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

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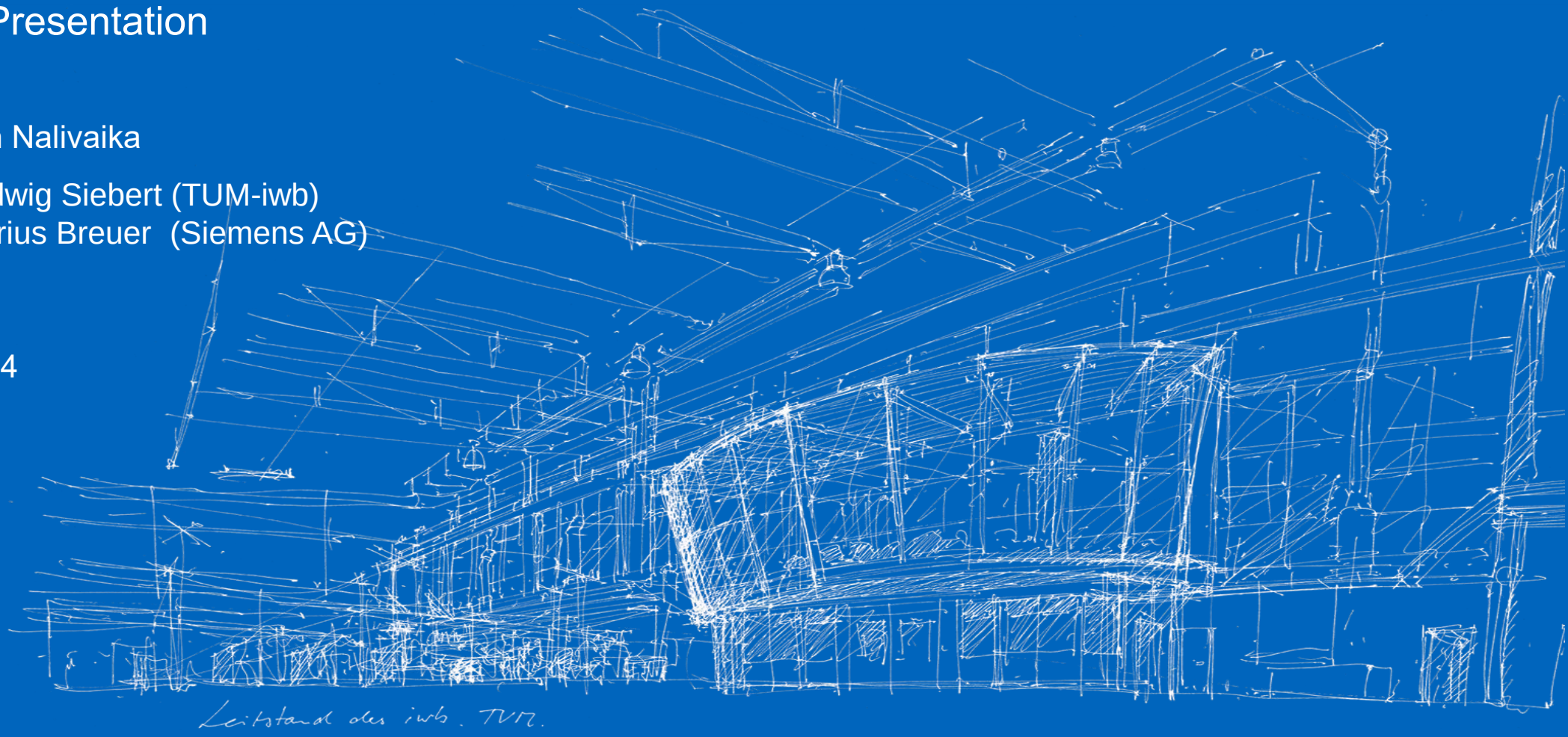
Marius Breuer (Siemens AG)

Garching 04.03.2024



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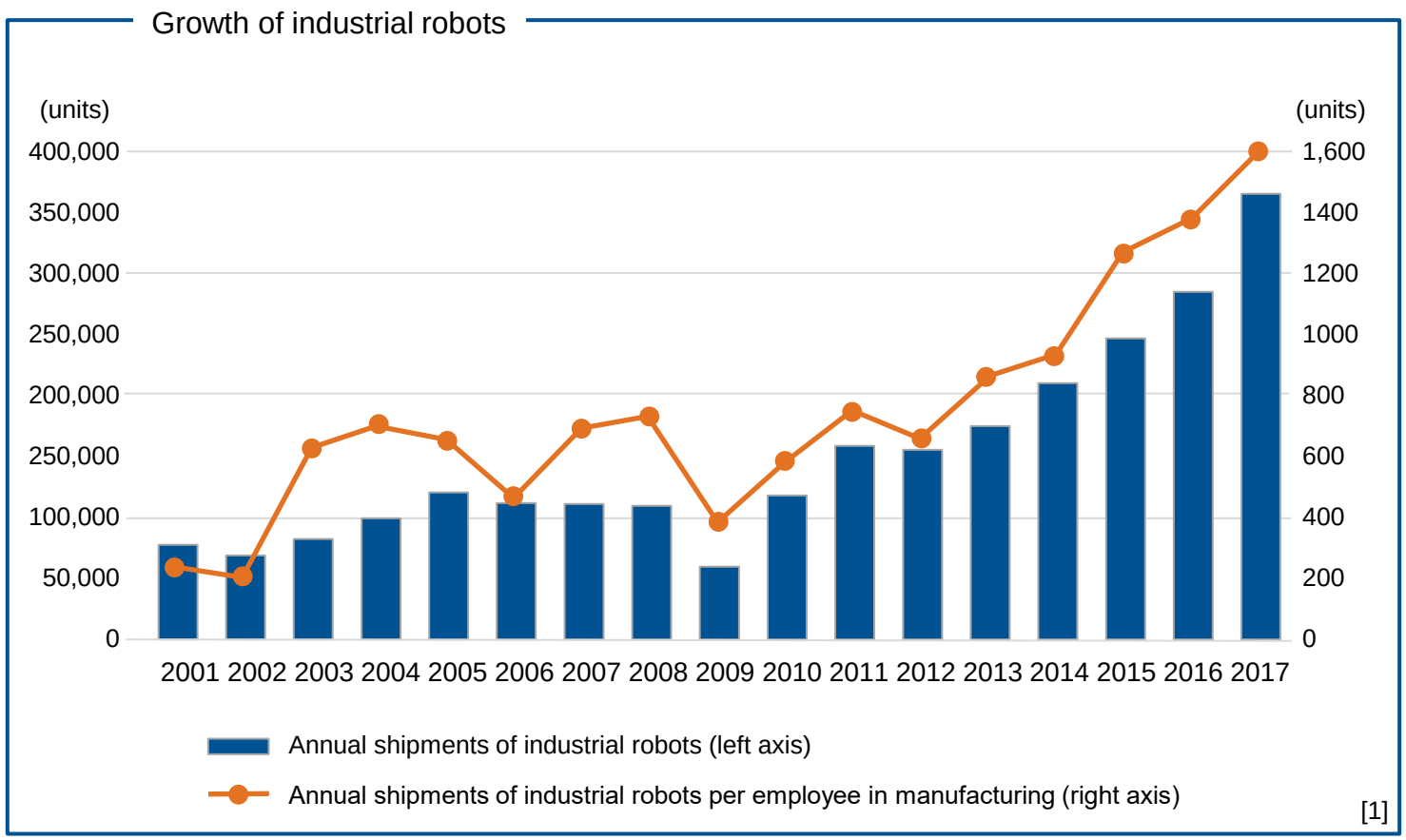
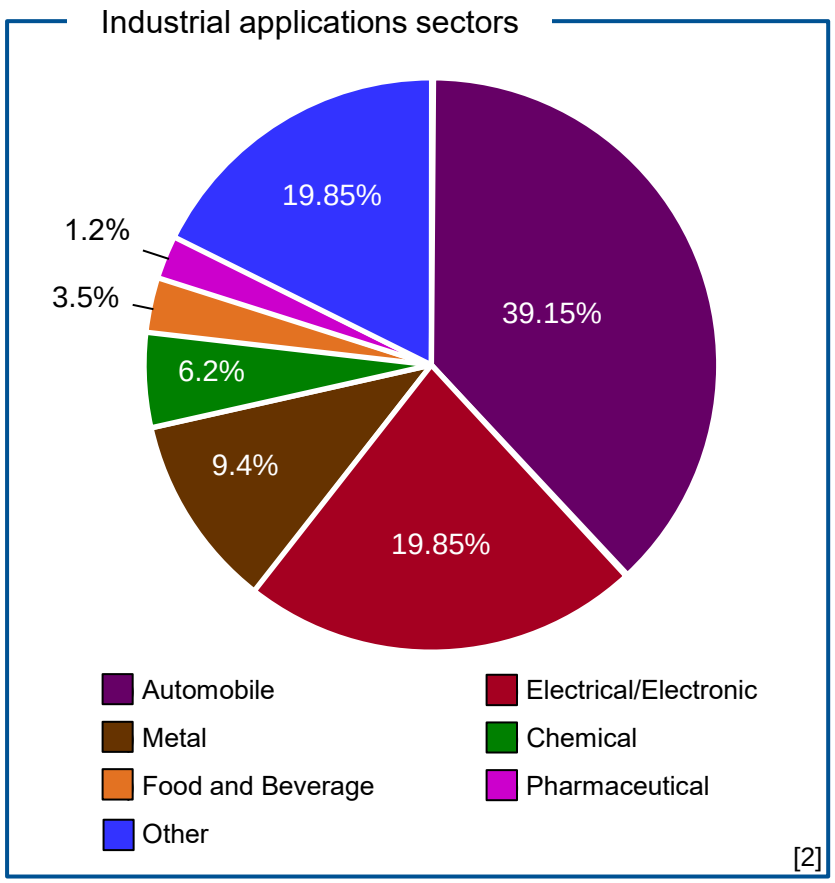
Growth of Industrial Robots and Applications

Motivation





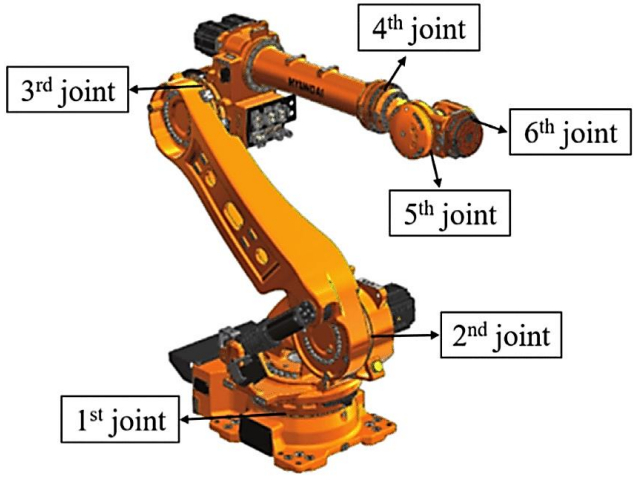
[1] Hwa Jung and Dong-Geon Lim 2020
[2] Jiangnan Ni and Vipin Balyan 2021

Manufacturing Methods

Motivation

CNC machines

- Designed for milling
- High precision
- Toolpaths in 5 DoFs
- X, Y, Z (translation)
- A, B (rotation)



Industrial robots

- 6 DoFs
- Used for WAAM
- Can be used for milling
- Highly versatile
- Sub-optimal stiffness

Milling with robots

- 5-DoF toolpath does not fully specify the robots' configuration
- Only X, Y, Z, A and B are defined
- Rotation C is not specified and **<u>can be chosen freely</u>**
- Rotation C is affecting how a toolpath is traversed
- Rotation C is considered a **<u>boundary condition</u>**

Influence of 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?

➔ Goal: Optimizing the robots' behavior by optimally setting the boundary condition

CNC: Computer numerical control; DoF: Degree of freedom WAAM: Wire Arc Additive Manufacturing

Example: Traversing a Toolpath With Different C-Rotation

Problem Formulation and Aim

Rotation C = 0°

THIS IS A VIDEO

Add video of robot here
Add video of NX here (if robot not available)

Rotation C = -30°

THIS IS A VIDEO

Add video of robot here
Add video of NX here (if robot not available)

- ➔ Rotation C can be chosen freely
- ➔ The rotation C significantly influences the behavior of the robot

Influenced **process variables**

Direction changes in the joints; Accelerations;
Energy consumption; Cable positioning; Stiffness; etc.

Shortcomings in Current Methodologies

Problem Formulation and Aim

Problem 1

No currently published method allows the user to select specific process variables to evaluate a process

Problem 2

As of now, it is not possible to weigh individual process parameters and thus describe the manufacturing process as a singular scalar value

Problem 3

No available method provides a solution to optimize boundary conditions based on a user defined goal

Aim 1

Provide a method that can work with specifically selected process variables and rate a manufacturing process

Aim 2

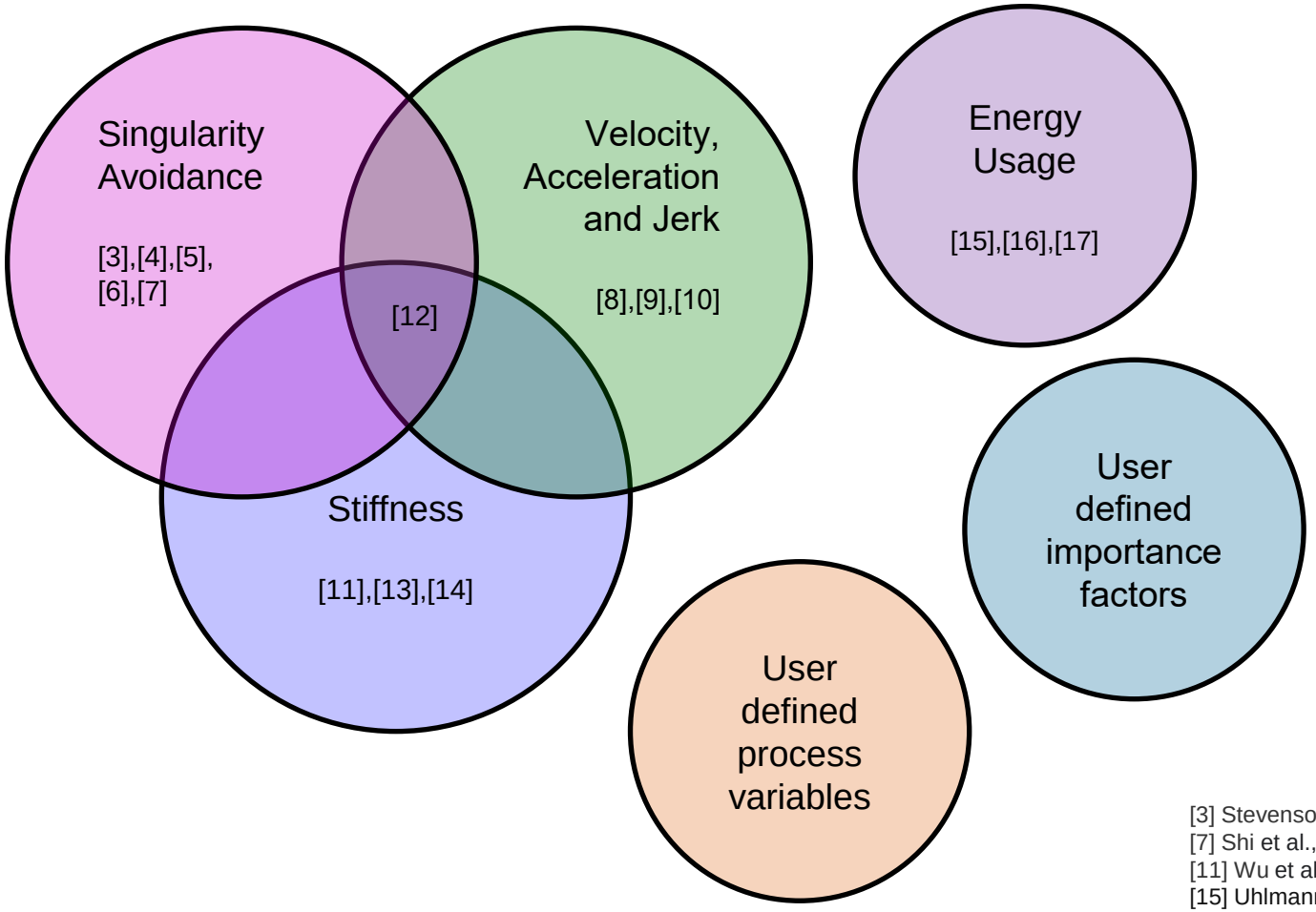
Extend the developed method with the option to add user-defined importance factor (weights) for the process variables

Aim 3

Provide system that can optimize the boundary conditions while considering the user defined goal

Elaboration of the Research Gap

State of the Art



Research Gap

➔ marginal overlap in the publications

➔ no method takes a holistic approach

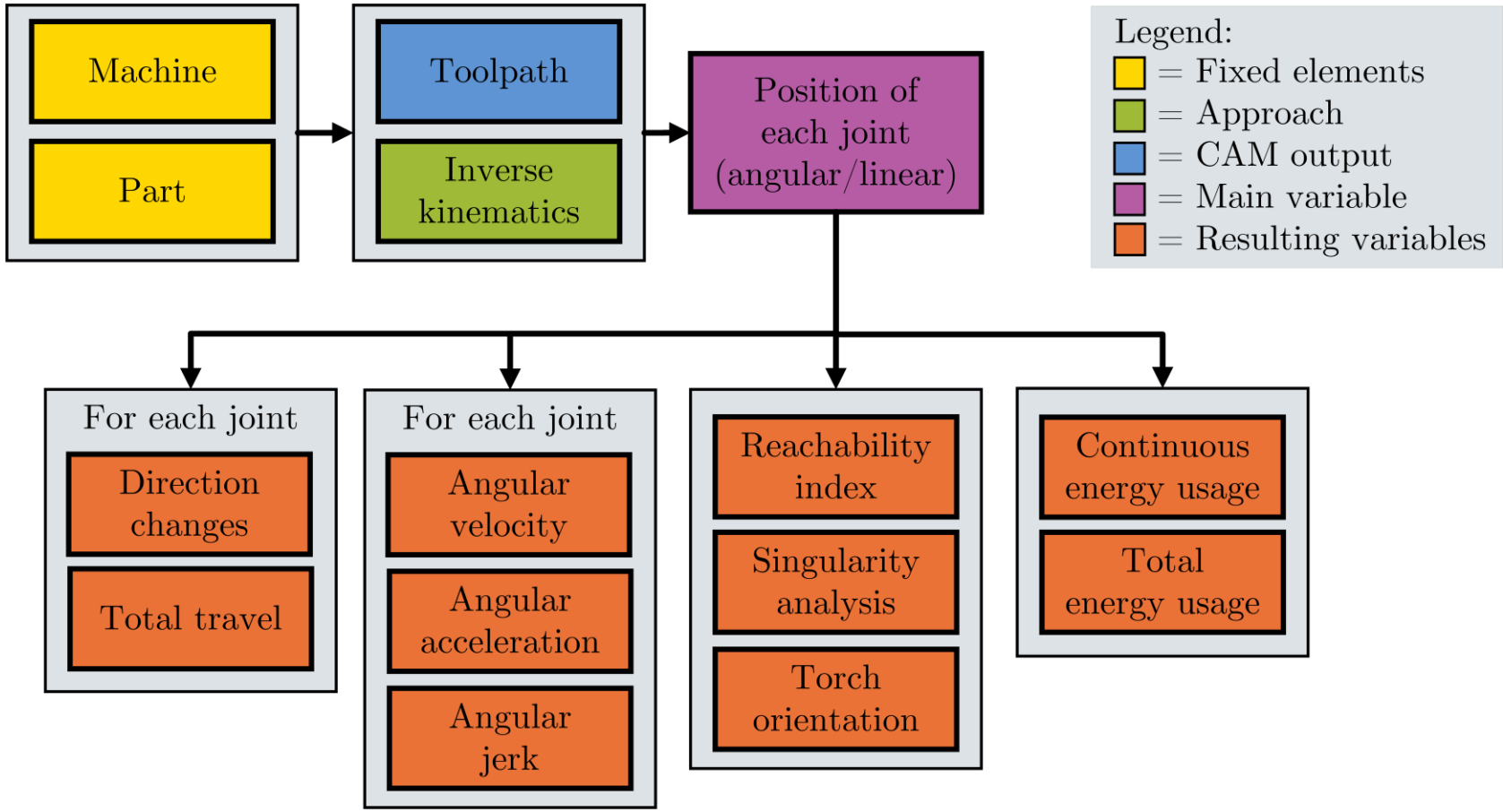
Missing elements

- No possibility for the user to select process variables
- No possibility for the user to weigh the individual process variables
- No possibility to optimize the setting of redundant DoFs towards a user-defined goal

[3] Stevenson et al., 2002 [4] Bedrossian,1990 [5] Huo and Baron, 2008 [6] Milenkovic, 2021
[7] Shi et al., 2021 [8] Dai et al., 2020 [9] Jiang et al., 2017 [10] Bien Duong 2021
[11] Wu et al., 2021 [12] Xiong et al., 2019 [13] Wang et al., 2022 [14] Cvitanic et al., 2020
[15] Uhlmann et al., 2016 [16] Boscariol et al., 2020 [17] Soori et al., 2015

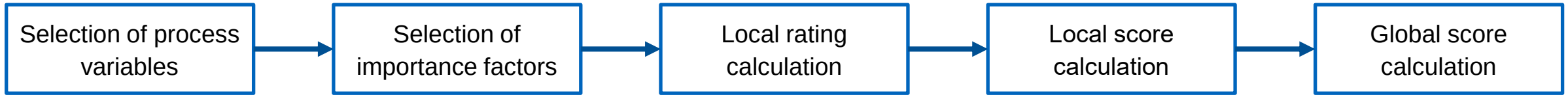
Extraction of Process Variables

Methodology

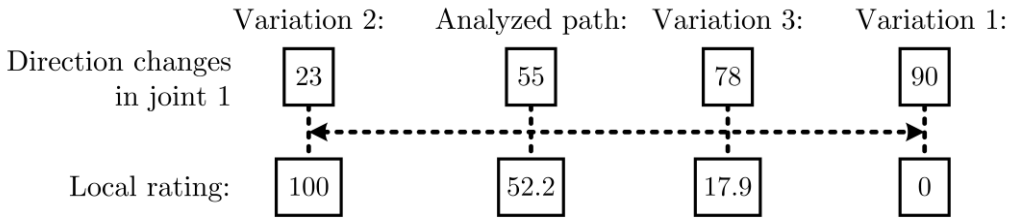


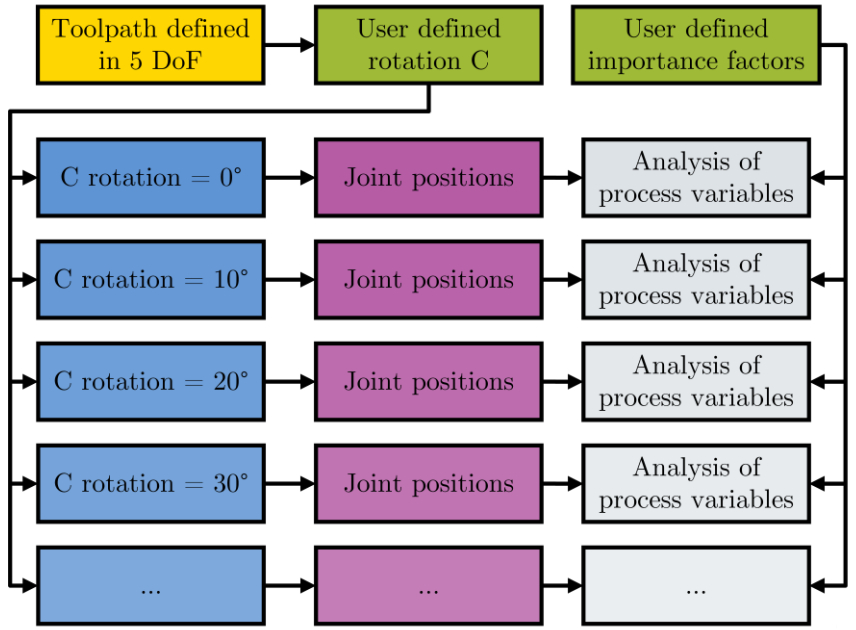
User Defined Importance Factors and Evaluation

