Optimal Path-Following Control for Redundant Manipulators: A Multi-Objective Optimization Approach

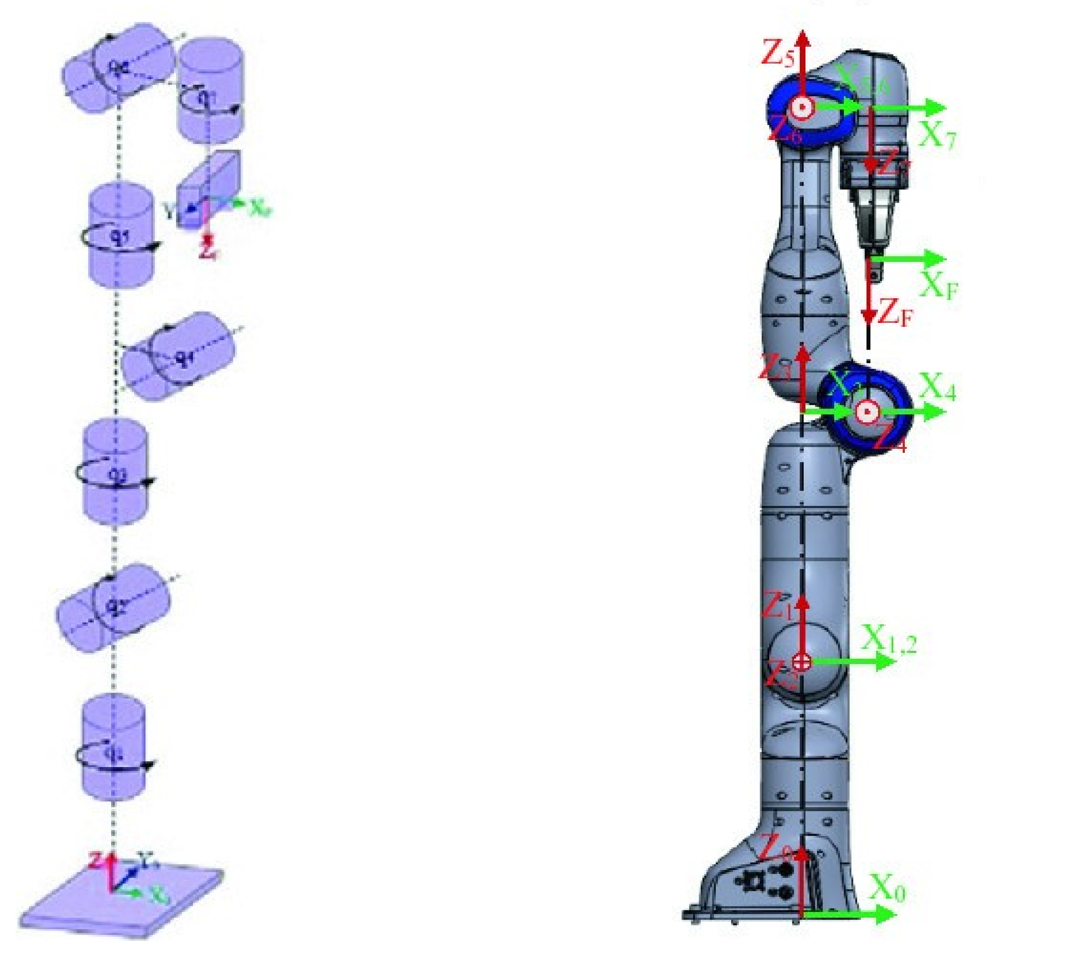
Ali DEEB[*,a], Ammar AAKEL[b], Vladimir KHOKHLOVSKIY[a] and Viacheslav SHKODYREV[a]

[a] Higher School of Cyberphysical Systems and Control, Institute of Computer Science and Cybersecurity, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation
[b] ITMO University, Saint Petersburg, Russian Federation
[*] Corresponding author's email: dib_a@spbstu.ru

