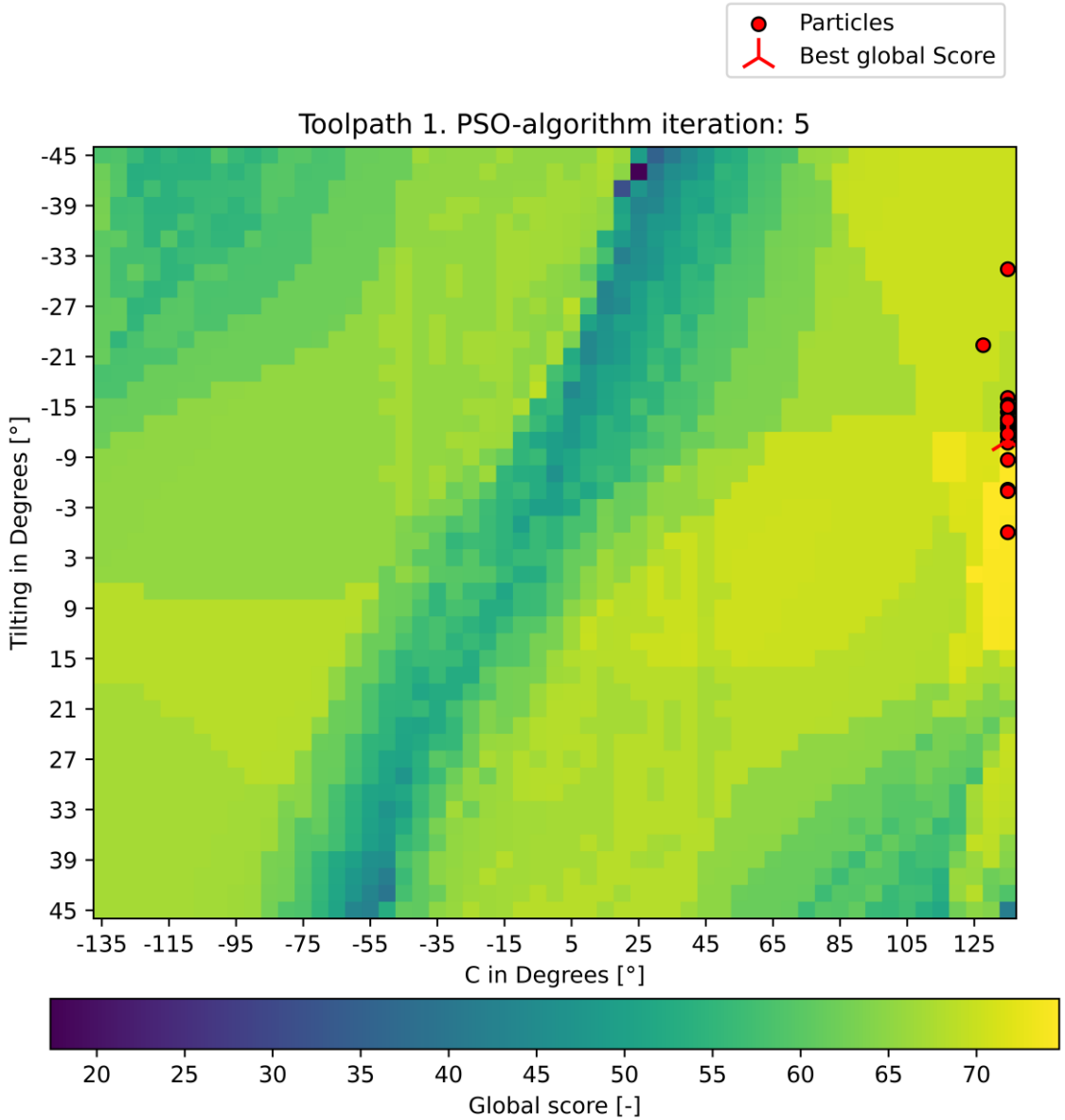

Joints
Endmill
Spindle
Traversed coordinates
Z'
Y'
X'
Z
Y
X
0
200
400
600
800
1000
1200
X
−600
−400
−200
0
200
400
600
Y
0
200
400
600
800
1000
1200
Z