Methodology



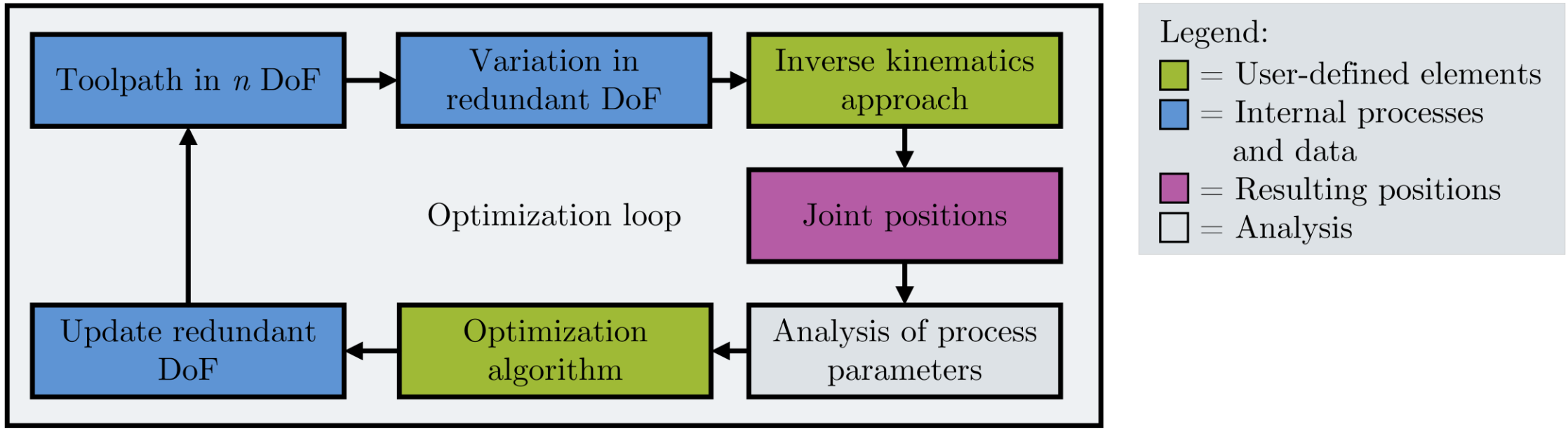
Process variable	Importance factor	Local rating	Local score
Process variable Nr. 1	0.5	74	37
Process variable Nr. 2	0.1	34	3.4
Process variable Nr. 3	0.1	65	6.5
Process variable Nr. 4	0.3	22	6.6
Global score			53.5