Introduction

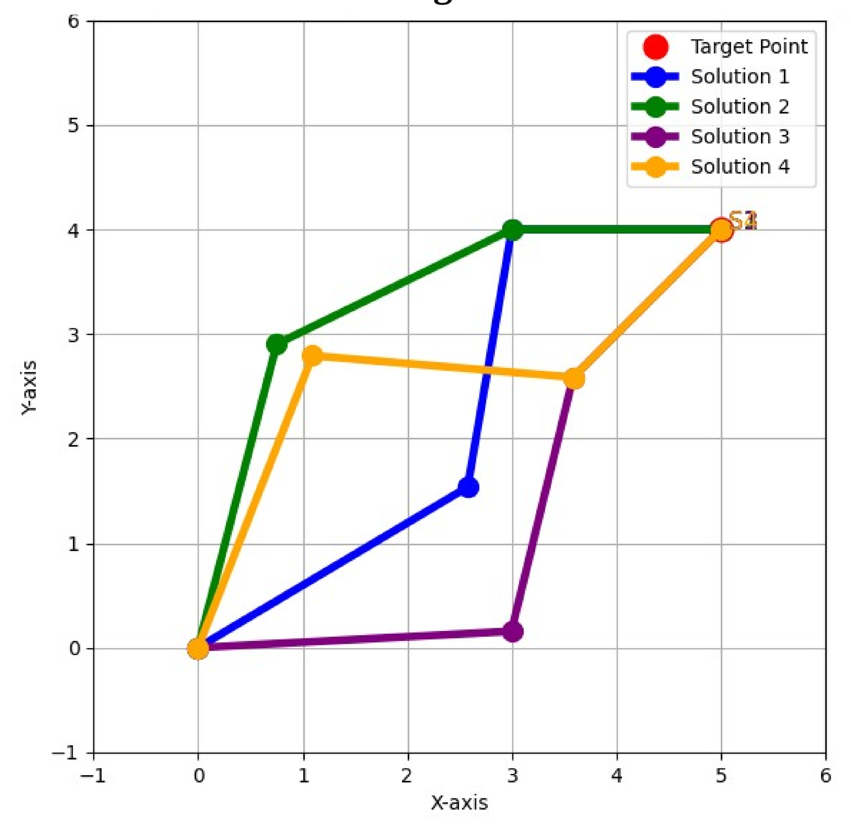
Robotic manipulators stand out as a confluence of mechanical, electrical, and computer engineering disciplines.

Figure 1: A redundant manipulator with 3D kinematic chain



The task of motion planning becomes quite complex due to the additional degrees of freedom.

Figure 2: Redundant Manipulator Reaching the Same Point with Different Joint Configurations