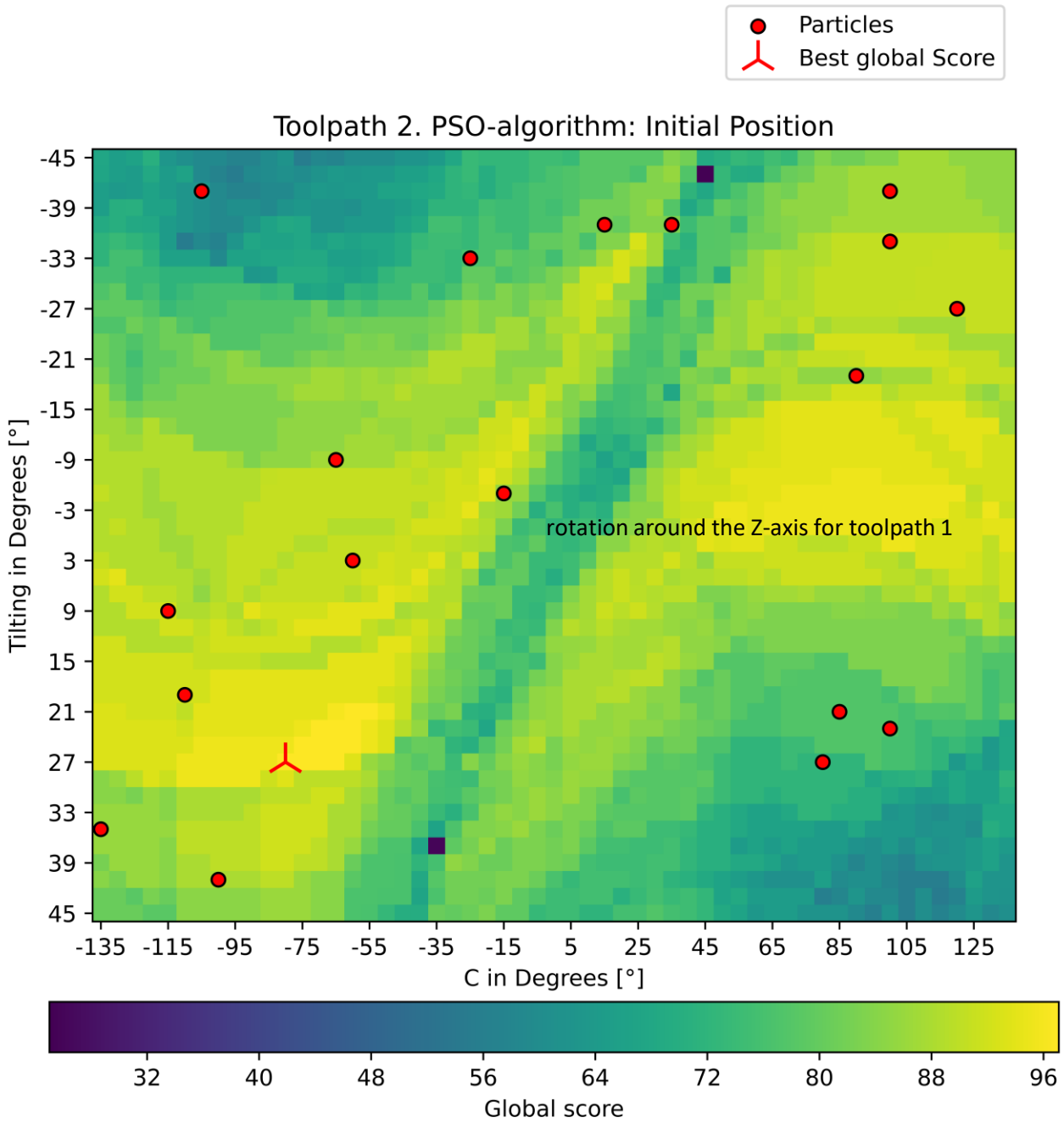

Best global Score
Score of the individual boundary conditions as a hyperplane
Tilting in degrees [°]
-45
-39
-33
-27
-21
-15
-9
-3
3
9
15
21
27
33
39
45
Global score = 74.7,
Optimal rotation C = 135°
Optimal tilt = -11°
-135
-115
-95
-75
-55
-35
-15
5
25
45
65
85
105
125
C in degrees [°]
20
25
30
35
40
45
50
55
60
65
70
Global score [-]