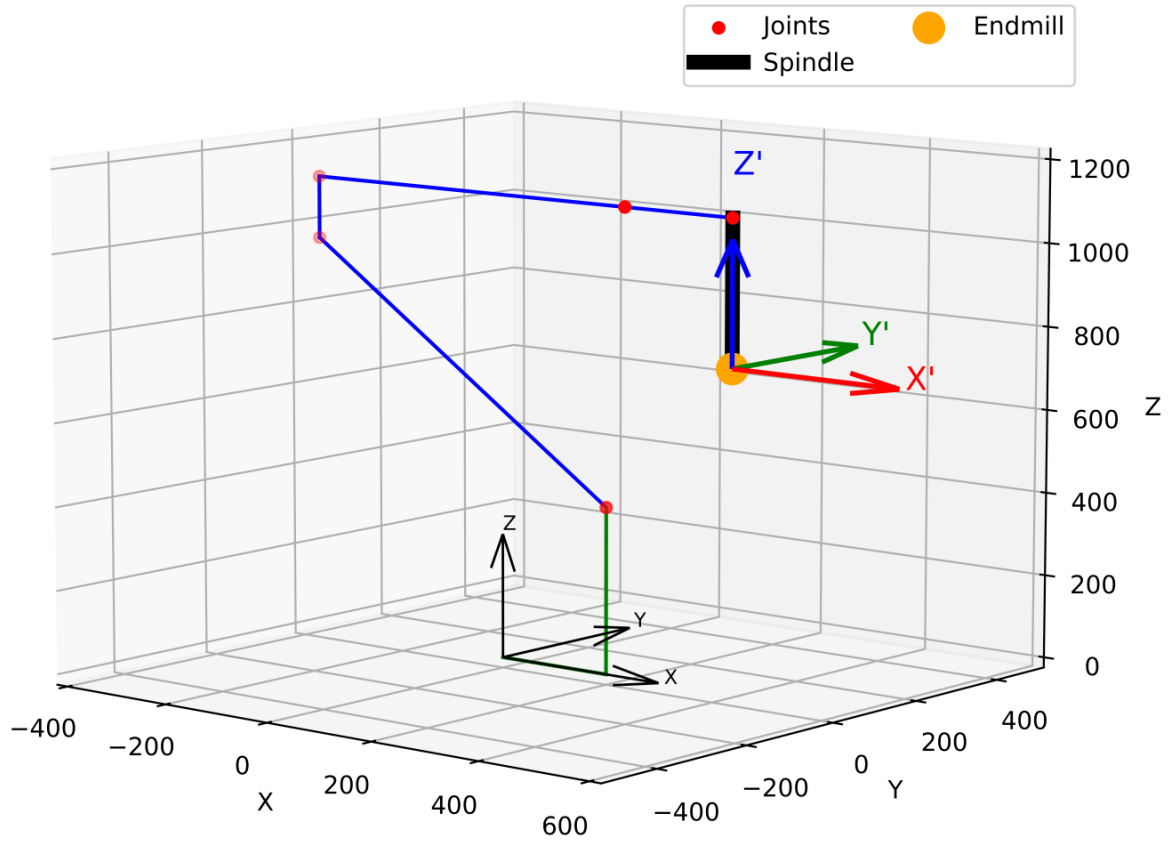
Boundary Condition Optimization

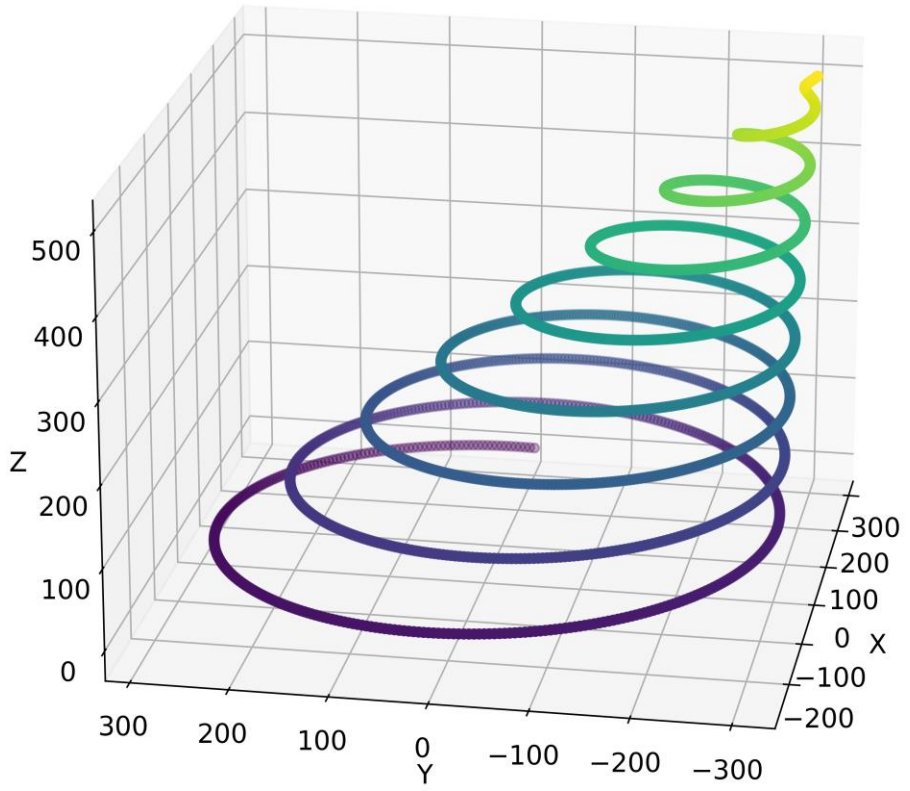
Methodology



Modeled Robot and Analyzed Toolpath

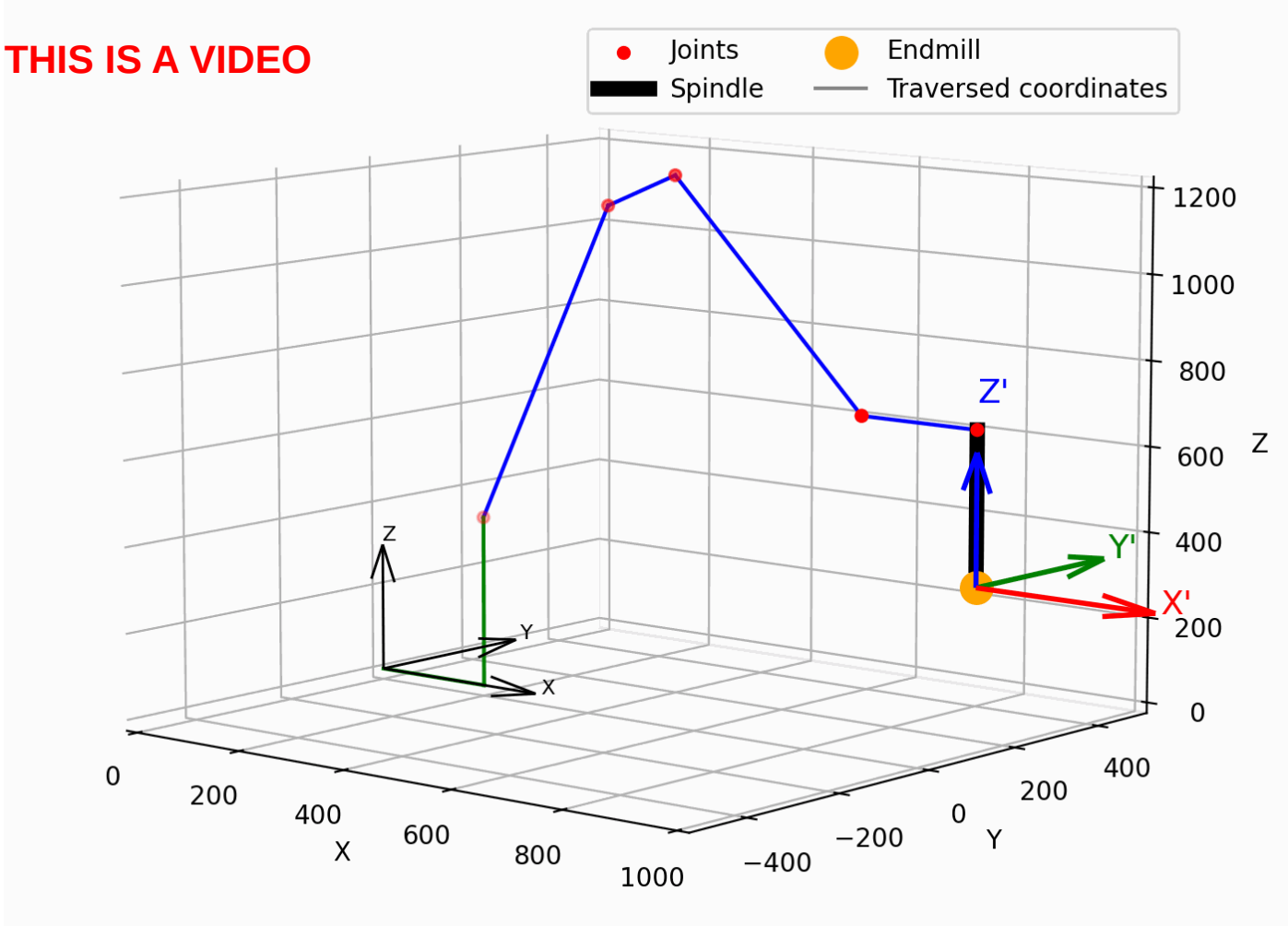
Implementation and Results





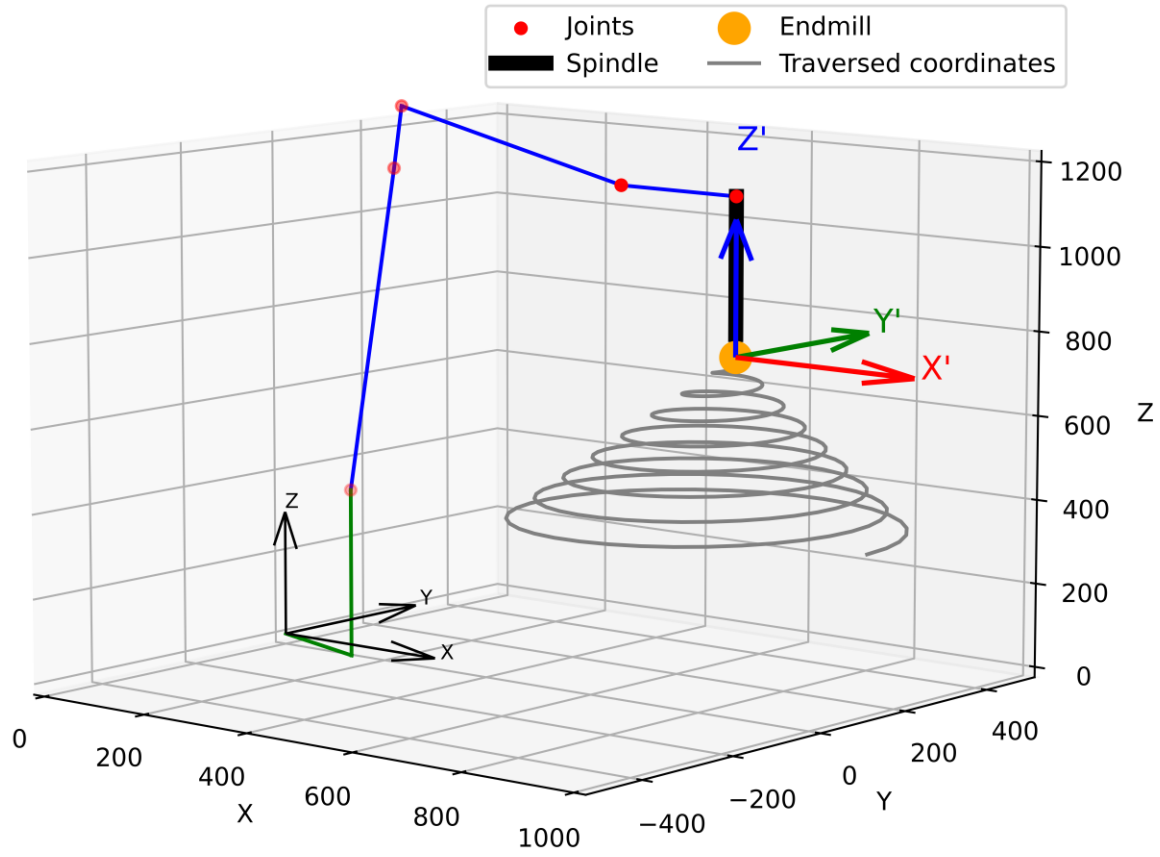
Traversing the Toolpath

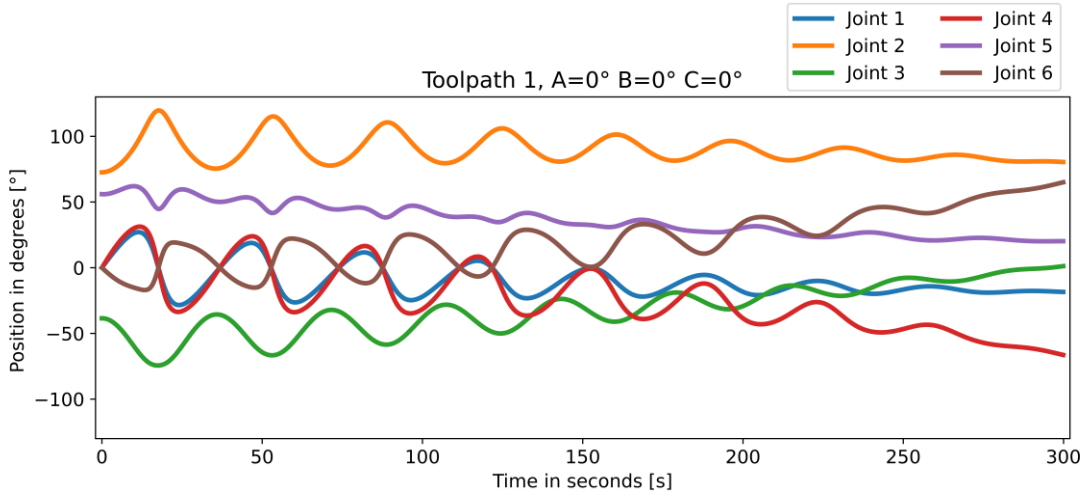
Implementation and Results

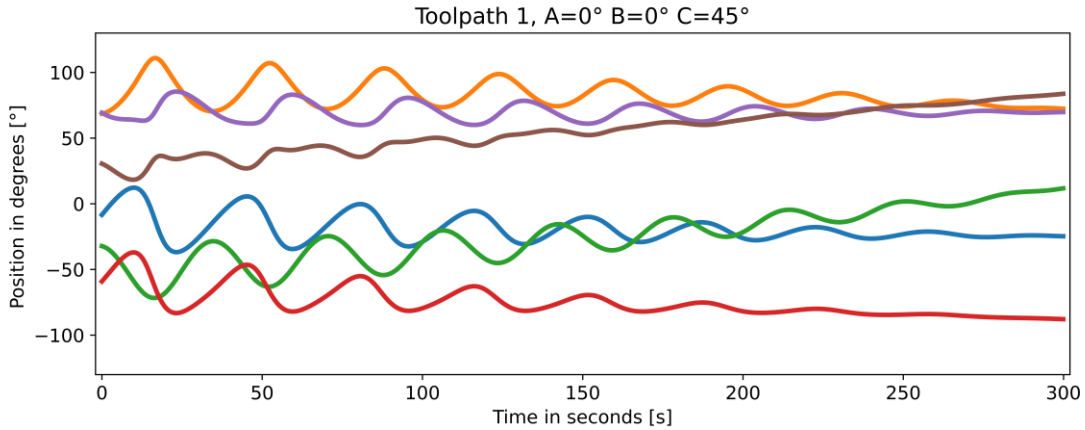


Extracting Joint Positions

Implementation and Results

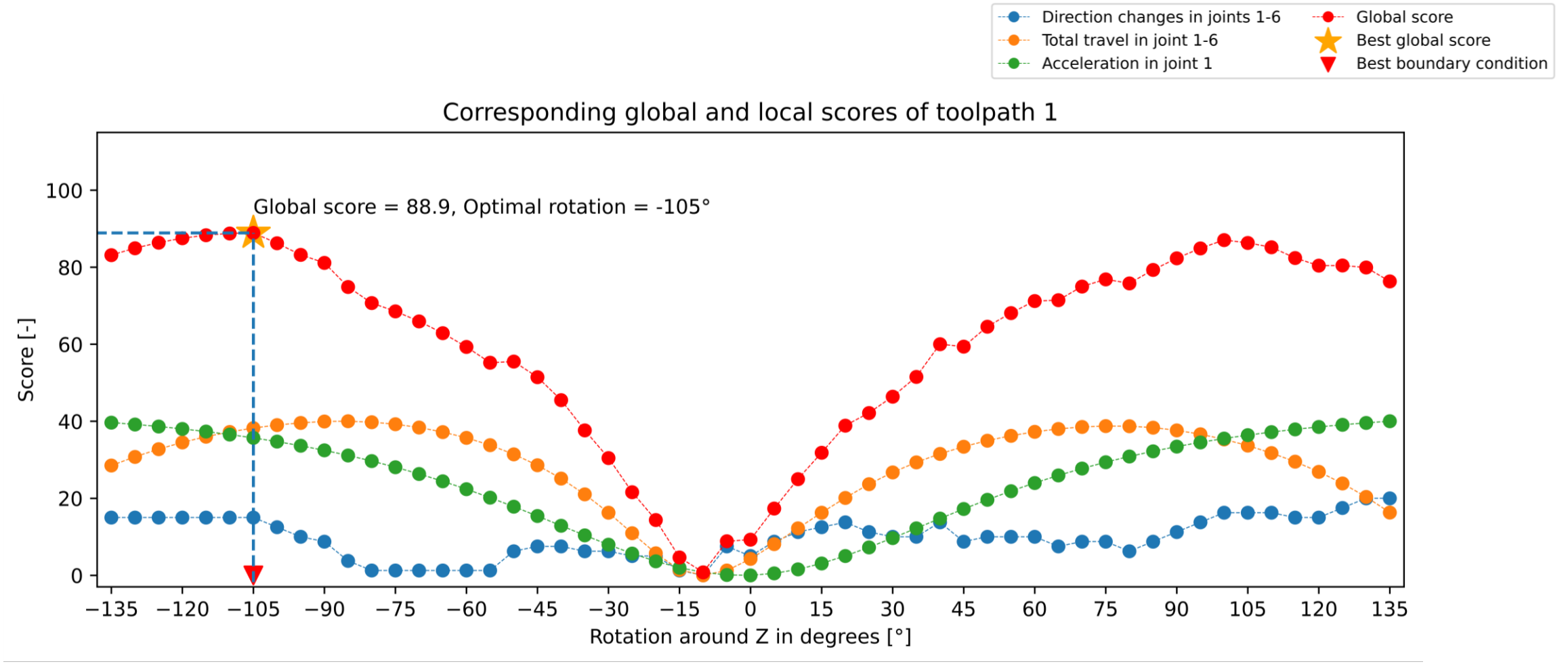






Local and Global Score

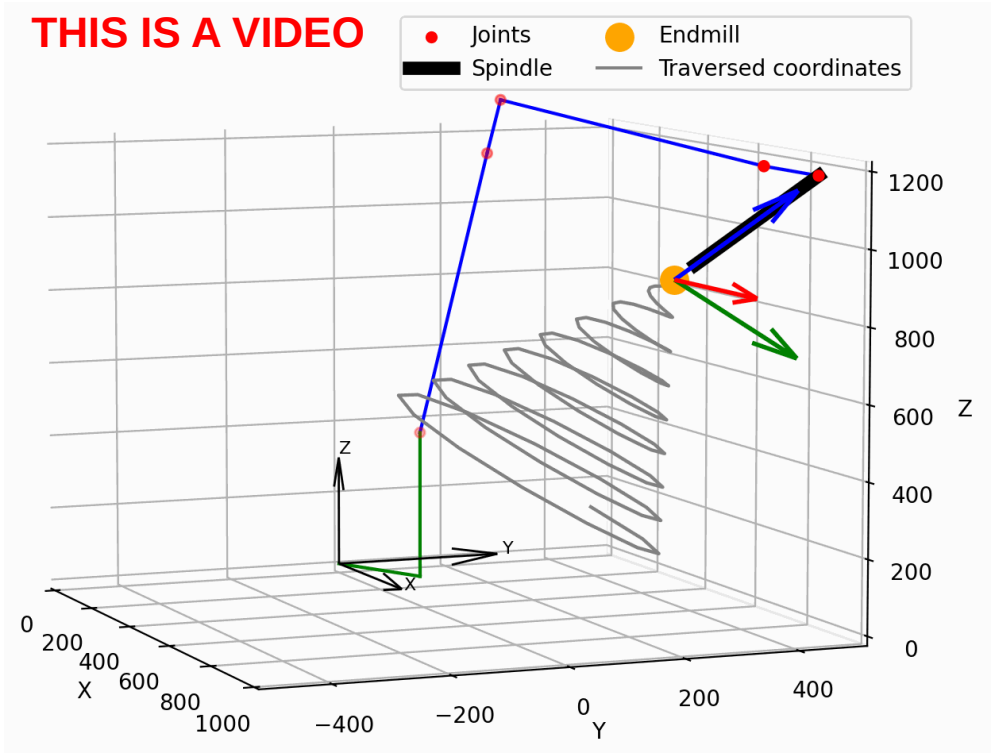
Implementation and Results

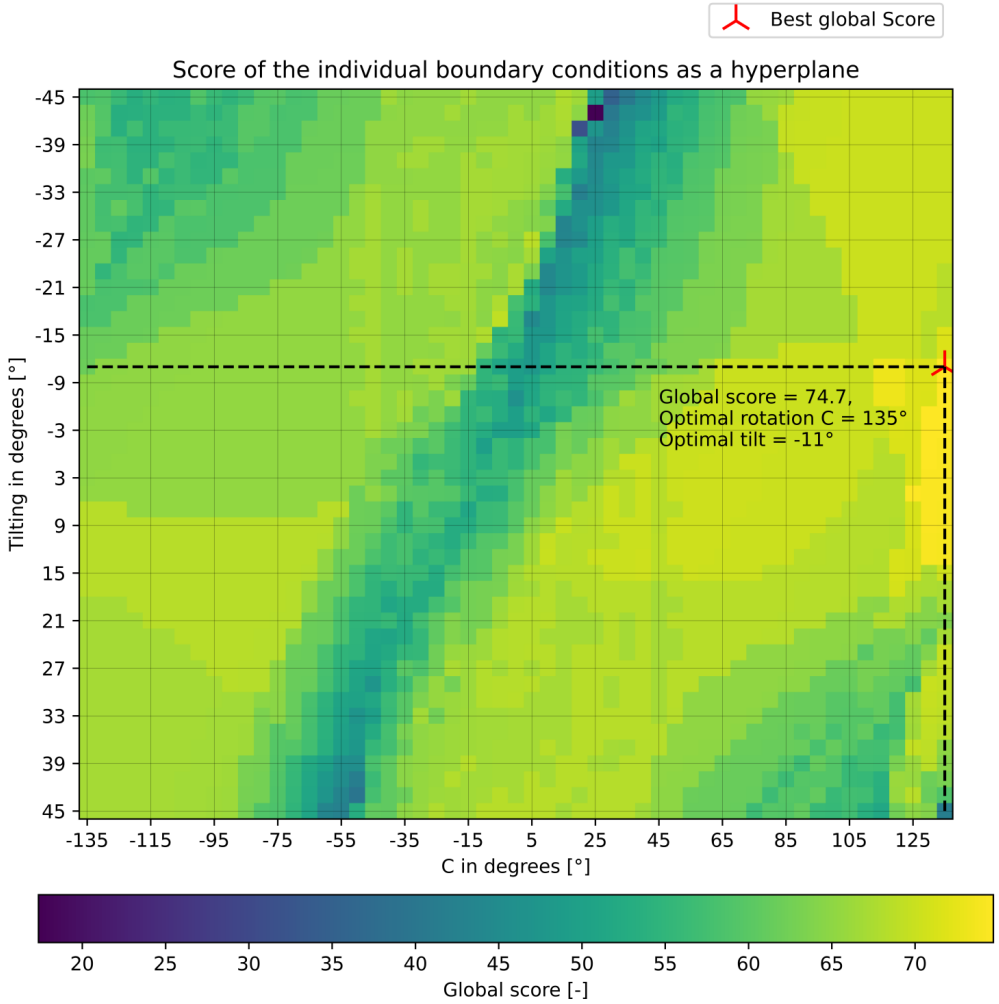


Addition of a Second Redundant DoF in Form of a Rotary-Tilt-Table

Implementation and Results

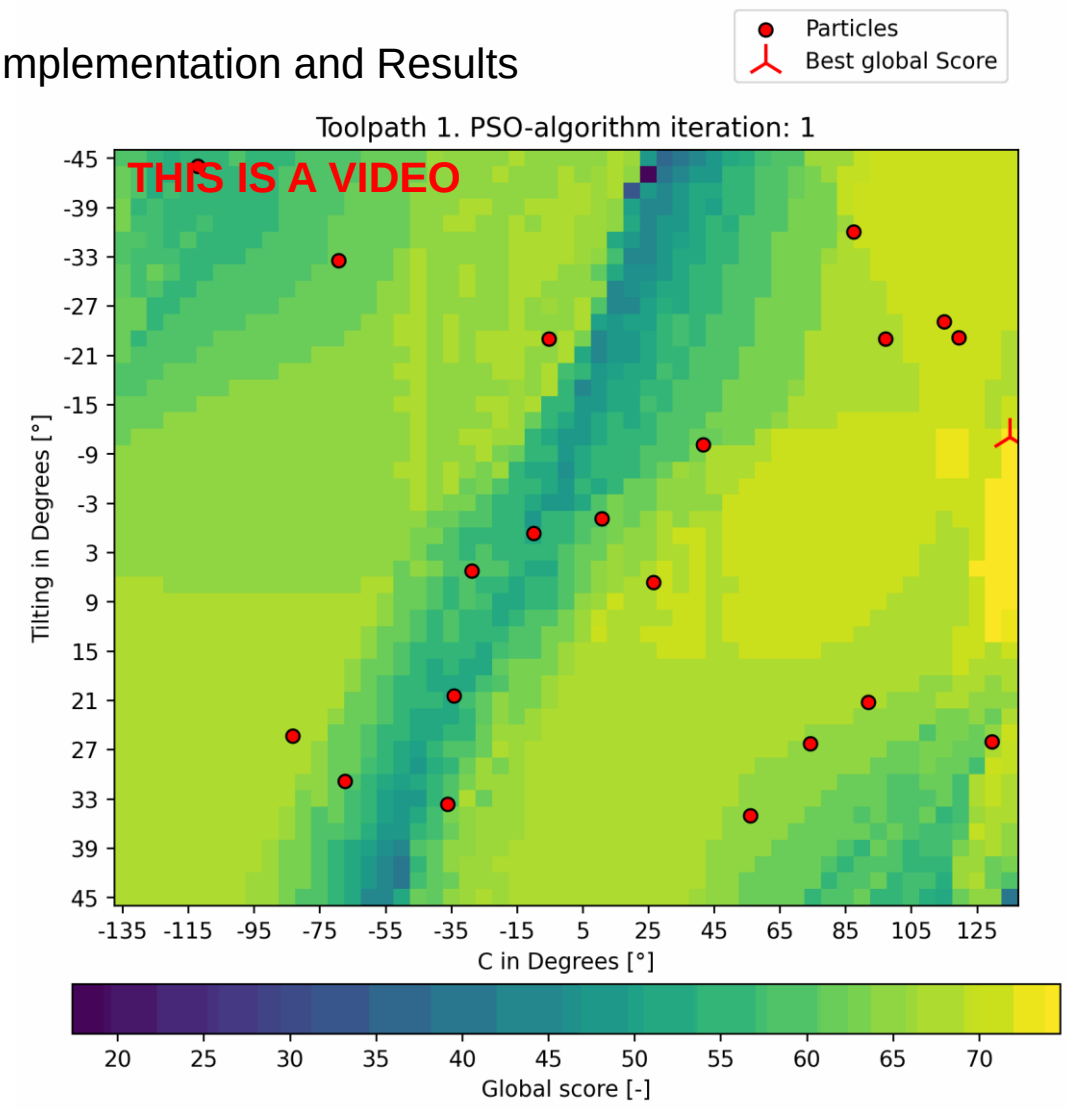
Two redundant DoFs: 1) Rotation C (tool symmetry axis)
2) Tilting of the base-plate

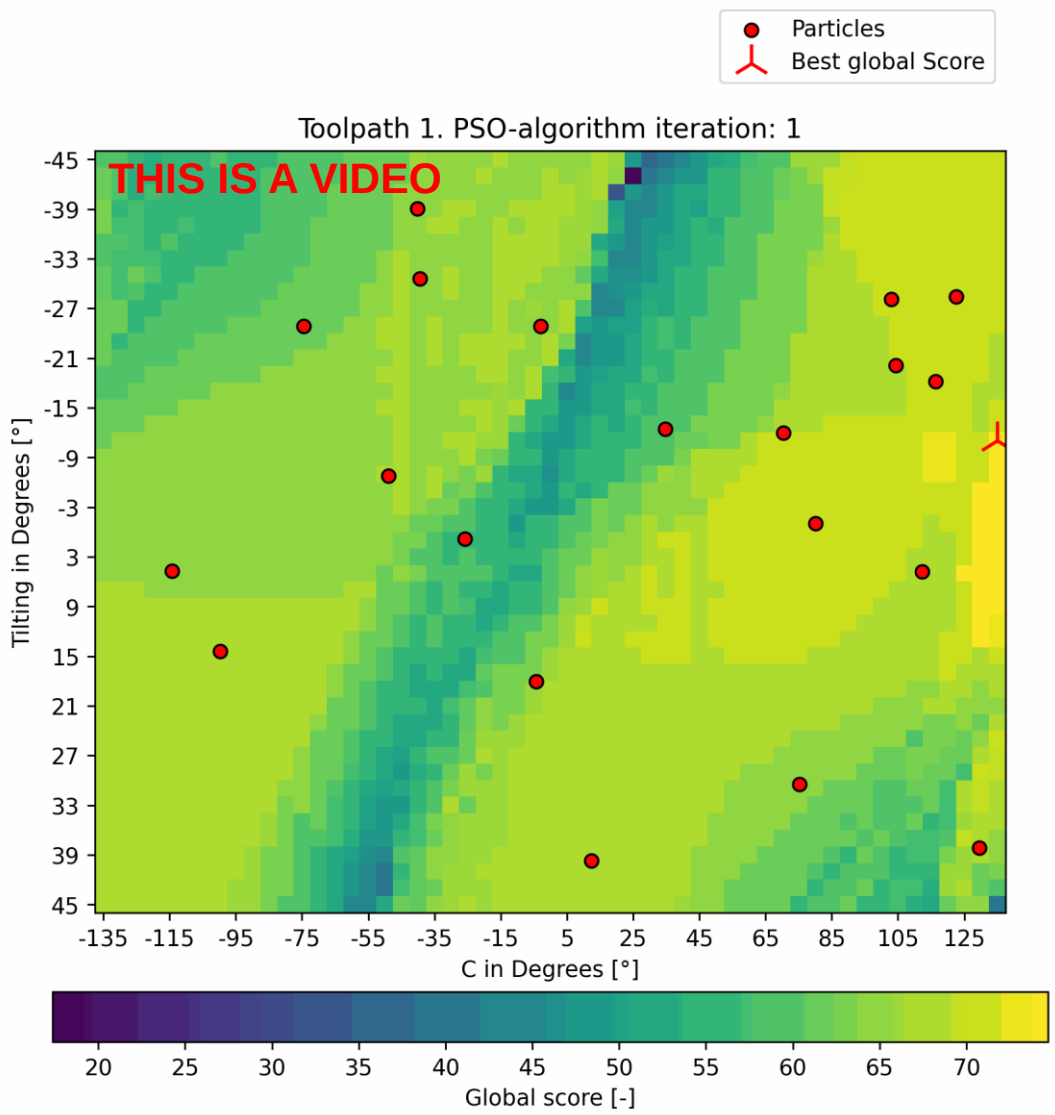




Visualization of the PSO-Algorithm

Implementation and Results





Valid Proof Of Concept

Summary and Outlook

Summary

- The validation provides a solid proof-of-concept
- Redundant DoFs can offer significant potential for improvement in the robot’s movement.
- A PSO-algorithm is reasonable choice for finding the optimal boundary conditions
- The method's adaptability allows for wide application to a broad spectrum of robotic systems
- For a more detailed validation, longer production G-codes and multi-axis operations with more than two redundant DoFs are necessary

Outlook

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

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Sources

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Bedrossian,(1990) Classification of singular configurations for redundant manipulators

Huo and Baron, (2008) The joint-limits and singularity avoidance in robotic welding

Milenkovic, (2021) Wrist singularity avoidance with a robot end-effector adding an oblique, redundant axis

Shi et al., (2021) Kinematics and Singularity Analysis of a 7-DOF Redundant Manipulator

Dai et al., (2020) Planning Jerk-Optimized Trajectory With Discrete Time Constraints for Redundant Robots

Jiang et al., (2017) Time-Jerk Optimal Trajectory Planning for a 7-DOF Redundant Robot Using the Sequential Quadratic Programming Method

Bien Duong (2021) On the Effect of the End-effector Point Trajectory on the Joint Jerk of the Redundant Manipulators

Wu et al., (2021) Review of Industrial Robot Stiffness Identification and Modelling

Xiong et al., (2019) Stiffness-based Pose Optimization of an Industrial Robot for Five-axis Milling

Wang et al., (2022) Optimization of redundant degree of freedom in robotic milling considering chatter stability

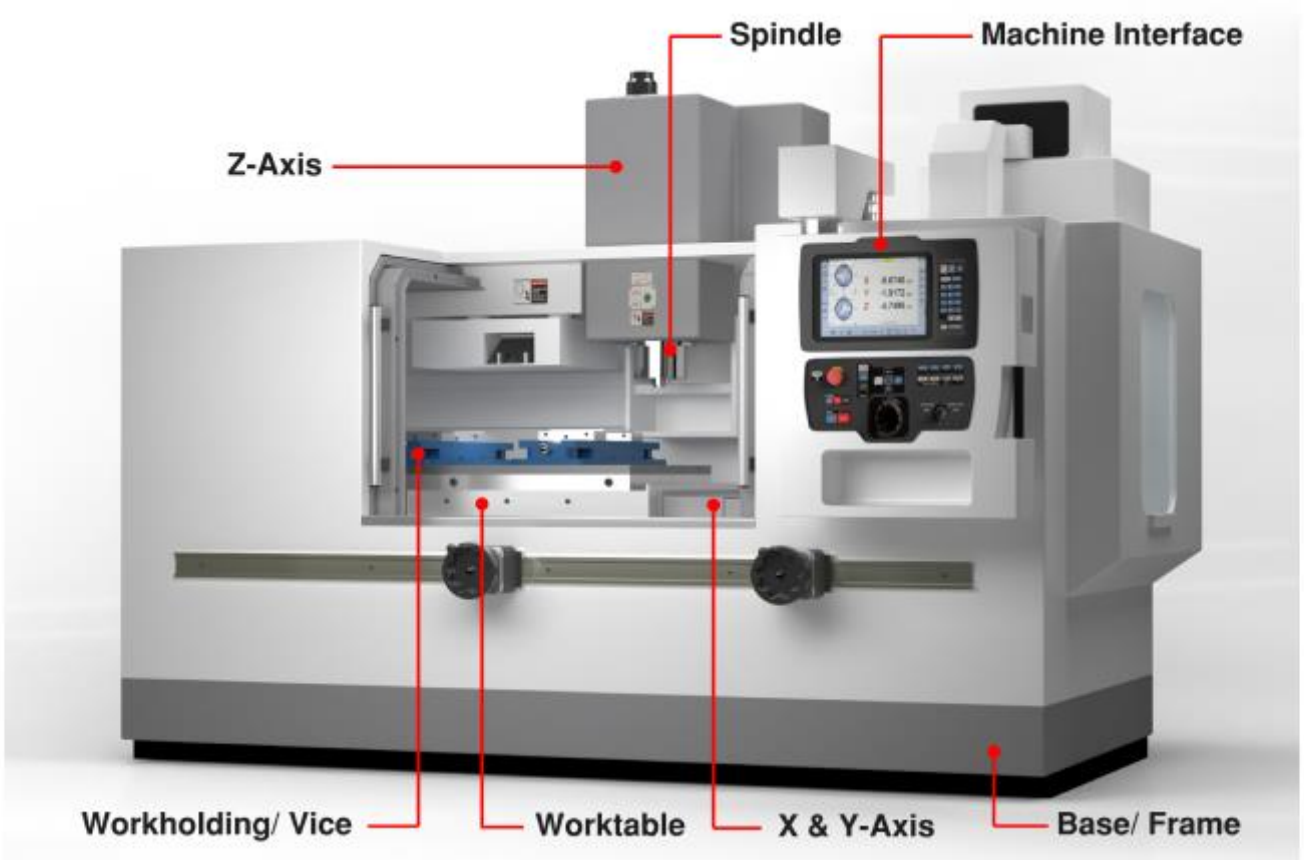
Cvitanic et al., (2020) Pose optimization in robotic machining using static and dynamic stiffness models

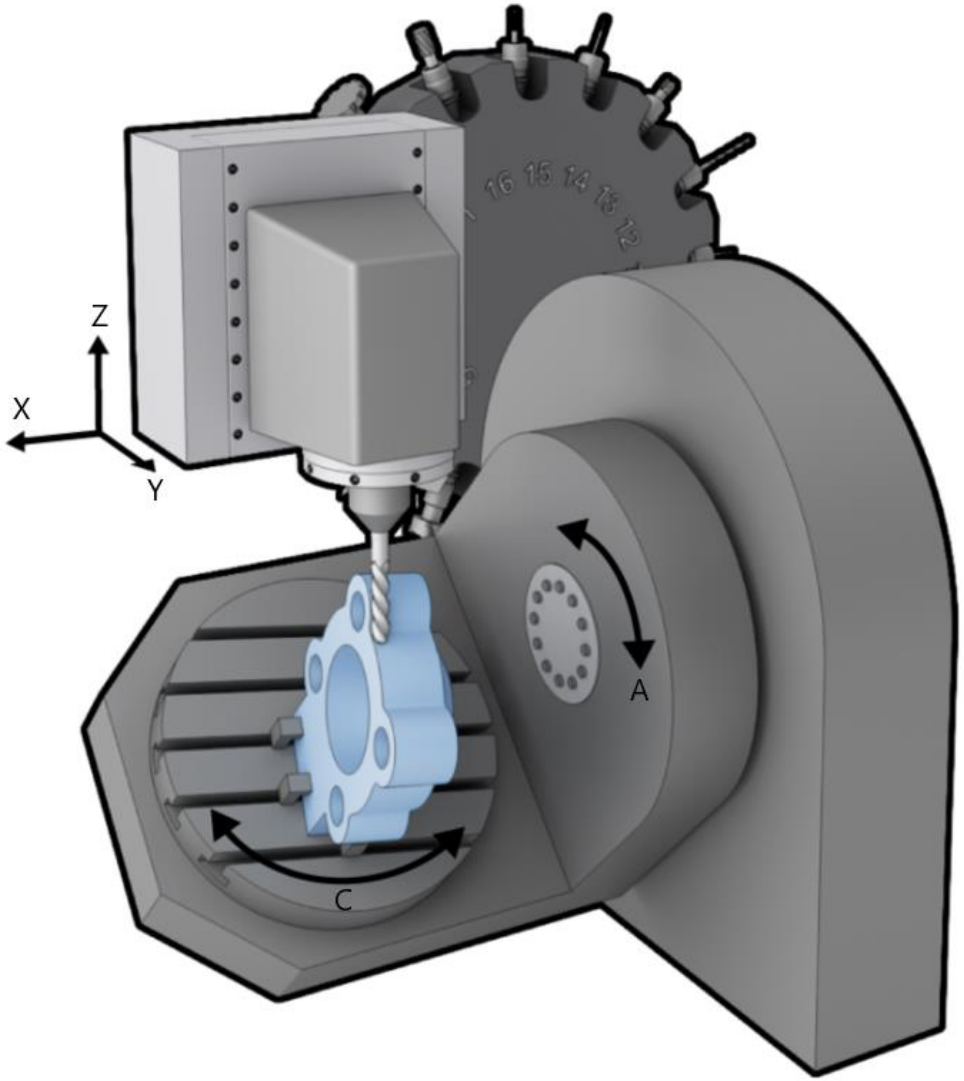
Uhlmann et al., (2016) Energy Efficient Usage of Industrial Robots for Machining Processes

Boscariol et al., (2020) Energy Optimization of Functionally Redundant Robots through Motion Design

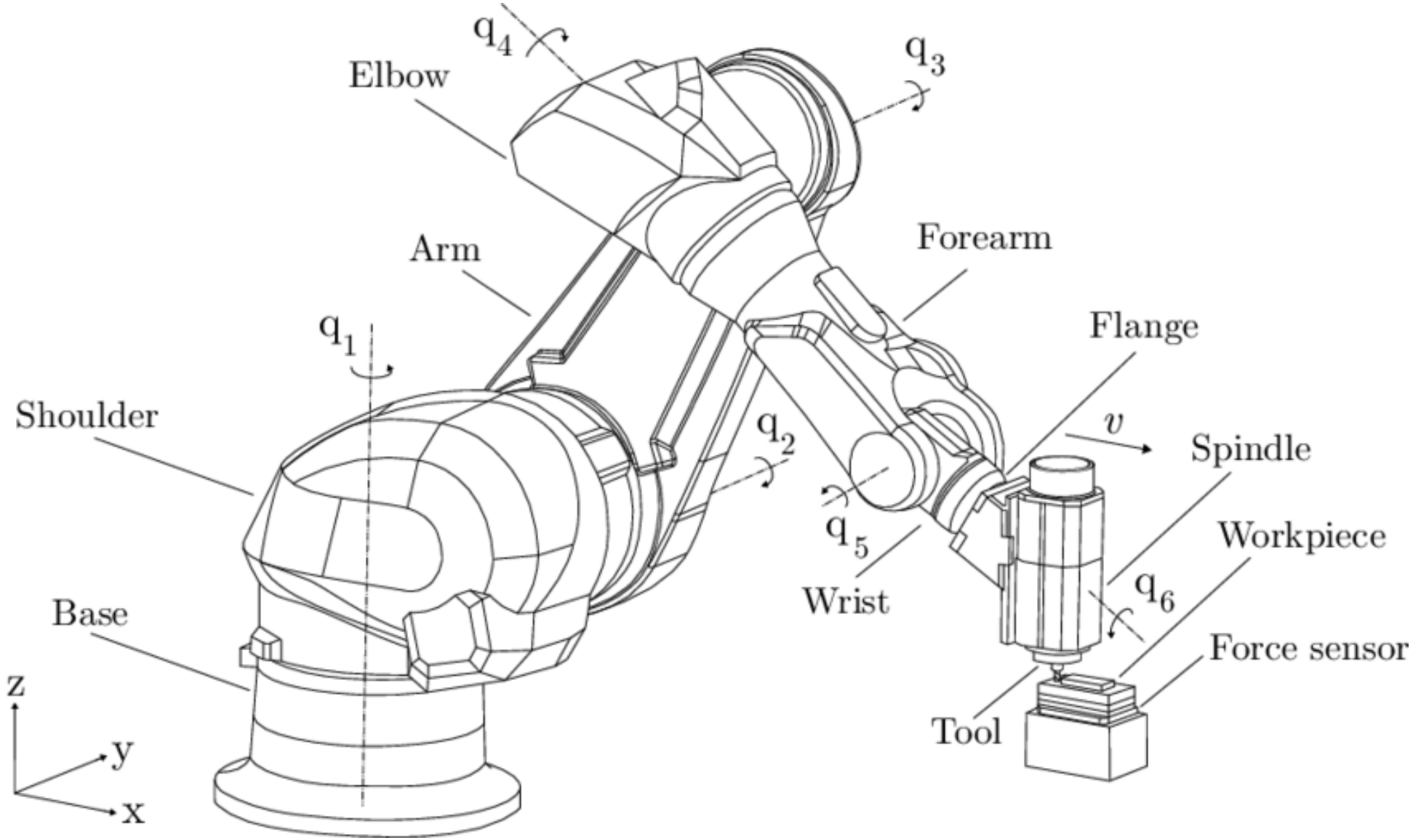
Soori et al., (2015) Optimization of energy consumption in industrial robots, a review