Research objectives

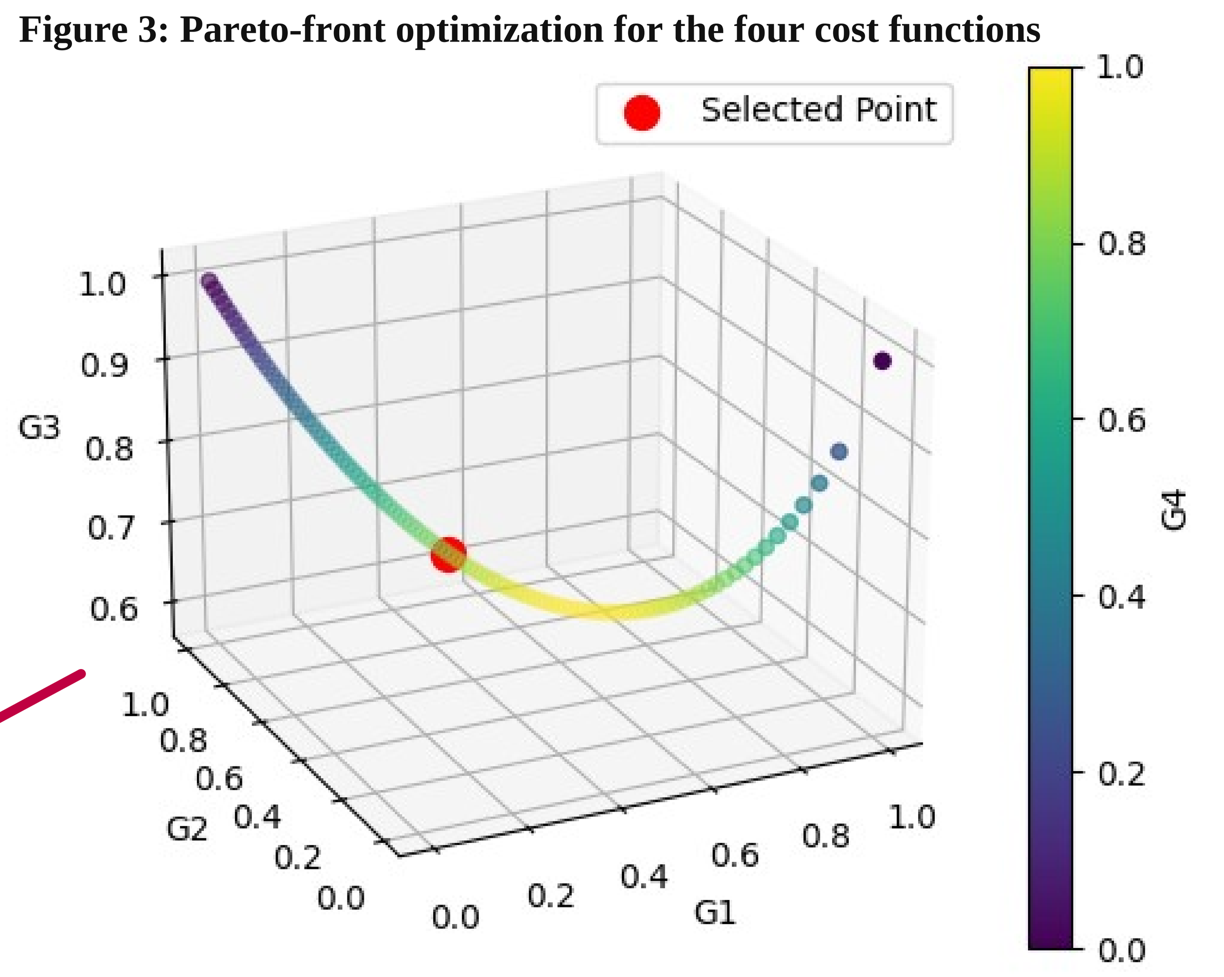
- For a given path, the inverse kinematics are solved as a Multi-Objective Optimization problem considering the end-effector position and angle and overall movement cost and speed.
- The optimization is solved with Genetic Algorithmic search, followed by Gradient-Descent refinement.

Methods

Genetic Algorithm: is used to find the optimal future horizon paran Calculations considers a future horizon of N points objectively mini the four cost functions:

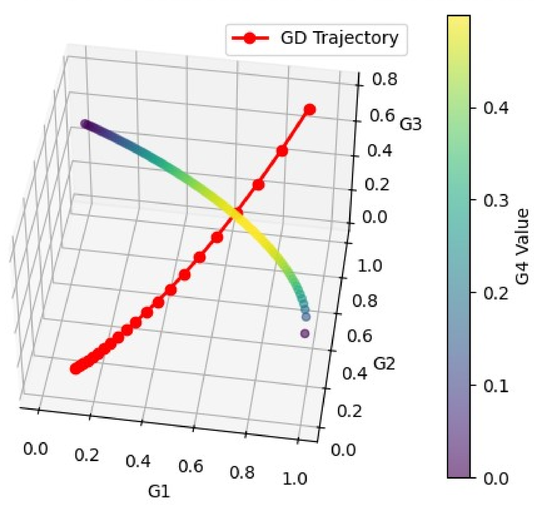
1. The Euclidean error component.
2. The control effort component.
3. A time minimization component.
4. End-effector vertical-alignment component.

Figure 3: Pareto-front optimization for the four cost functions



Gradient-Descent is used afterwards, to assure a proper minimization of G1.