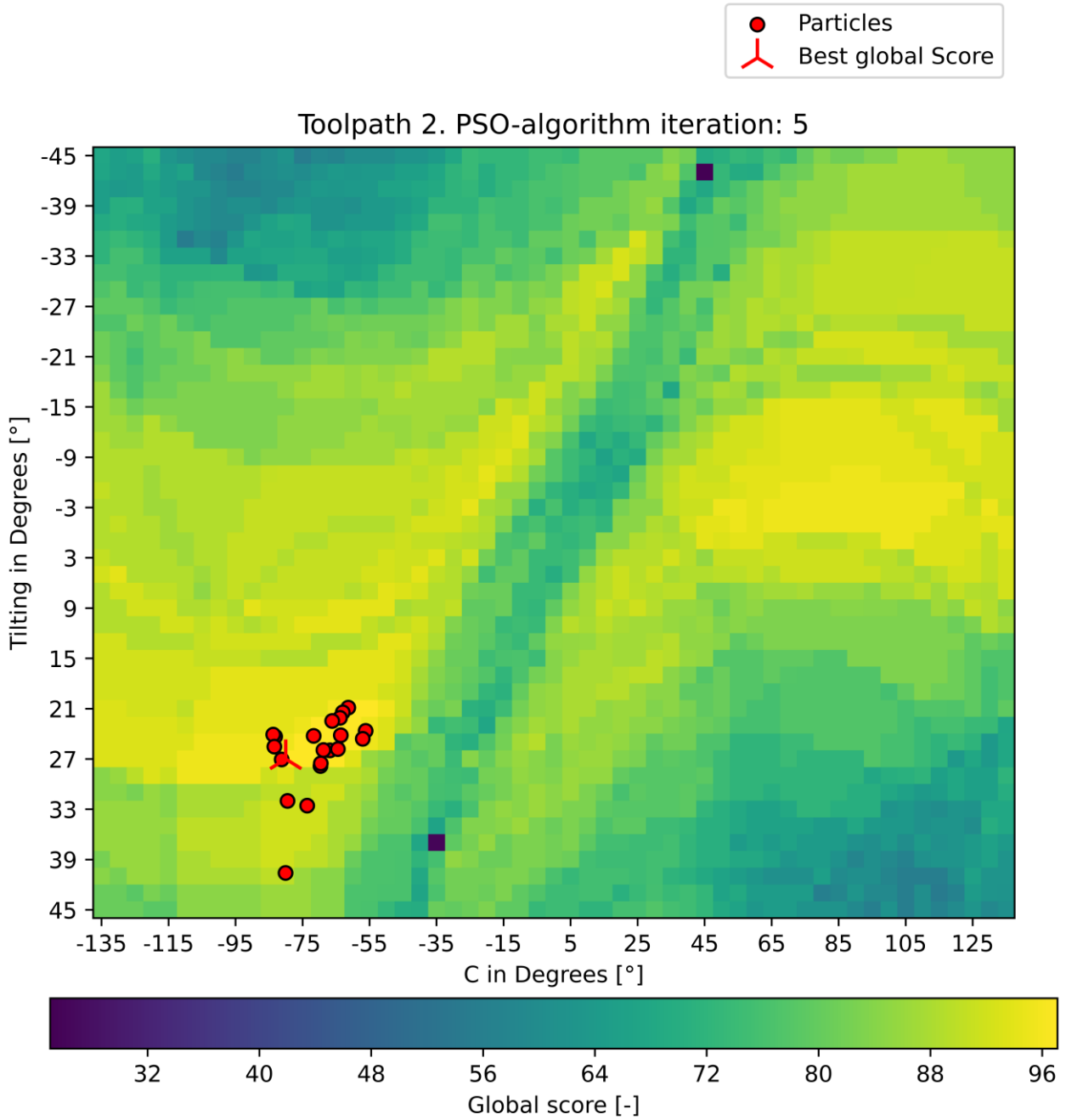

Best global Score
Score of the individual boundary conditions as a hyperplane
Tilting in degrees [°]
-45
-39
-33
-27
-21
-15
-9
-3
3
9
15
21
27
33
39
45
Global score = 97.1,
Optimal rotation C = -80°
Optimal tilt = 27°
-135
-115
-95
-75
-55
-35
-15
5
25
45
65
85
105
125
C in degrees [°]
32
40
48
56
64
72
80
88
96
Global score [-]