CNC machines

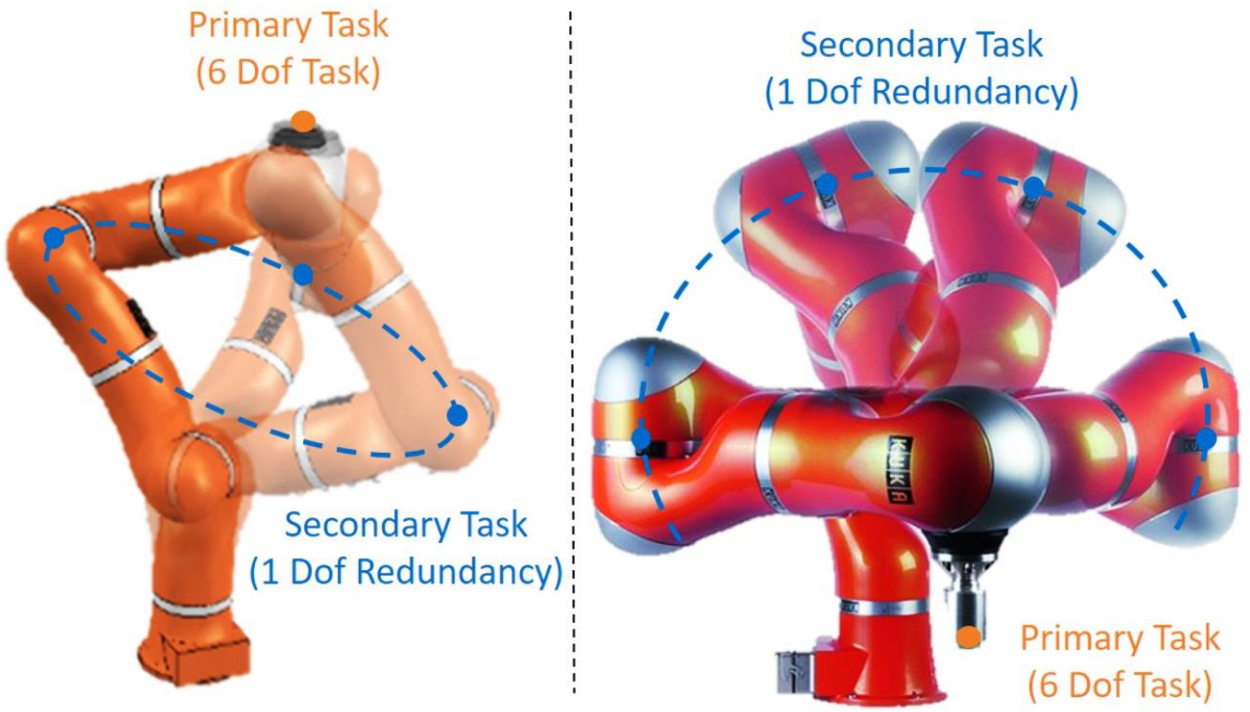




Industrial Robot

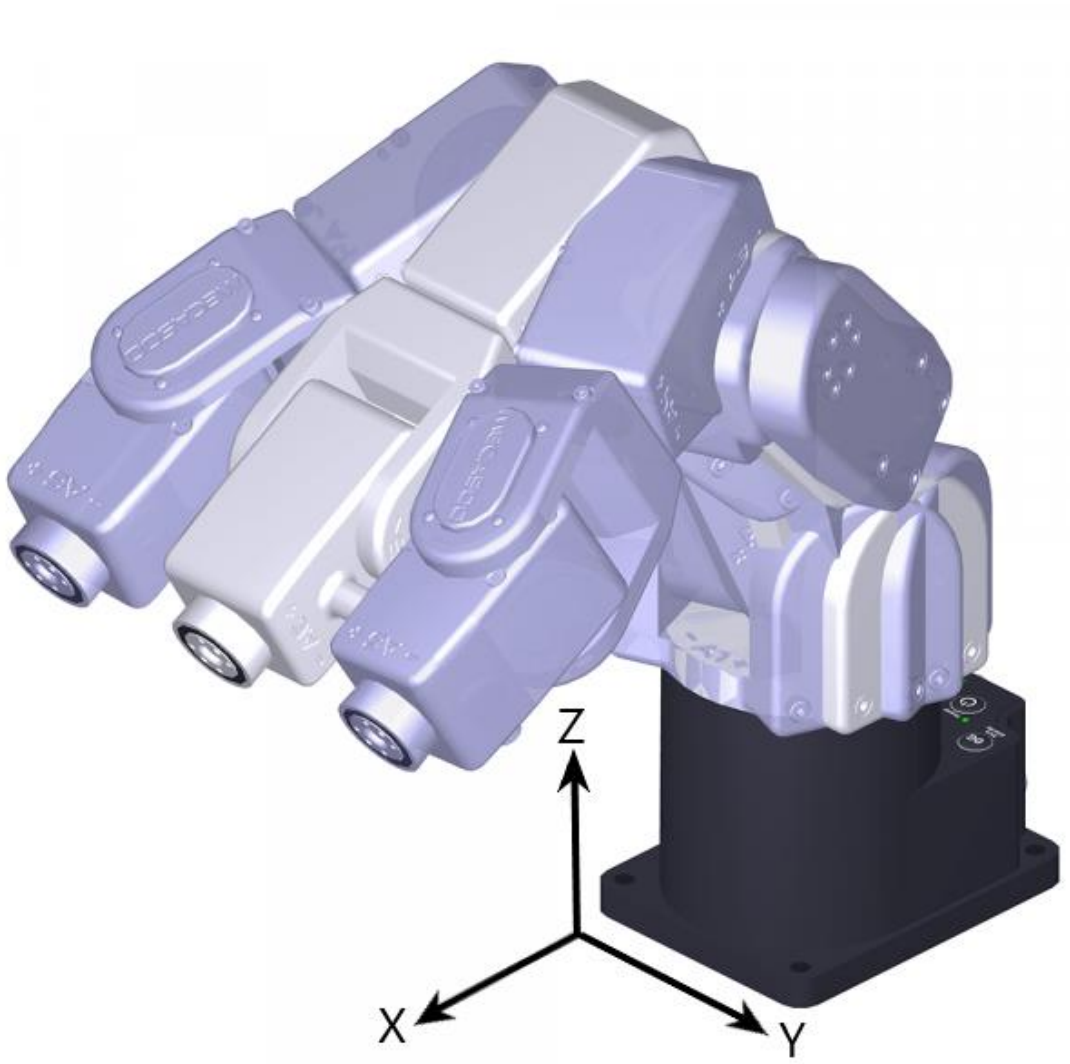


Manufacturing Systems with Redundant DoFs

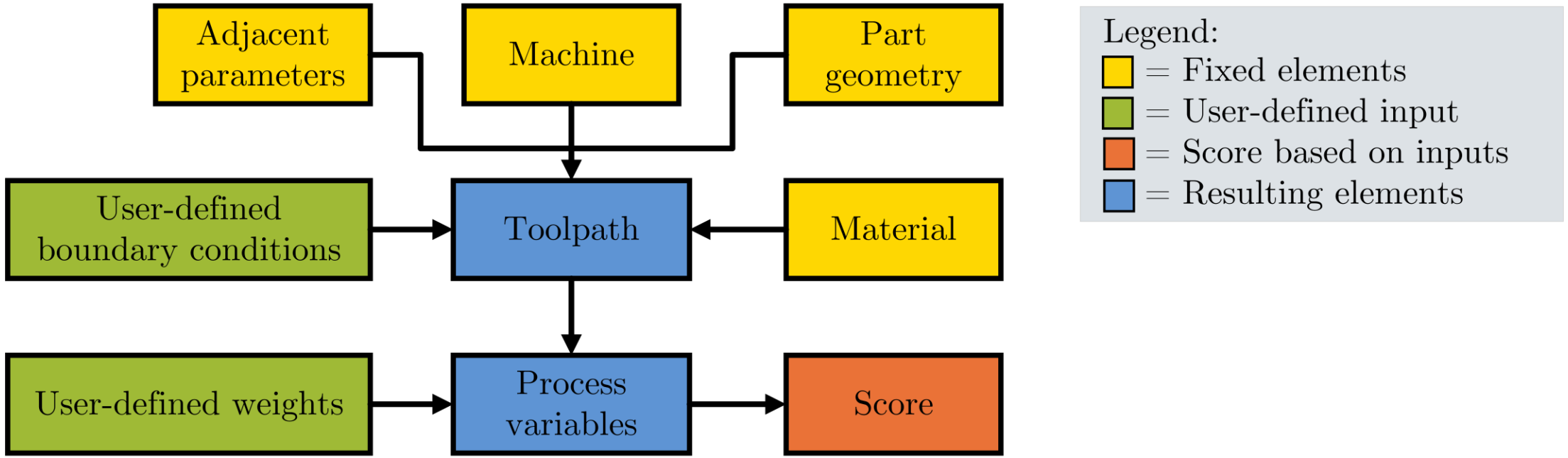


7 Dof Robot (KUKA LWR)

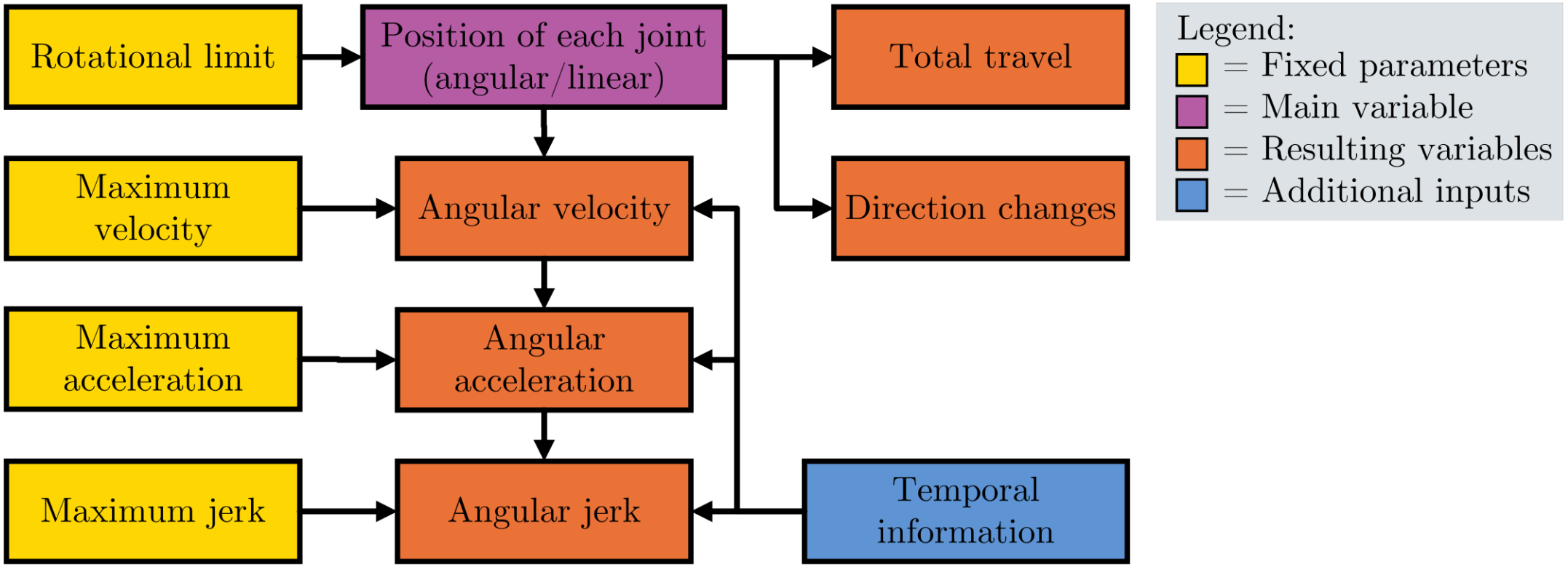
Singularity



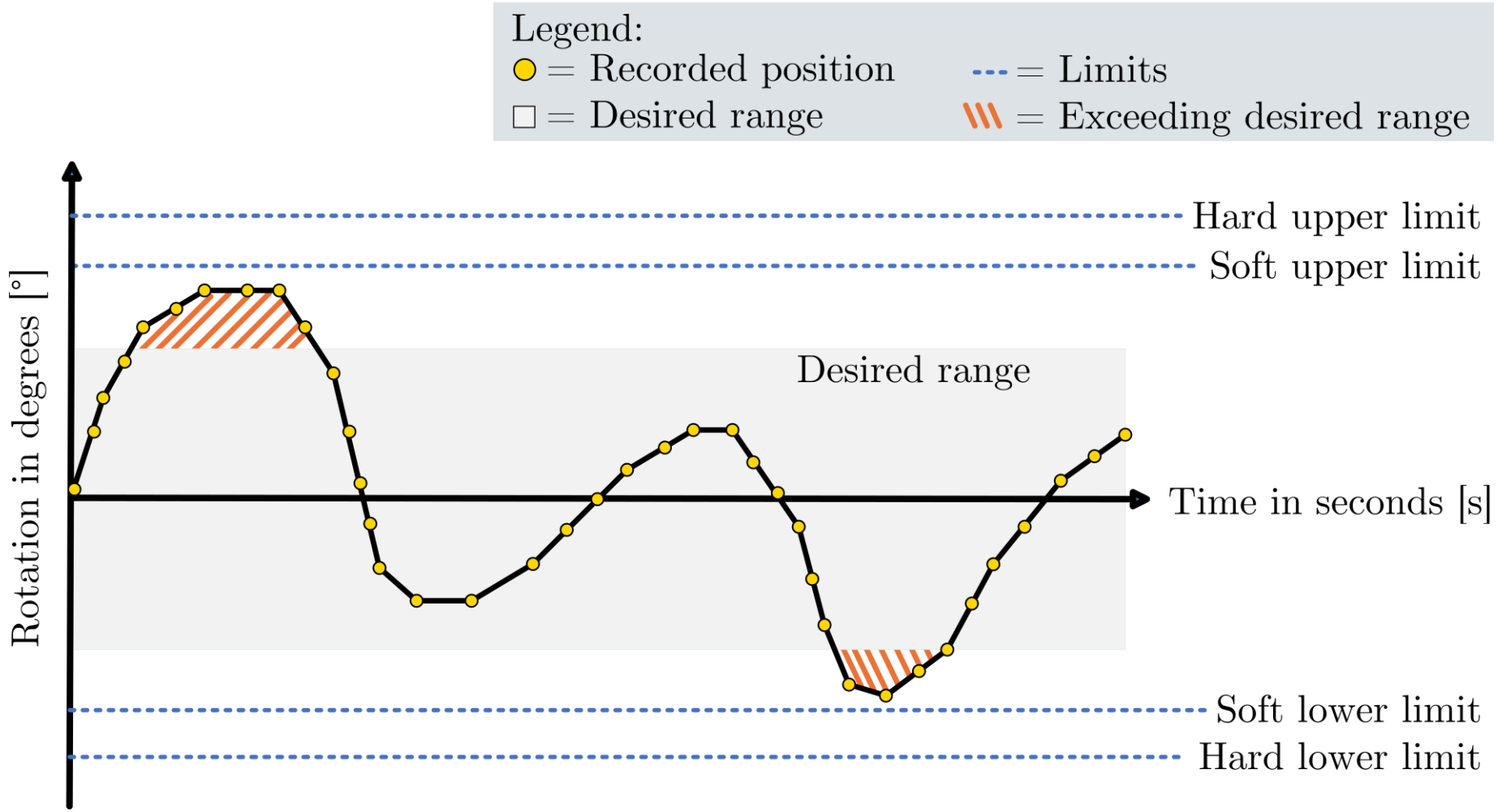
Interdependence of various parameters and elements



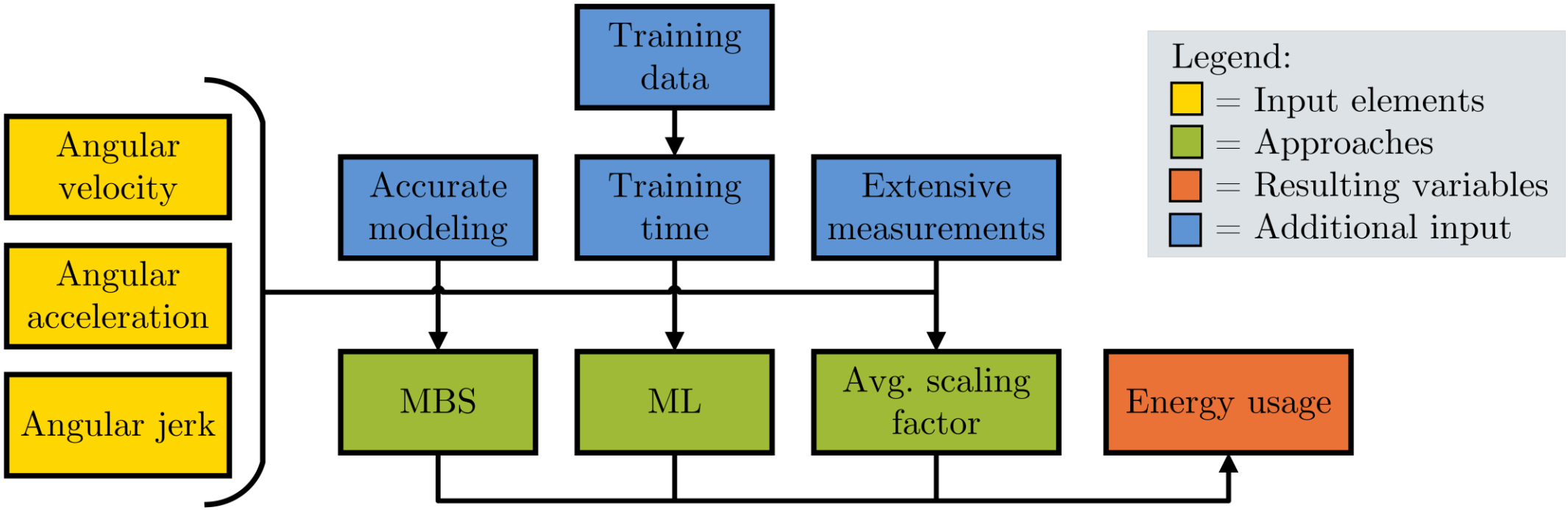
Additional information for angular position of each joint



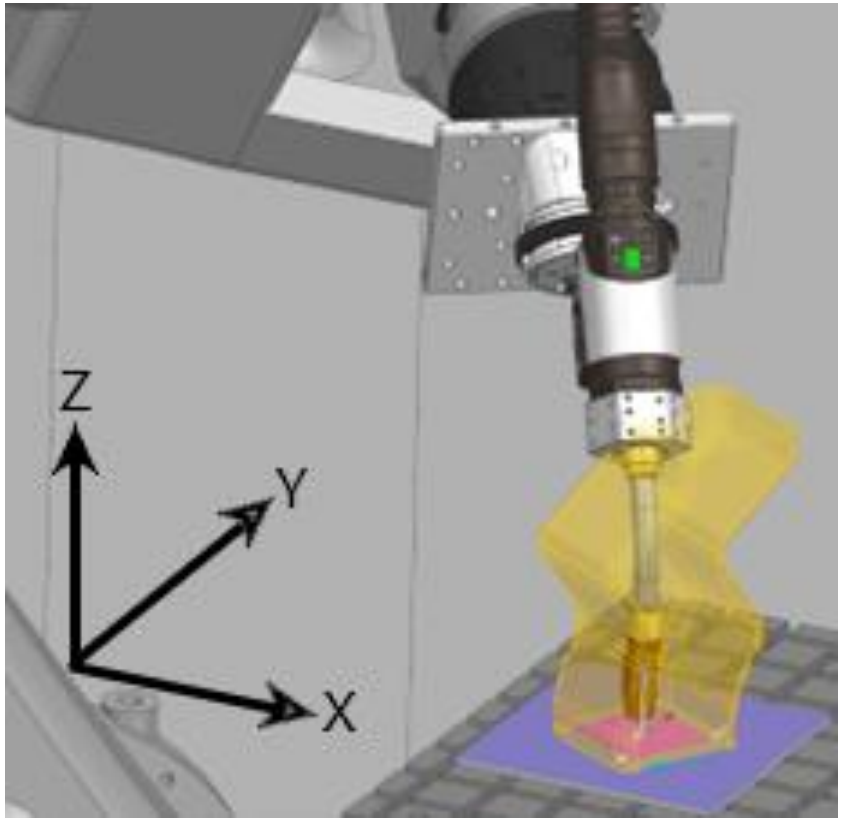
Hard and soft limits with desired range

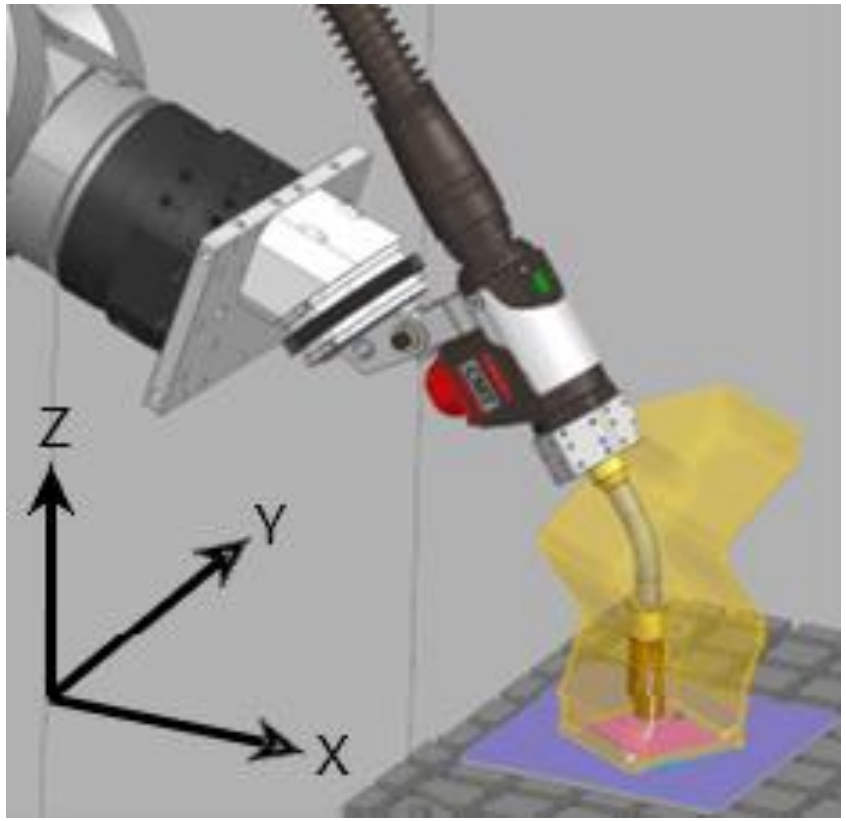


Exemplary methods for energy usage calculations



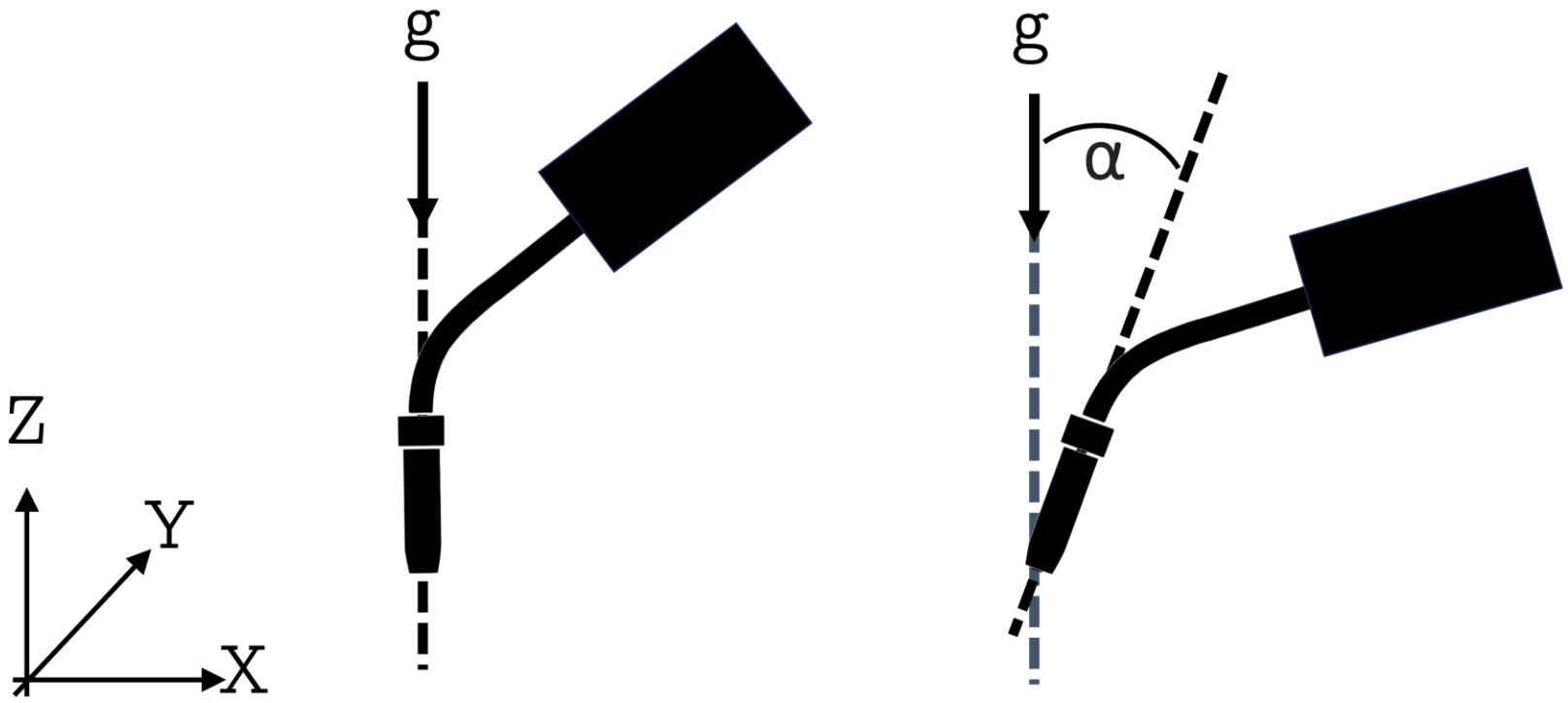
Rotation around the C-Axis of a welding torch





Torch Orientation

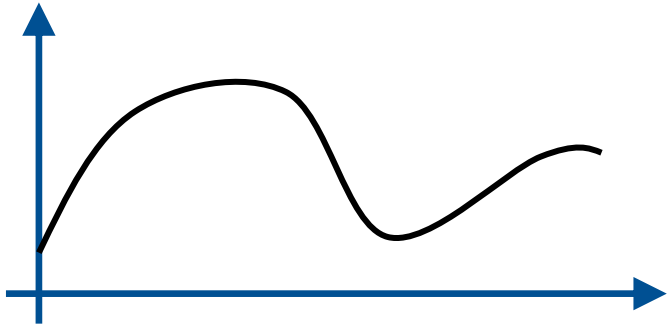
Example of optimal and non-optimal tilt in the welding torch



Transforming Time-Series Data into Scalar Values

Time-series data:

- Velocity
- Acceleration
- Jerk
- …

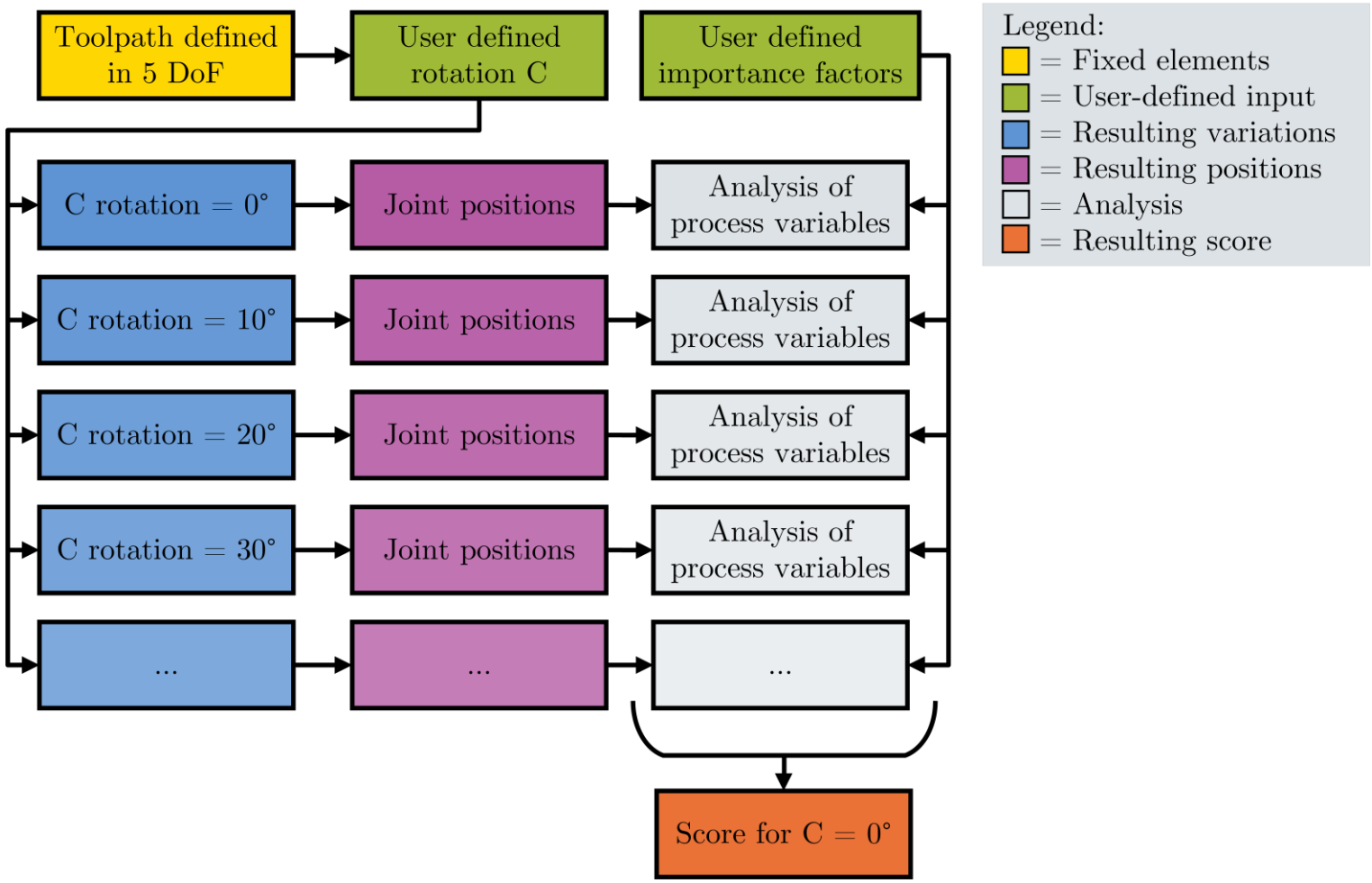


Optional procedures:

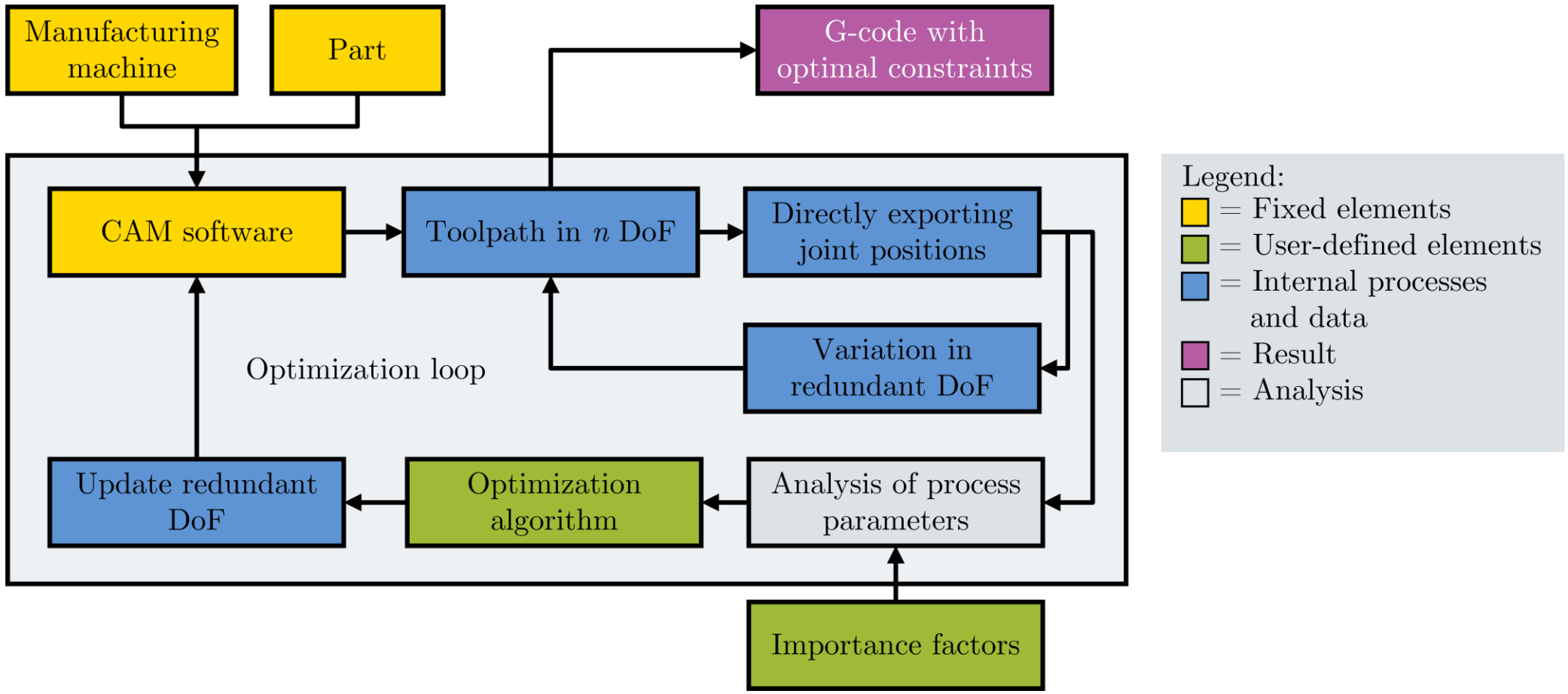
- Squaring and aggregation
- Cubing and aggregation
- Definition of thresholds
- Machine learning

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

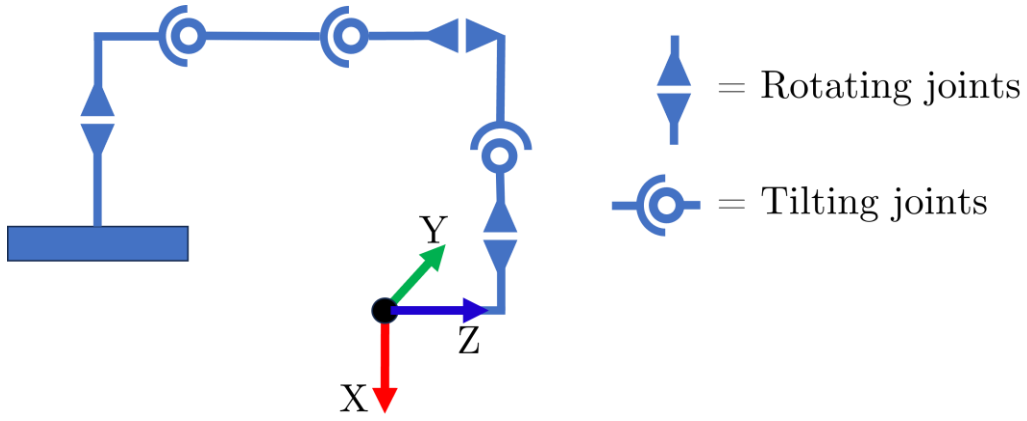


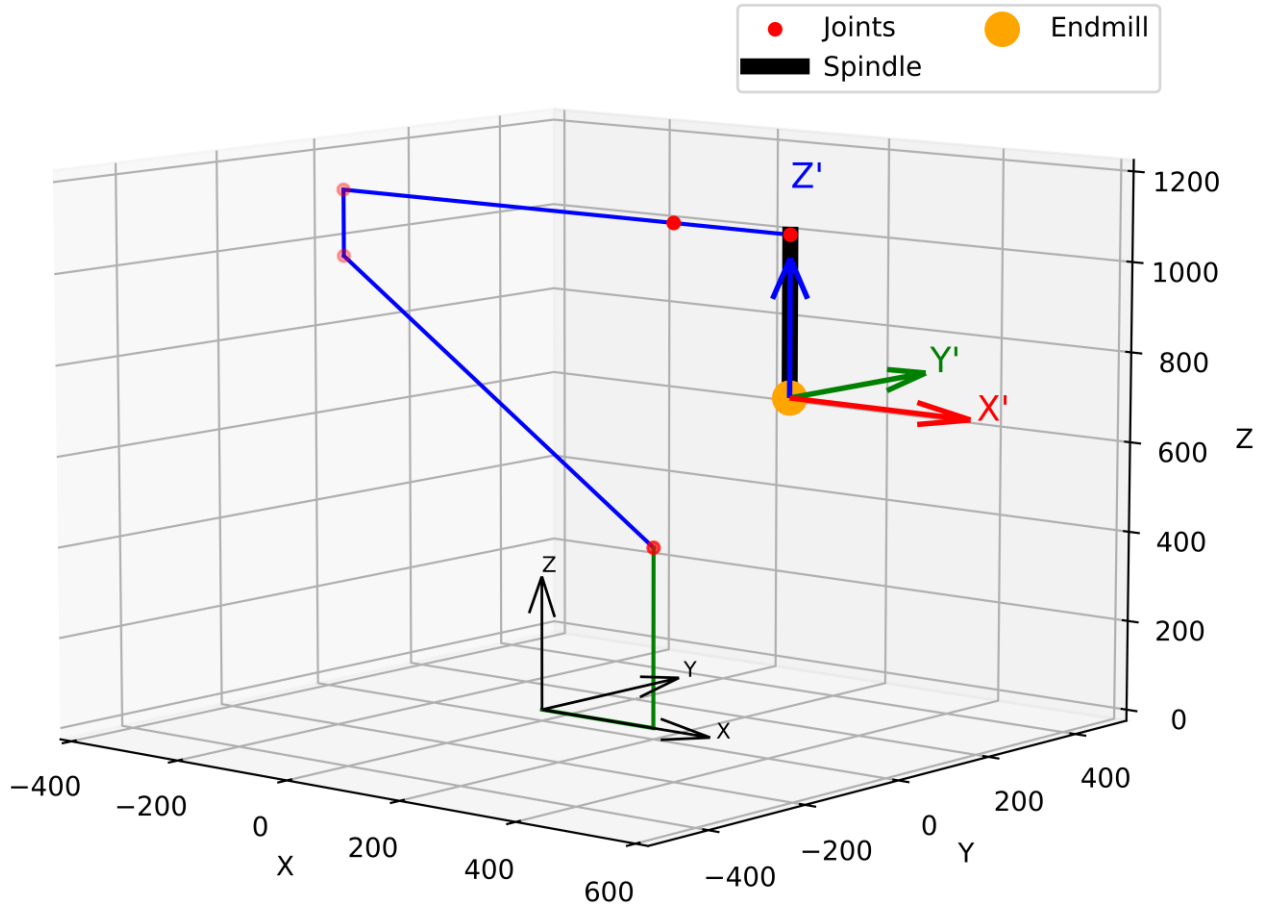
Optimization Loop With CAM Software in the Loop



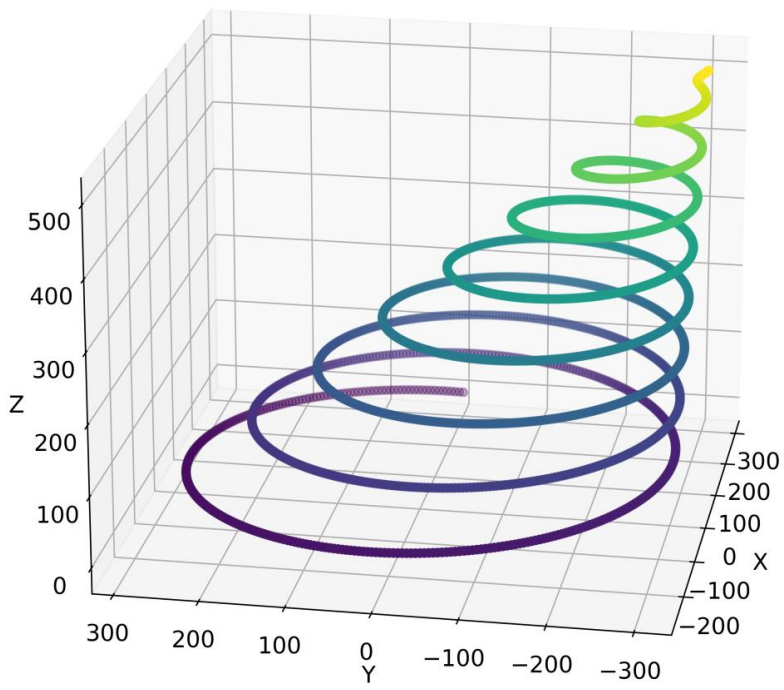
Modeled Robot

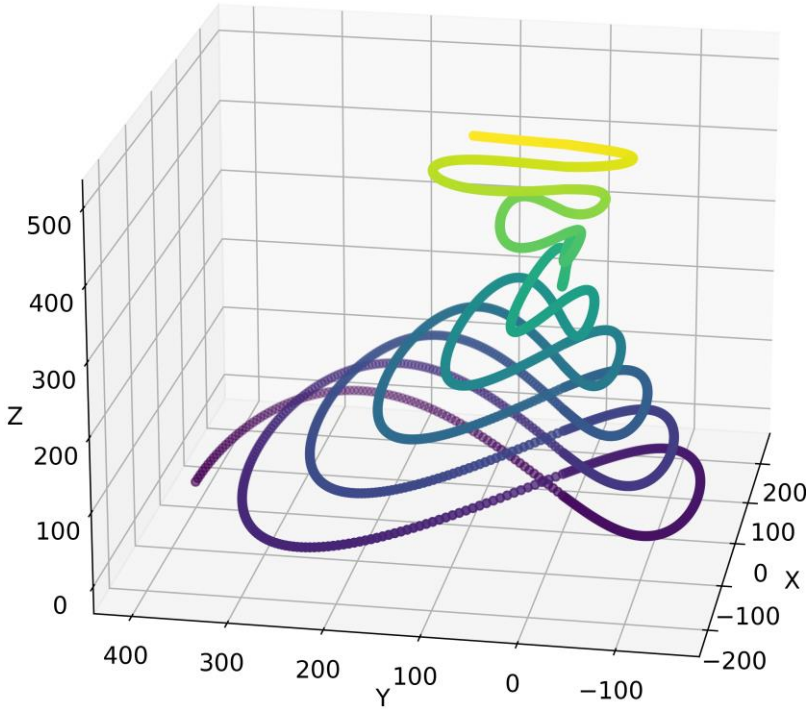
Parameters	Values
a in [mm]	[200, 800, 150, 0, 0, 0]
alpha in [°]	[90, 0, 90, -90, 90, 0]
d in [mm]	[400 0, 0, 600, 0, 200]