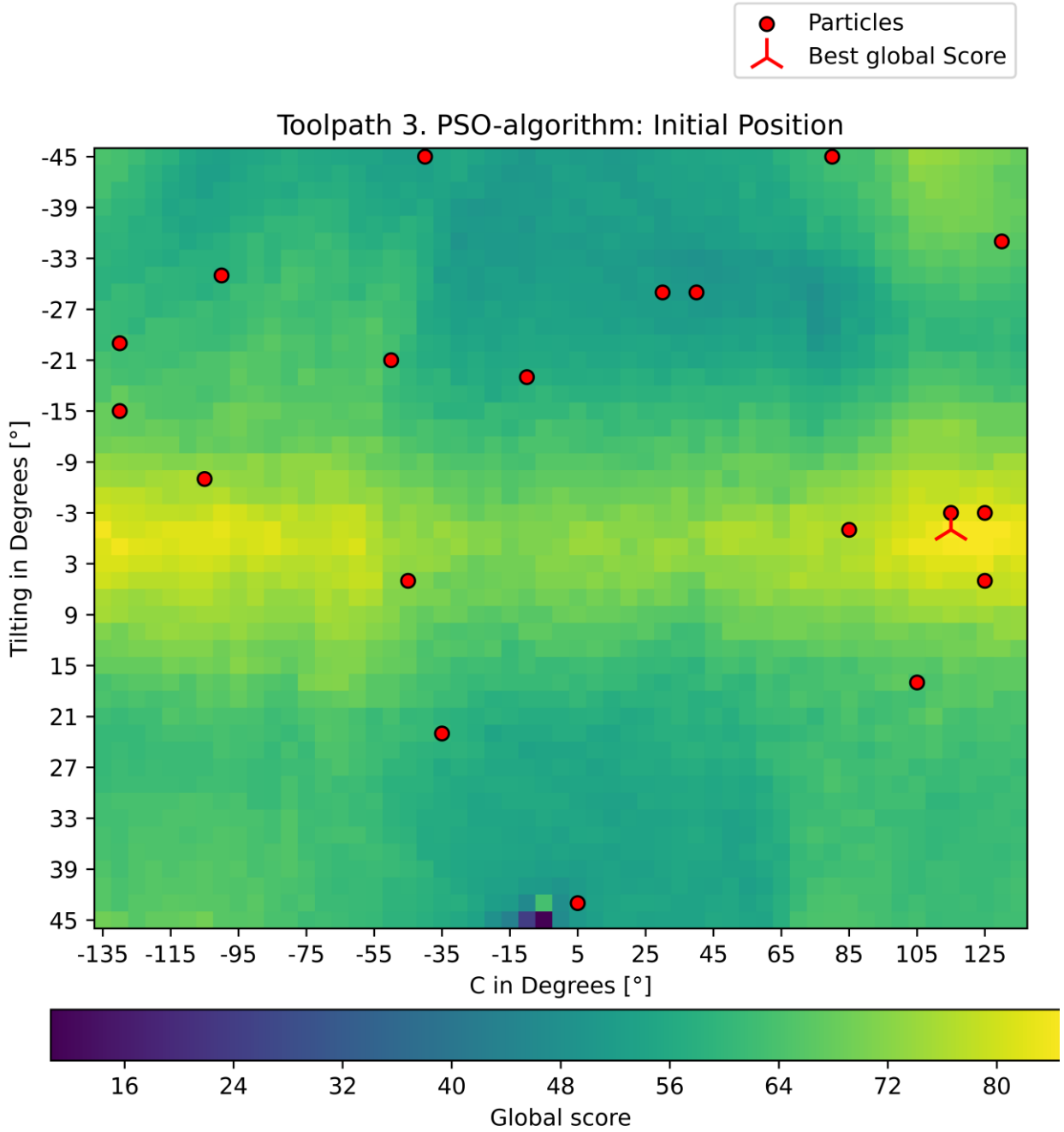

Best global Score
Score of the individual boundary conditions as a hyperplane
Tilting in degrees [°]
-45
-39
-33
-27
-21
-15
-9
-3
3
9
15
21
27
33
39
45
Global score = 85.4,
Optimal rotation C = 115°
Optimal tilt = -1°
-135
-115
-95
-75
-55
-35
-15
5
25
45
65
85
105
125
C in degrees [°]
16
24
32
40
48
56
64
72
80
Global score [-]