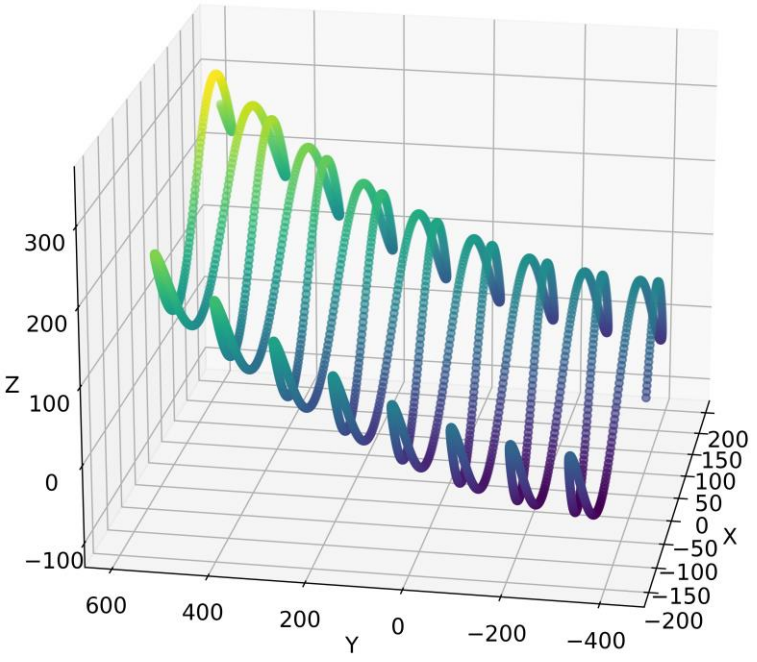




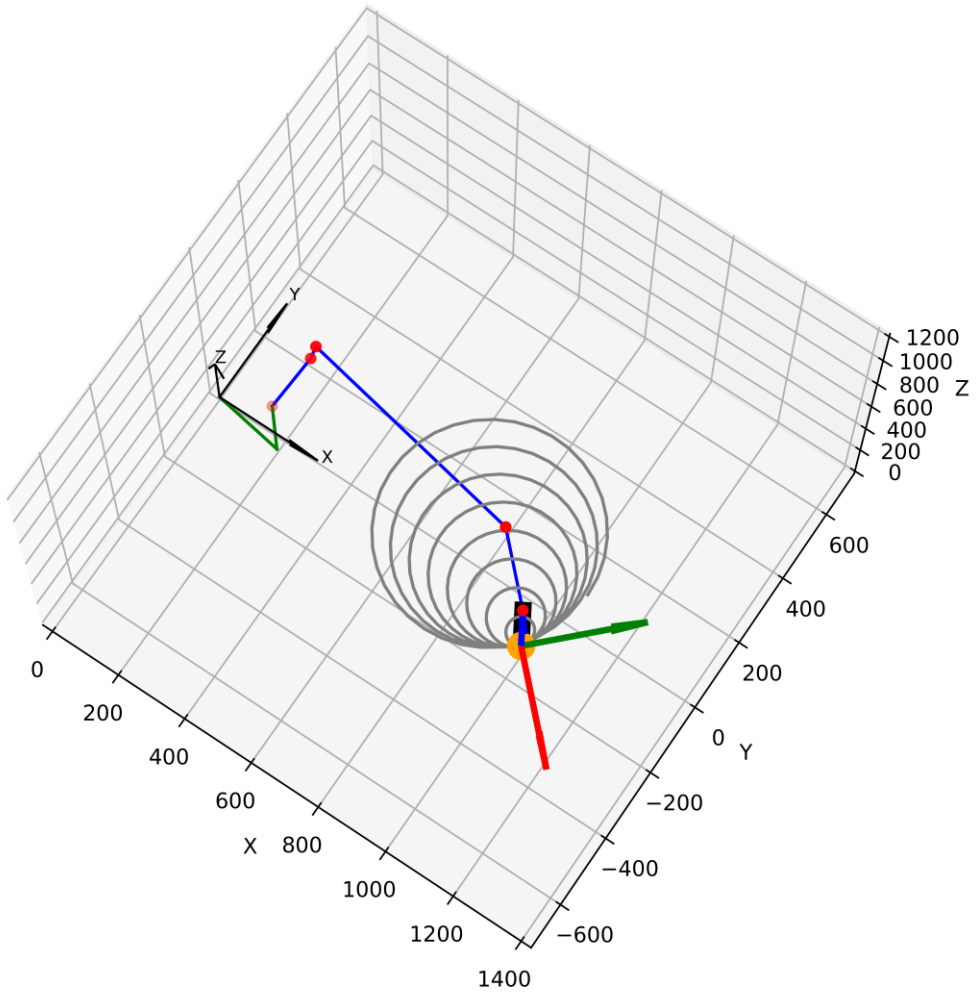
Modeling a Basic Toolpath

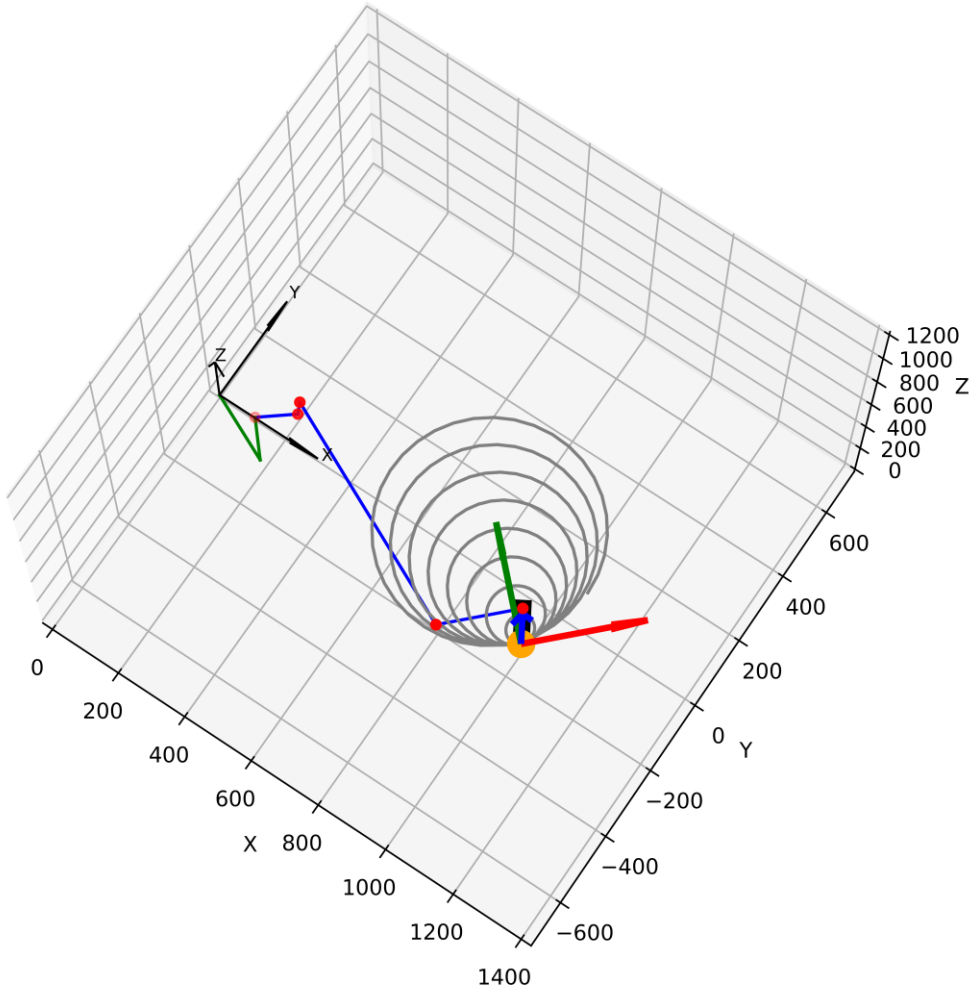




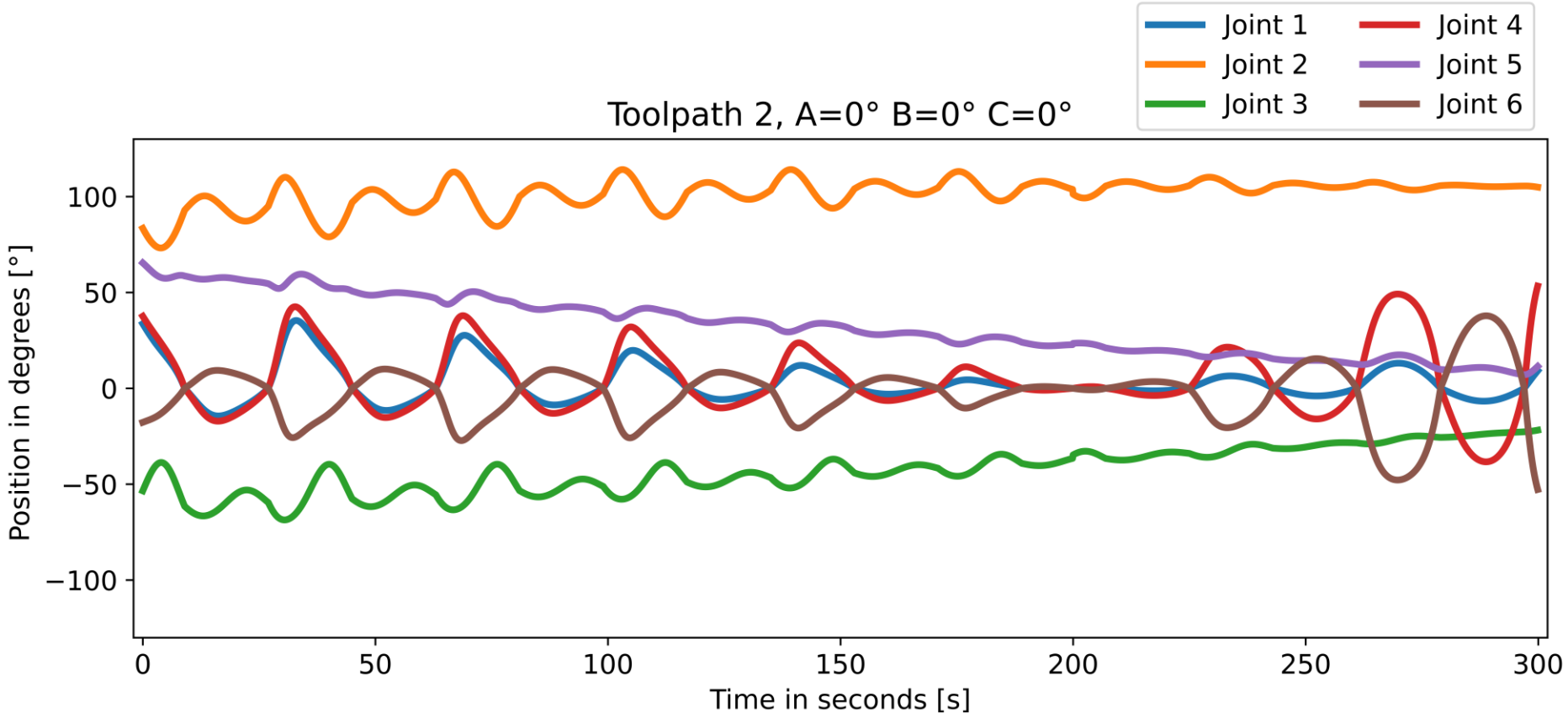


Rotation around the Z-axis for toolpath 1

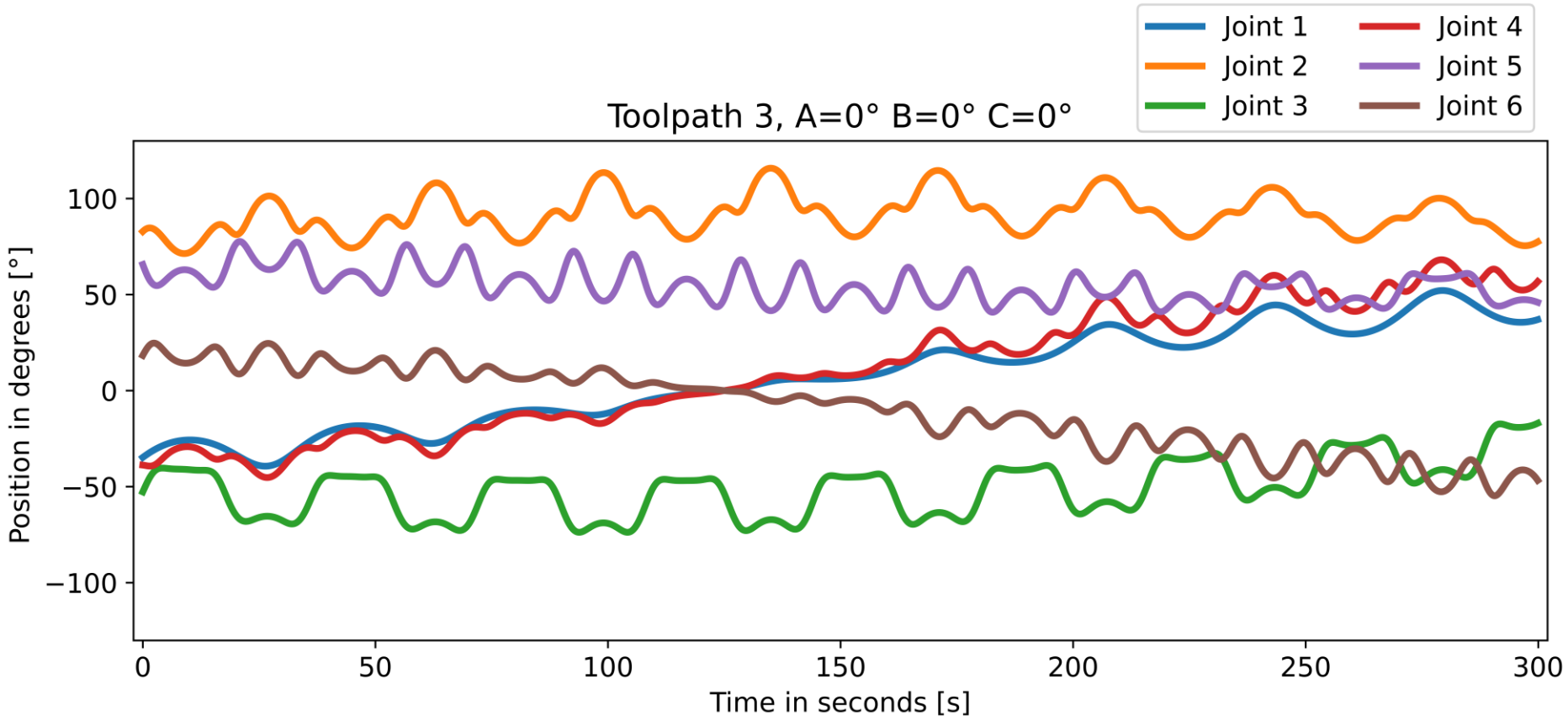




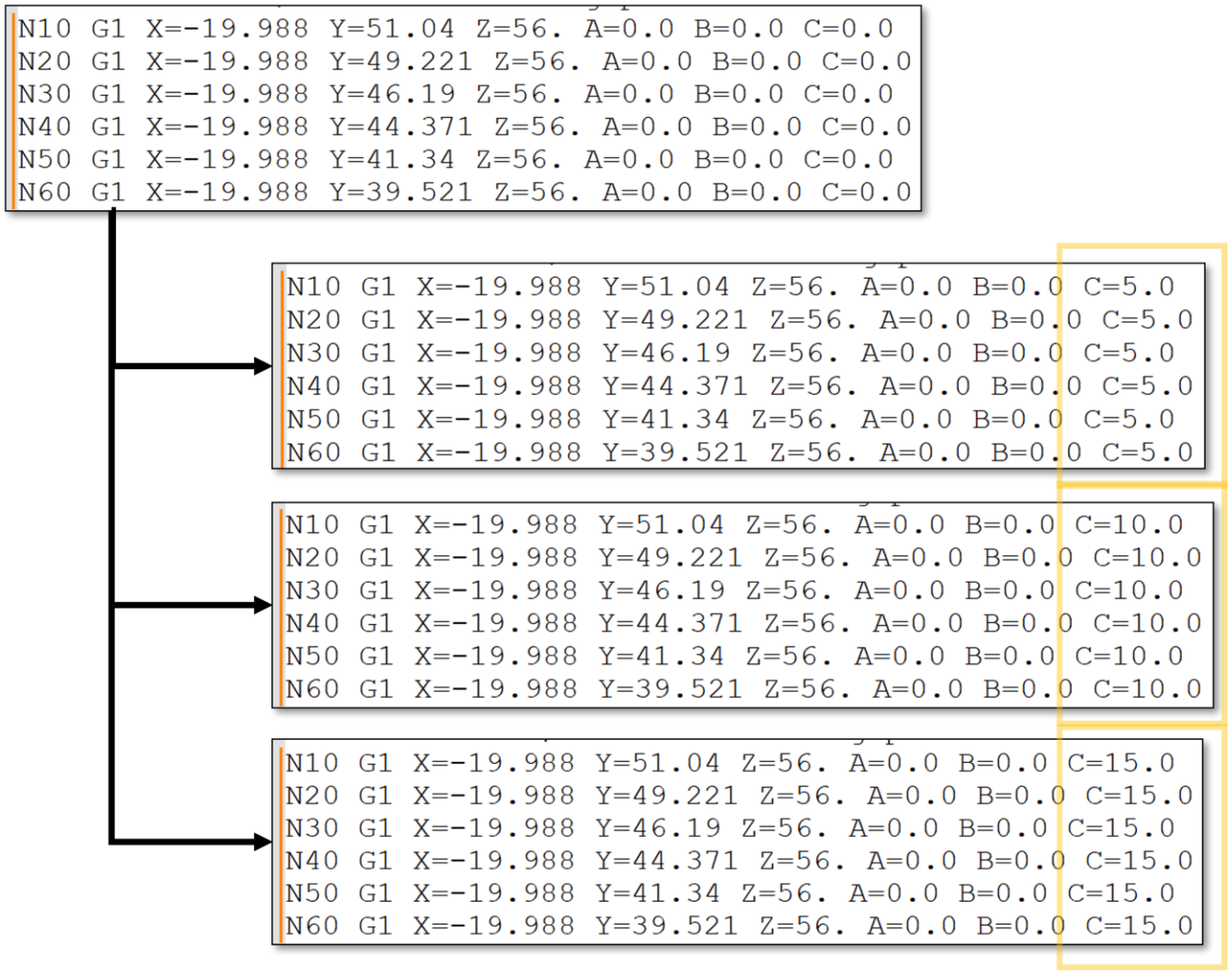
Toolpath 2


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]

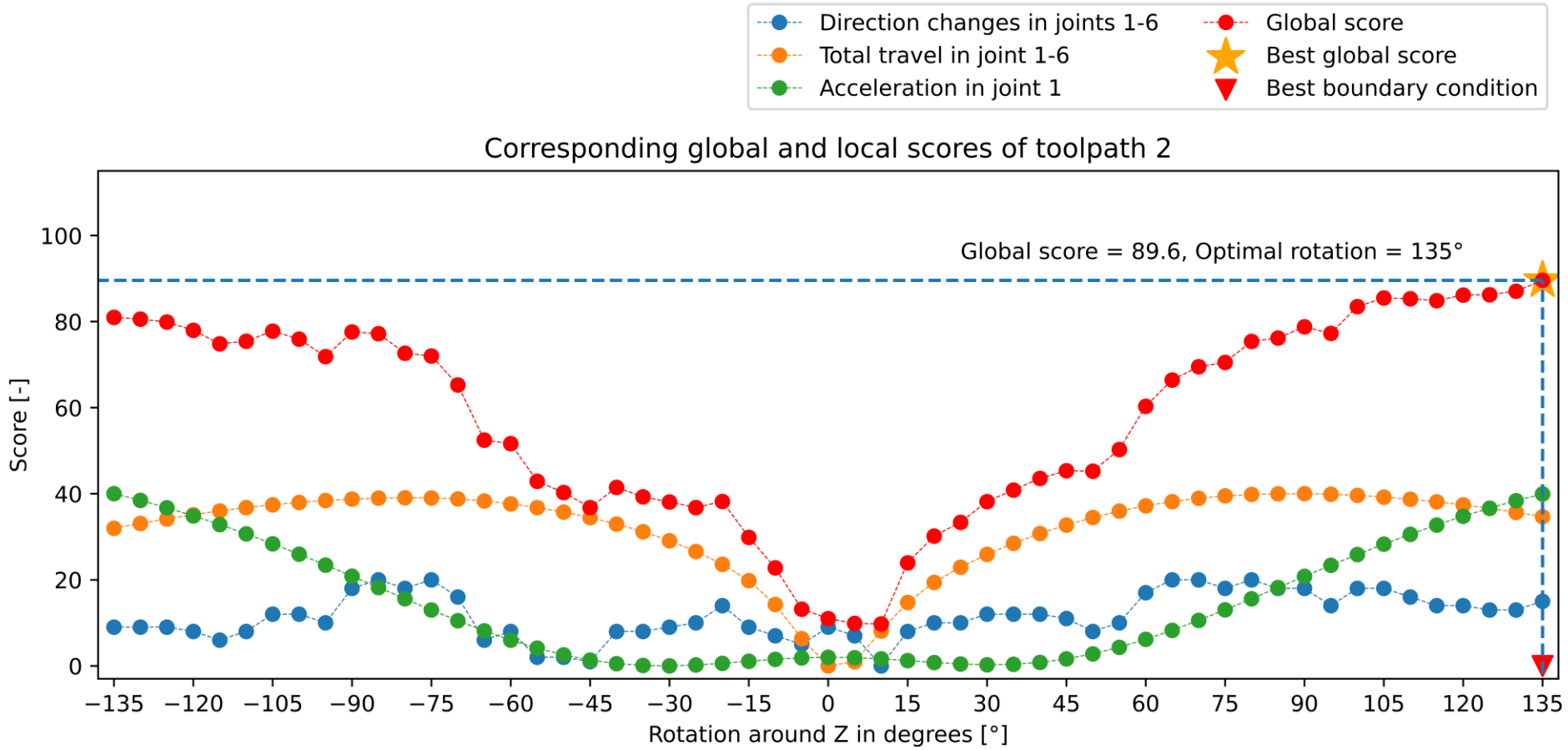
Toolpath 3


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]

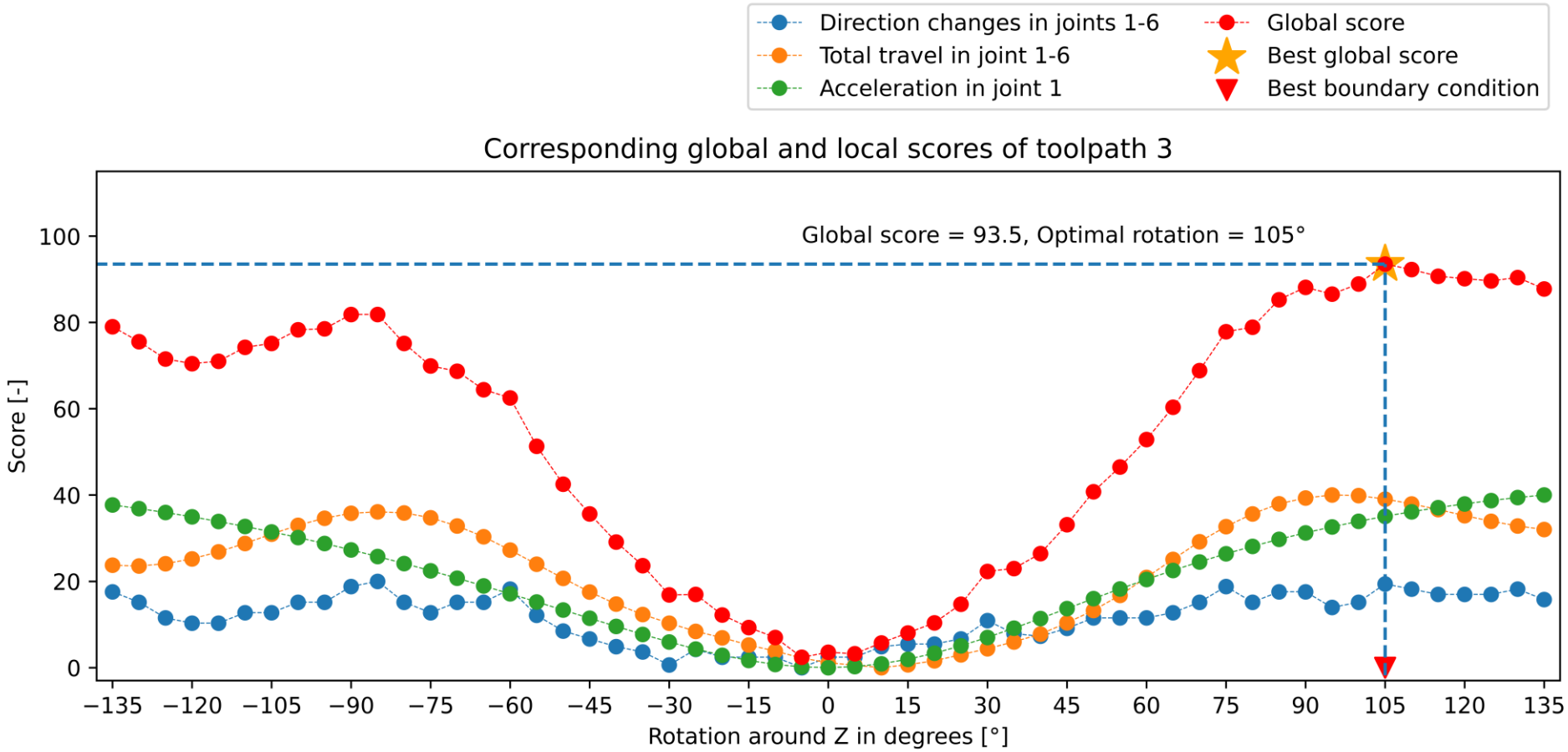
G-code Variation

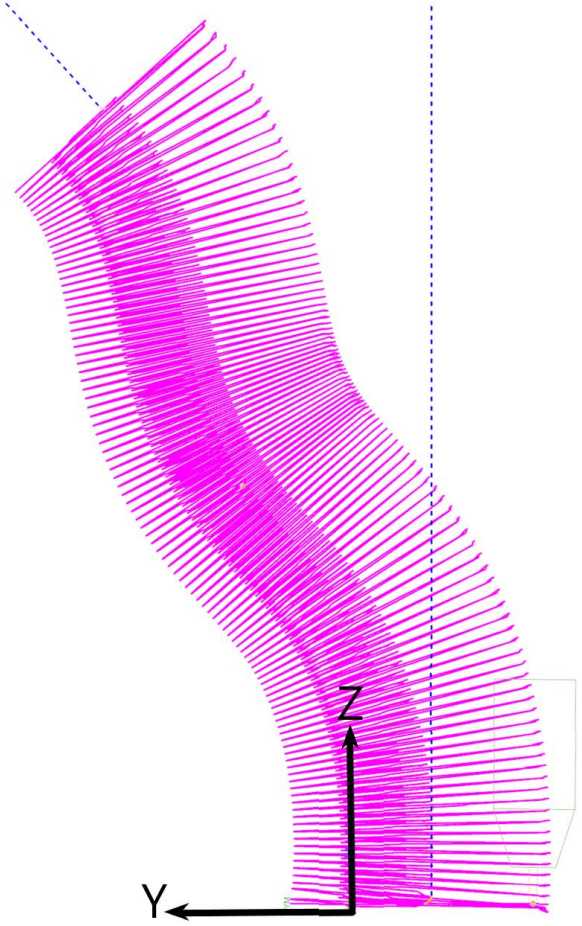


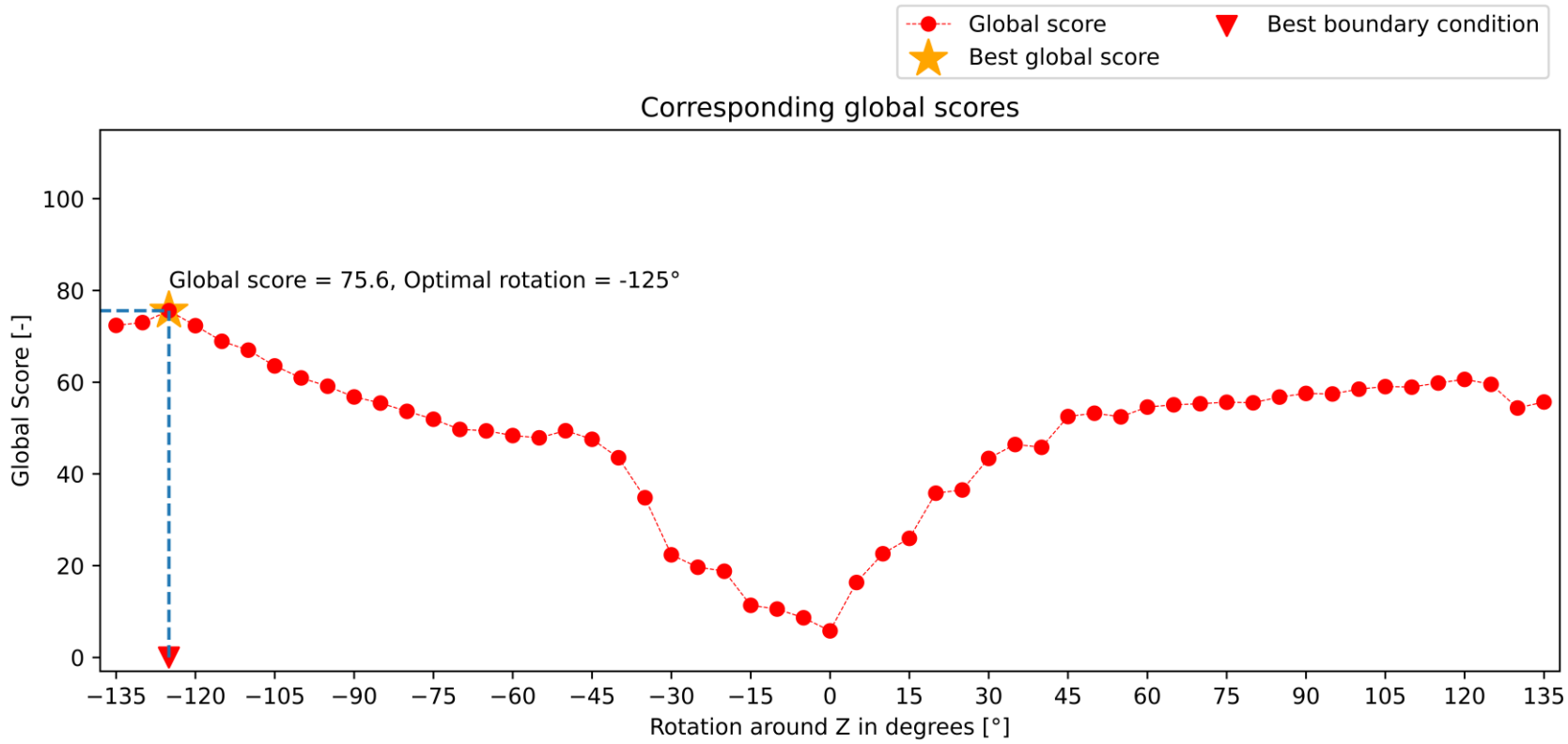
Toolpath 2 and Score



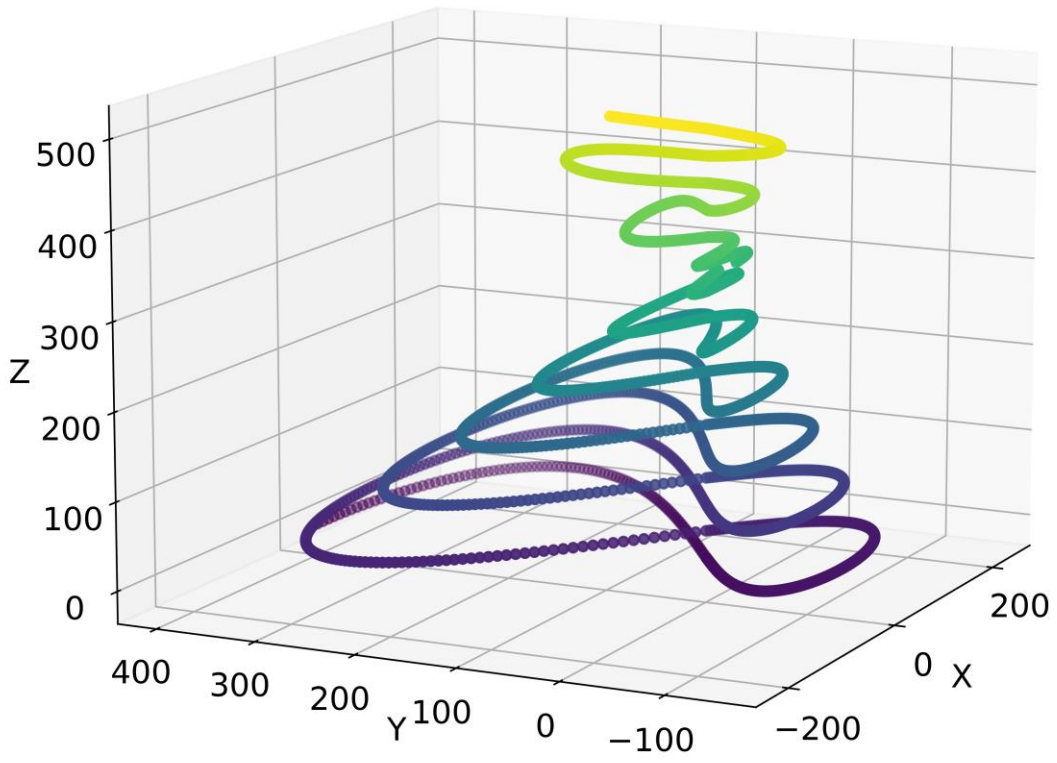
Toolpath 3 and Score

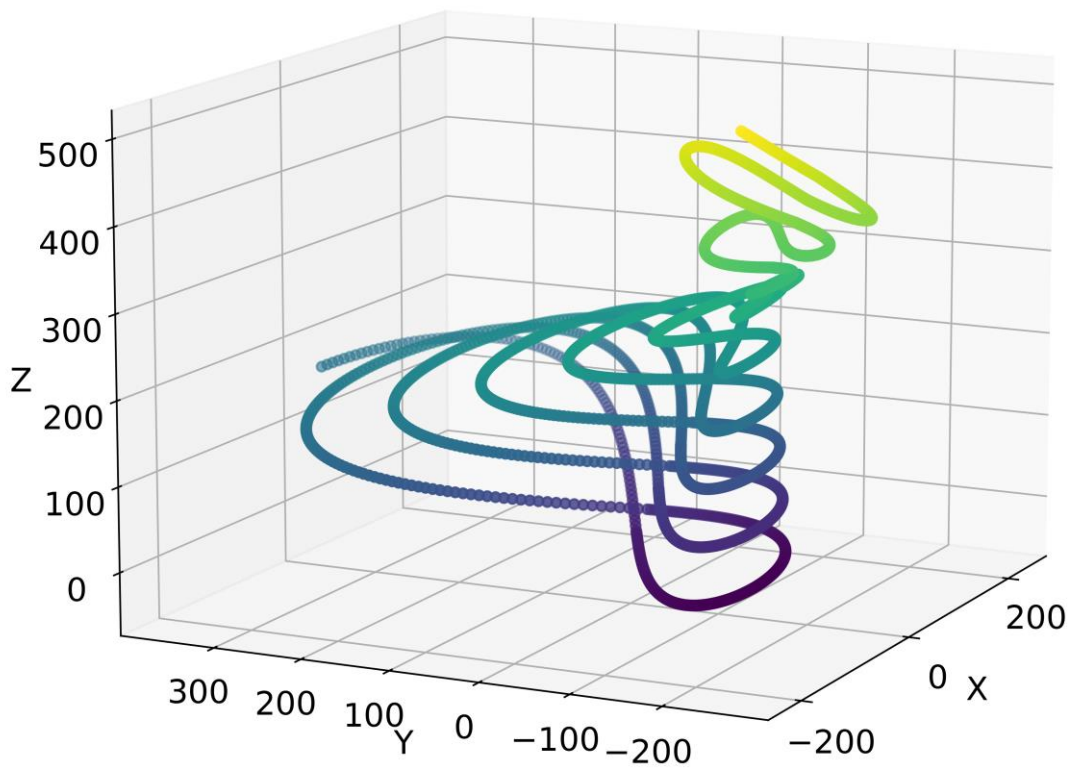



Z
Y

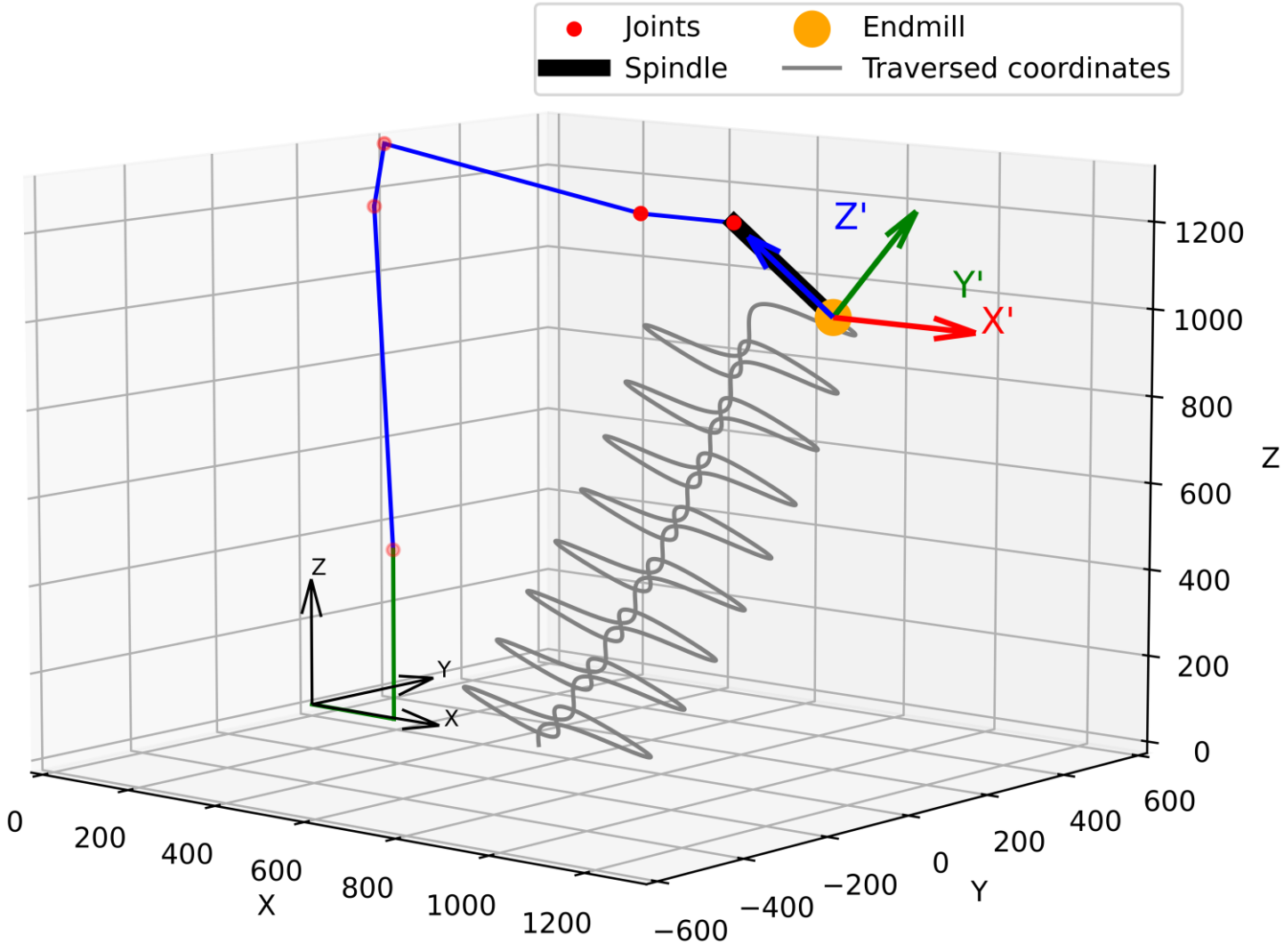

Global score
Best global score
Best boundary condition
Corresponding global scores
Global score = 75.6, Optimal rotation = -125°
Global Score [-]
Rotation around Z in degrees [°]
100
80
60
40
20
0
−135
−120
−105
−90
−75
−60
−45
−30
−15
0
15
30
45
60
75
90
105
120
135