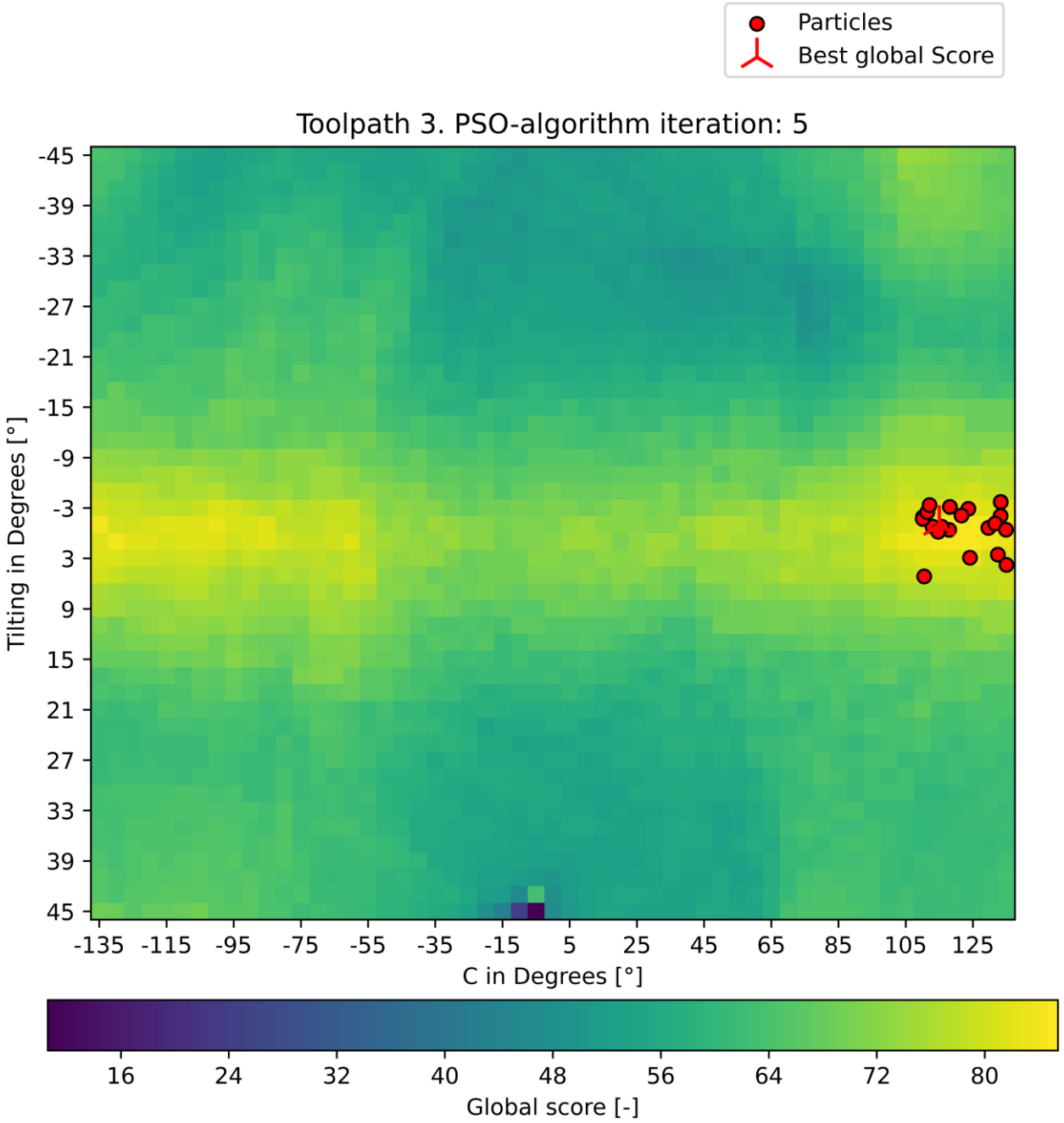

Particles
Best global Score
Toolpath 1. PSO-algorithm: Initial Position
Tilting in Degrees [°]
-45 -39 -33 -27 -21 -15 -9 -3 3 9 15 21 27 33 39 45
-135 -115 -95 -75 -55 -35 -15 5 25 45 65 85 105 125
C in Degrees [°]
20 25 30 35 40 45 50 55 60 65 70
Global score


Particles
Best global Score
Toolpath 1. PSO-algorithm iteration: 5
Tilting in Degrees [°]
-45 -39 -33 -27 -21 -15 -9 -3 3 9 15 21 27 33 39 45
-135 -115 -95 -75 -55 -35 -15 5 25 45 65 85 105 125
C in Degrees [°]
20 25 30 35 40 45 50 55 60 65 70
Global score [-]


Particles
Best global Score
Toolpath 2. PSO-algorithm: Initial Position
rotation around the Z-axis for toolpath 1
Tilting in Degrees [°]
C in Degrees [°]
Global score


Particles
Best global Score
Toolpath 2. PSO-algorithm iteration: 5
Tilting in Degrees [°]
C in Degrees [°]
Global score [-]





Swarm Optimization