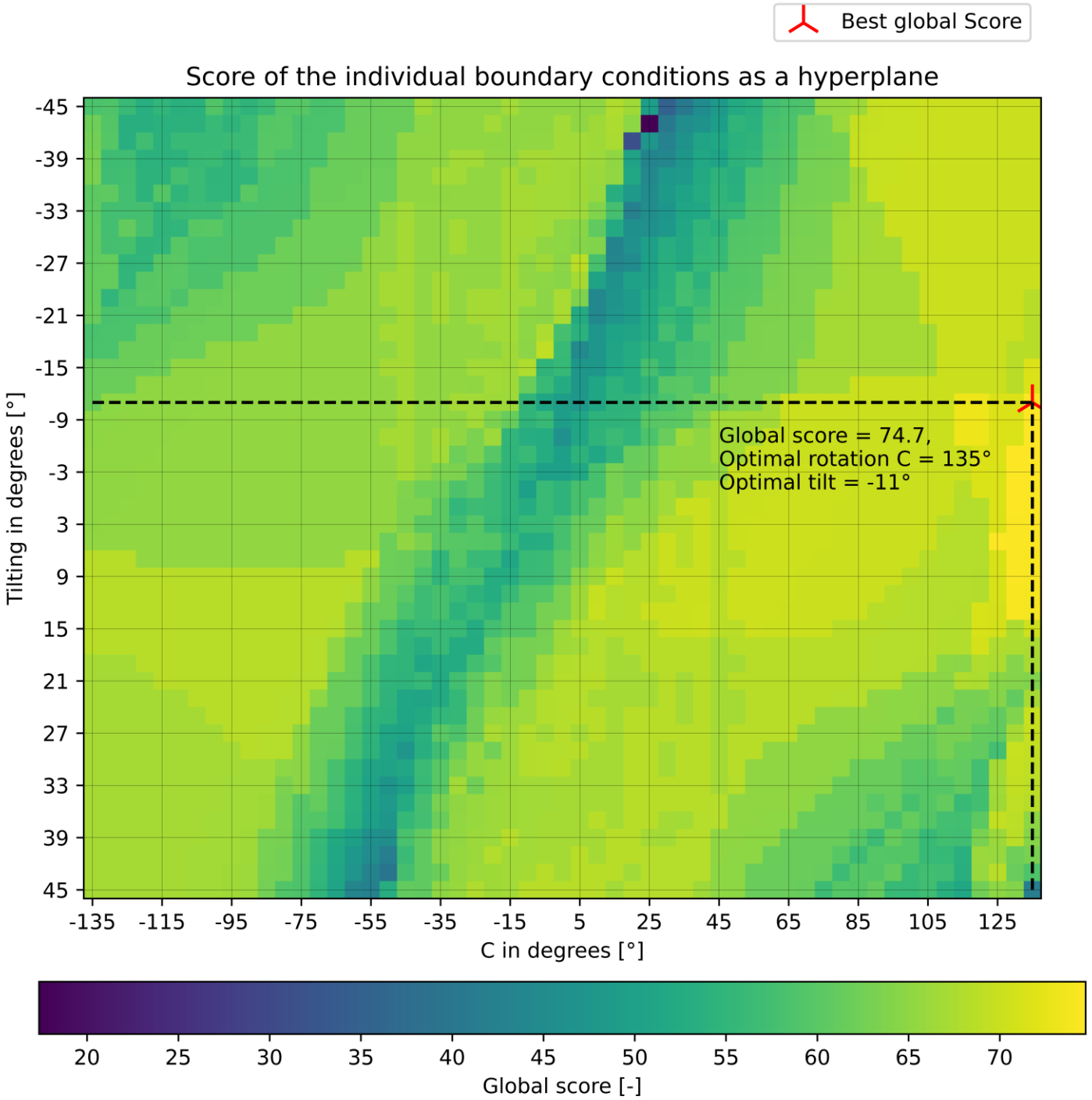
Rotation toolpath 2

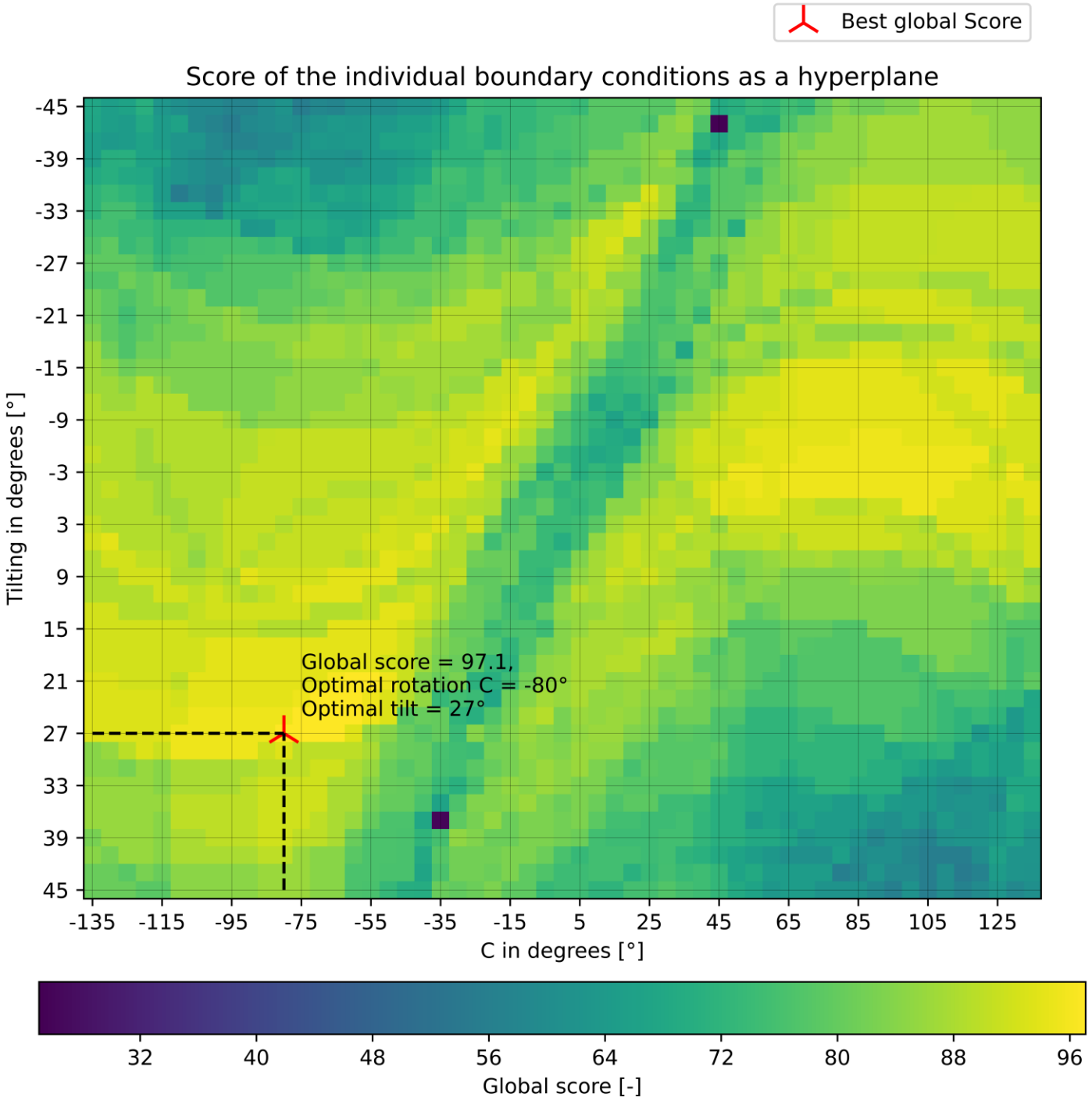


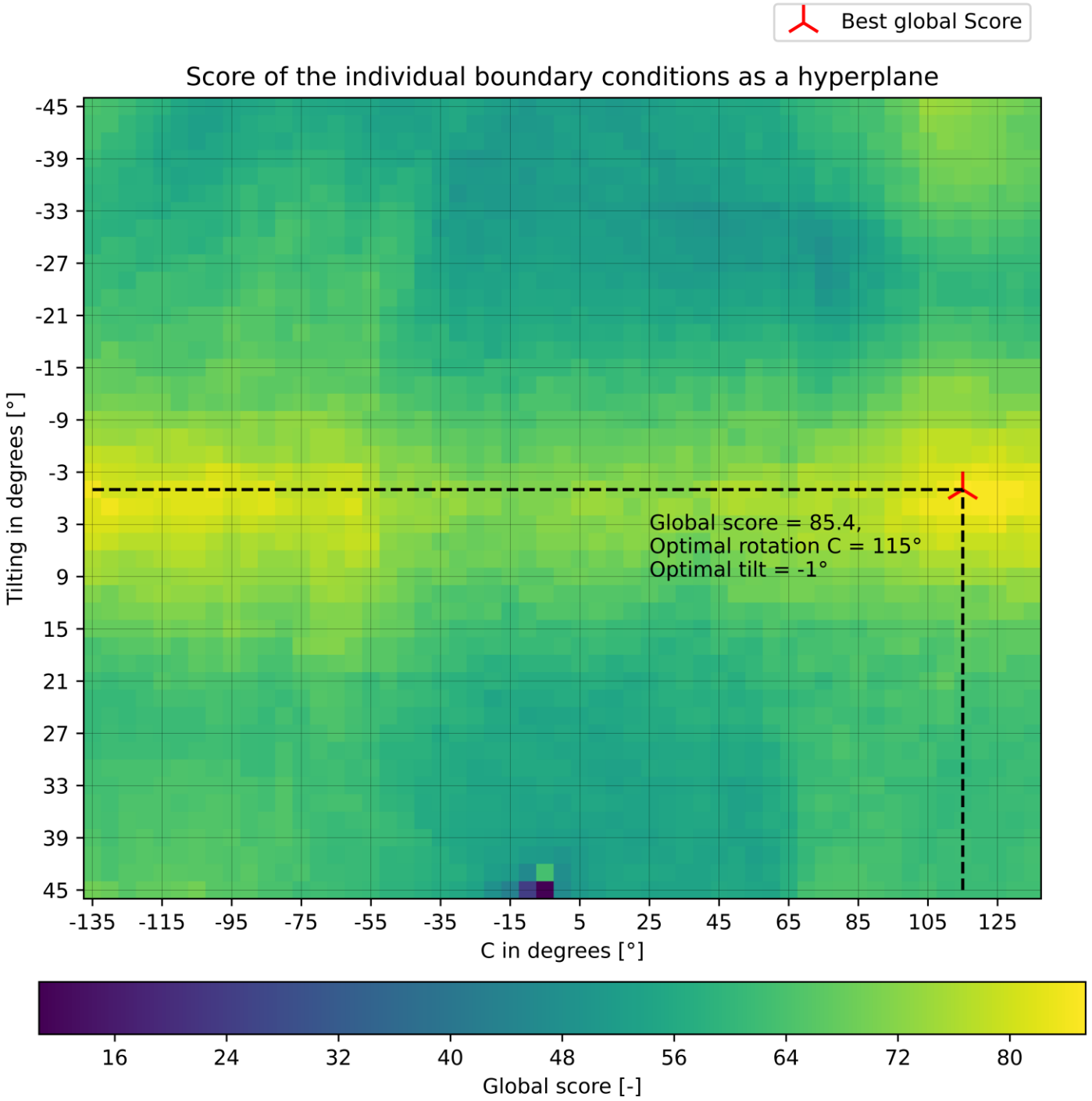


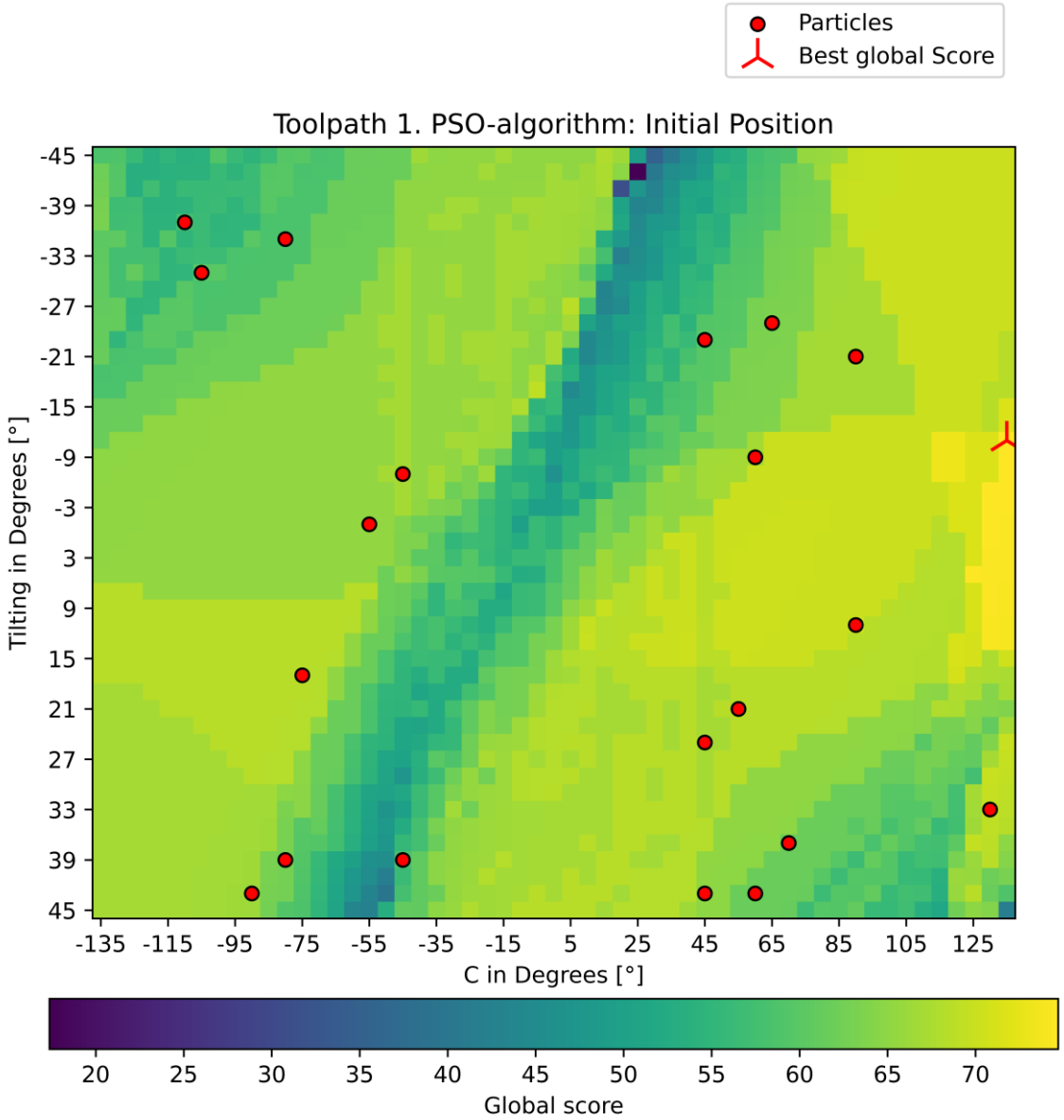
Toolpath 3

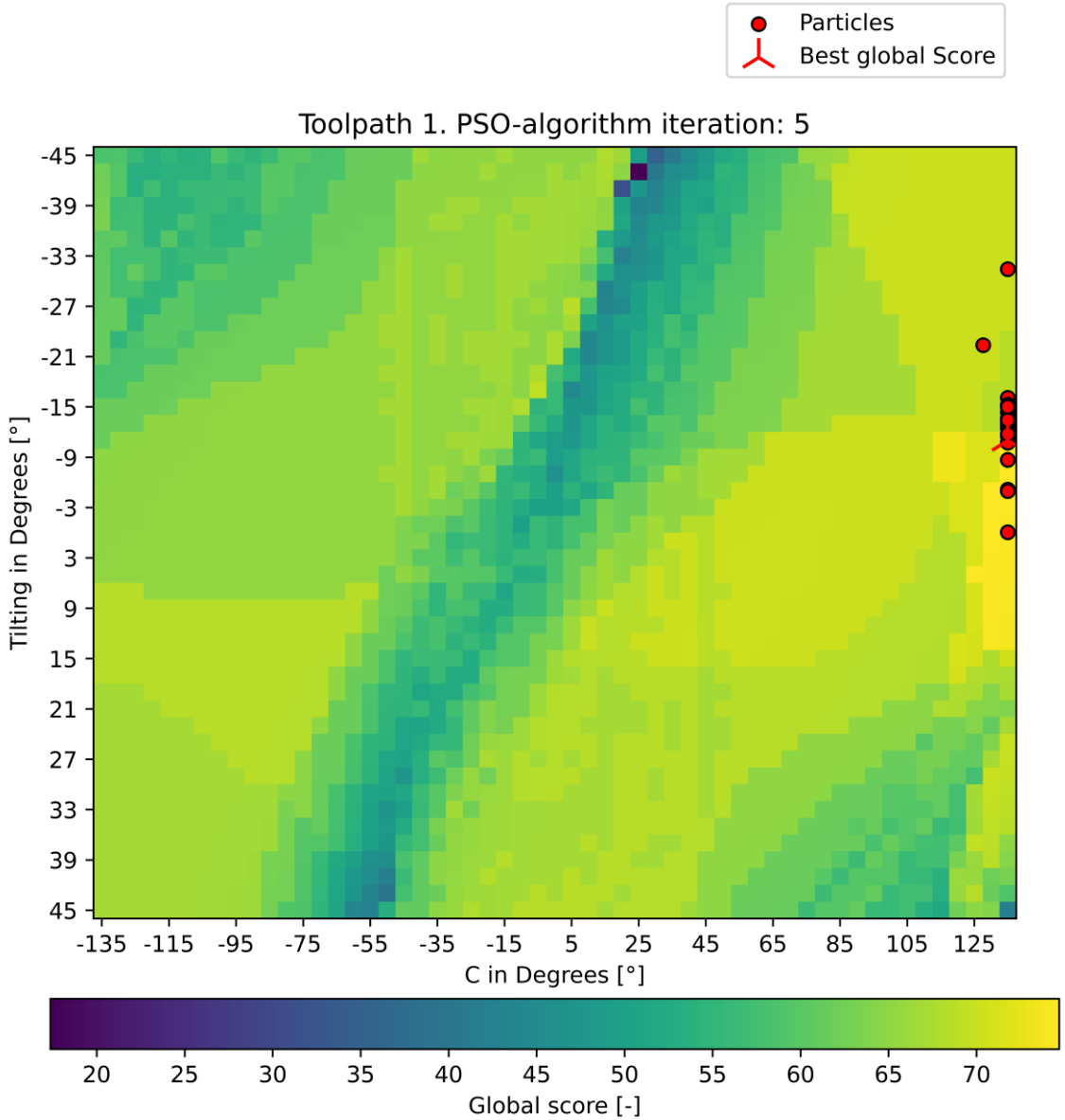

Joints
Endmill
Spindle
Traversed coordinates
Z'
Y'
X'
Z
Y
X
0
200
400
600
800
1000
1200
X
−600
−400
−200
0
200
400
600
Y
0
200
400
600
800
1000
1200
Z

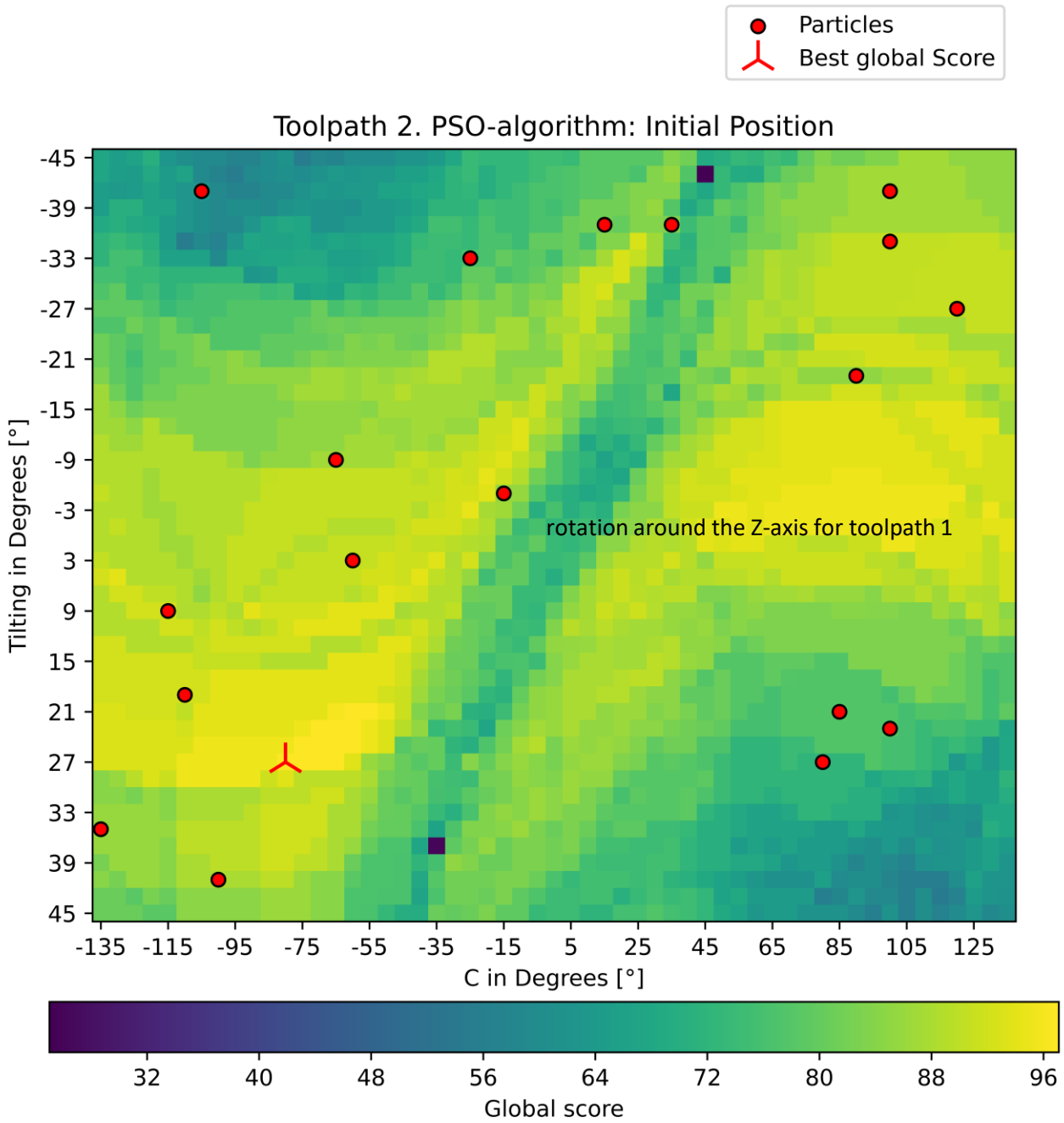

Best global Score
Score of the individual boundary conditions as a hyperplane
Tilting in degrees [°]
-45
-39
-33
-27
-21
-15
-9
-3
3
9
15
21
27
33
39
45
Global score = 74.7,
Optimal rotation C = 135°
Optimal tilt = -11°
-135
-115
-95
-75
-55
-35
-15
5
25
45
65
85
105
125
C in degrees [°]
20
25
30
35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

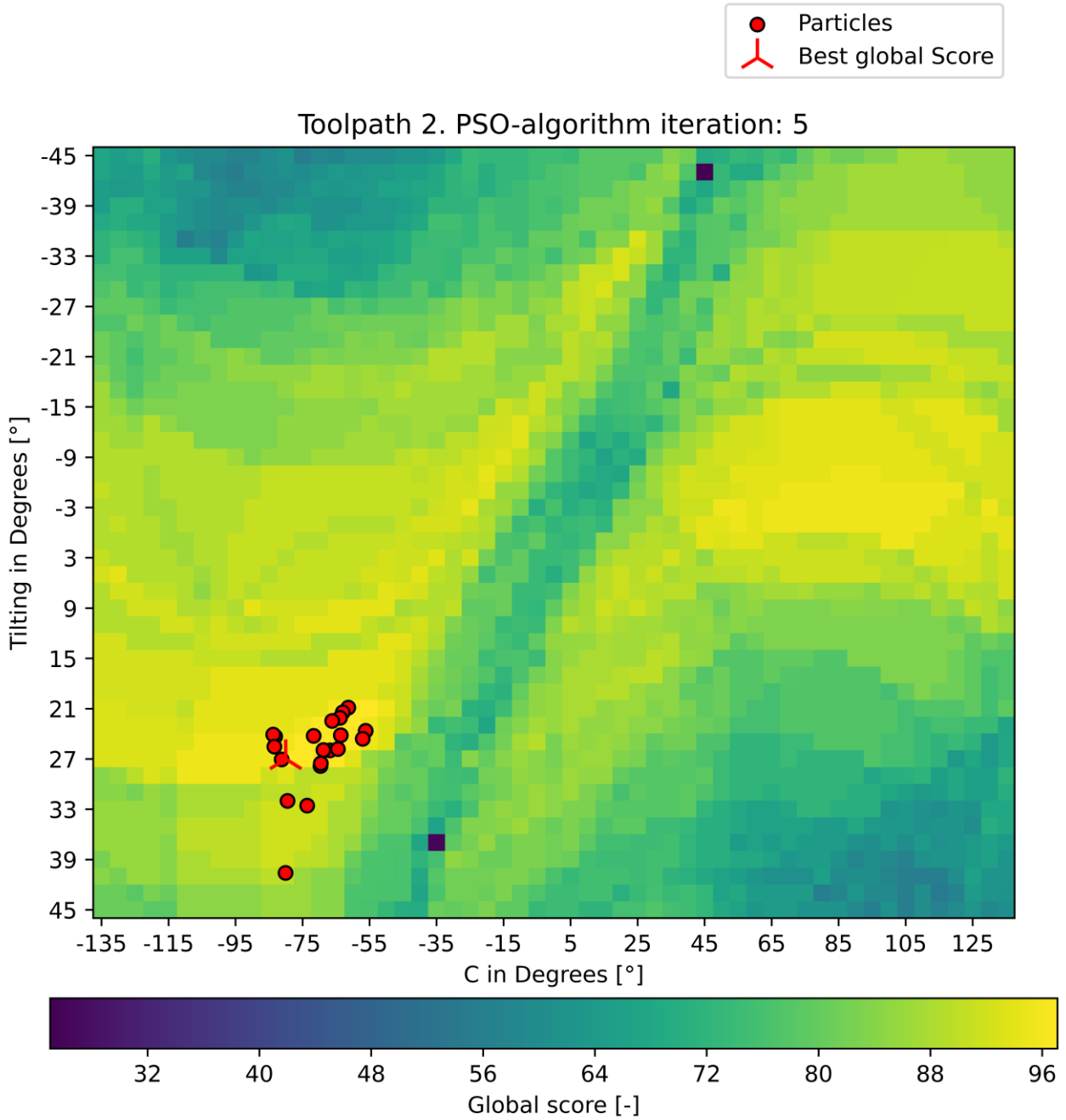

Best global Score
Score of the individual boundary conditions as a hyperplane
Tilting in degrees [°]
-45
-39
-33
-27
-21
-15
-9
-3
3
9
15
21
27
33
39
45
Global score = 97.1,
Optimal rotation C = -80°
Optimal tilt = 27°
-135
-115
-95
-75
-55
-35
-15
5
25
45
65
85
105
125
C in degrees [°]
32
40
48
56
64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

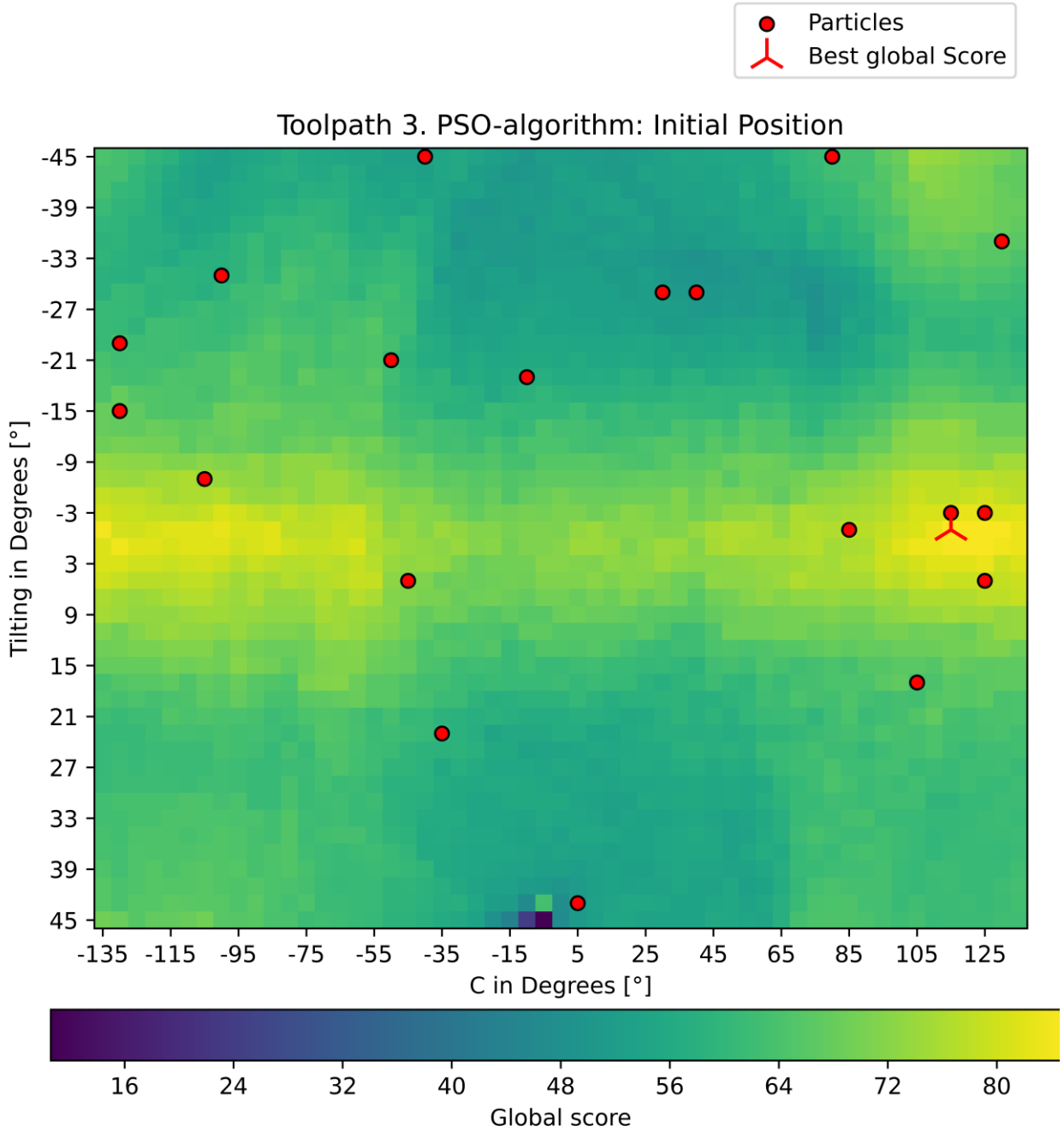

Best global Score
Score of the individual boundary conditions as a hyperplane
Tilting in degrees [°]
-45
-39
-33
-27
-21
-15
-9
-3
3
9
15
21
27
33
39
45
Global score = 85.4,
Optimal rotation C = 115°
Optimal tilt = -1°
-135
-115
-95
-75
-55
-35
-15
5
25
45
65
85
105
125
C in degrees [°]
16
24
32
40
48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

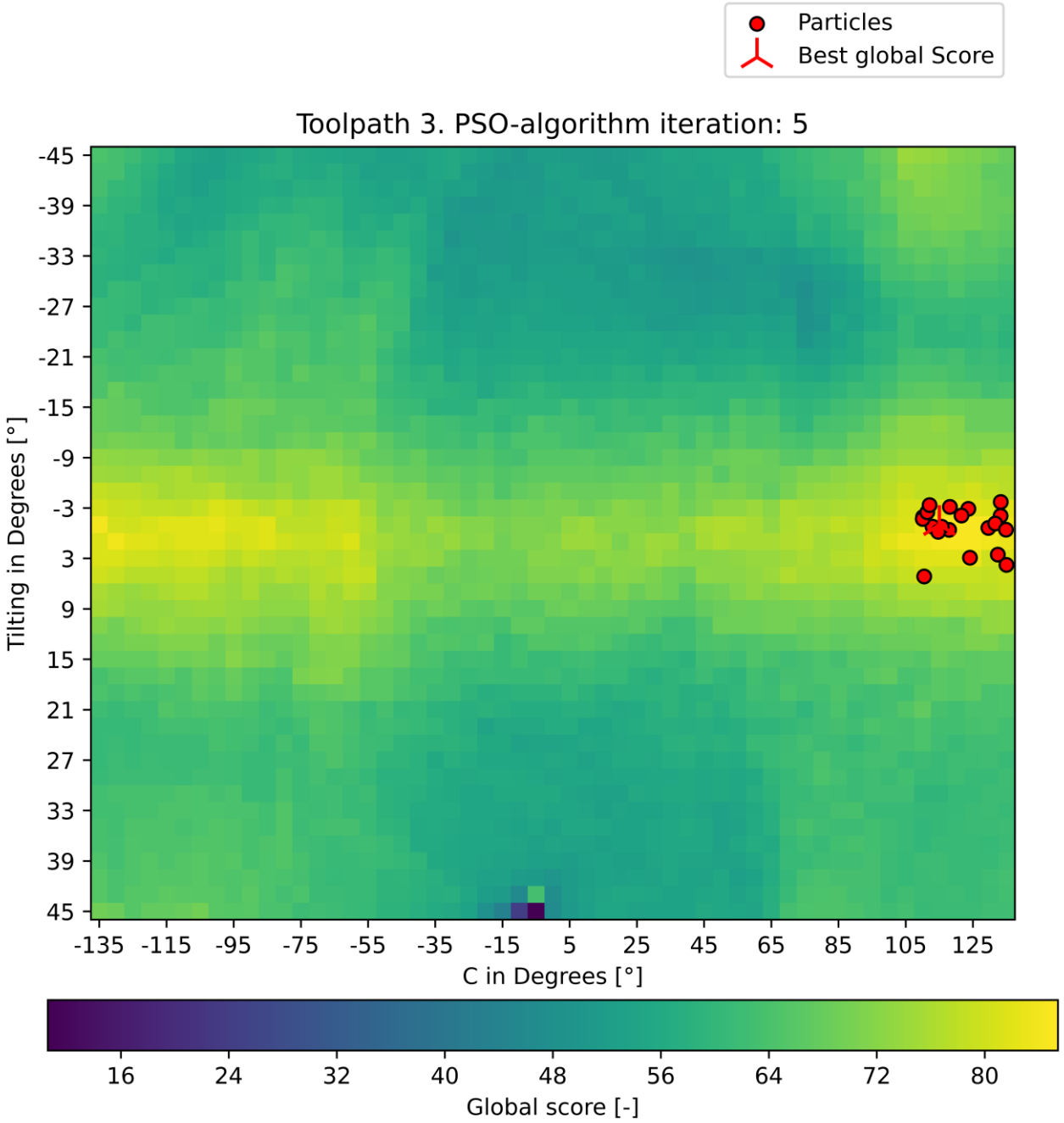

Particles
Best global Score
Toolpath 1. PSO-algorithm: Initial Position
Tilting in Degrees [°]
-45 -39 -33 -27 -21 -15 -9 -3 3 9 15 21 27 33 39 45
-135 -115 -95 -75 -55 -35 -15 5 25 45 65 85 105 125
C in Degrees [°]
20 25 30 35 40 45 50 55 60 65 70
Global score


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