Figure 4: GD refinement for Euclidean error



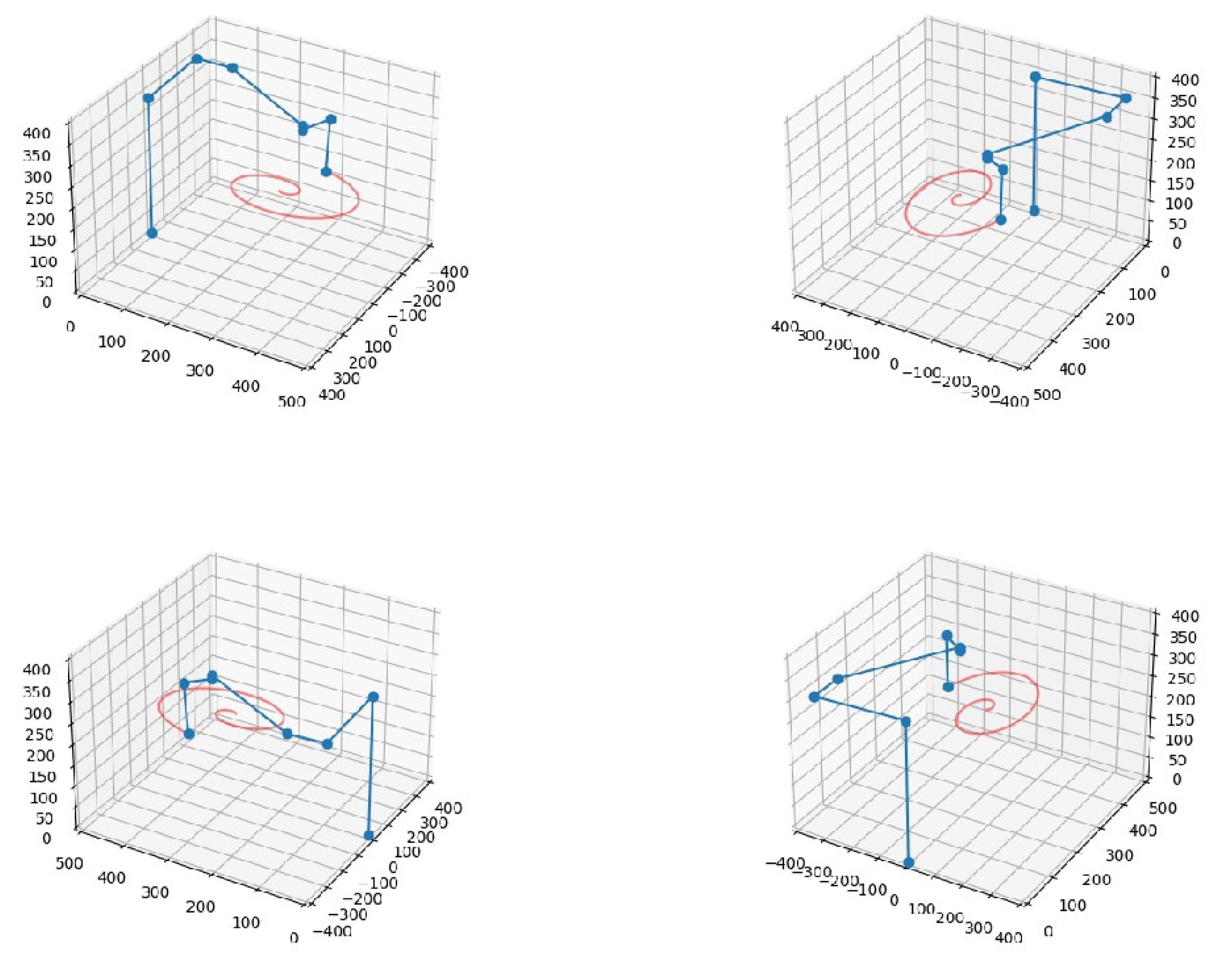
Simulation

A simulation of Franka-Emika robot was built to build results upon.

Table 1. D-H Parameters

i	a_i (mm)	θ_i	α_i	d_i (mm)
1	0	θ_1	0	333
2	0	θ_2	$-\pi/2$	0
3	0	θ_3	$\pi/2$	316
4	82.5	θ_4	$\pi/2$	0
5	-82.5	θ_5	$-\pi/2$	384
6	0	θ_6	$\pi/2$	0
7	88	θ_7	$\pi/2$	0
8	0	θ_8	0	107

Figure 5: The simulation built of Franka-Emika manipulator



Results

The numerical results show minimization of the cost functions overall the trajectory. Here we show the results for an Archimedean spiral

Figure 7: Desired vs resulted path points

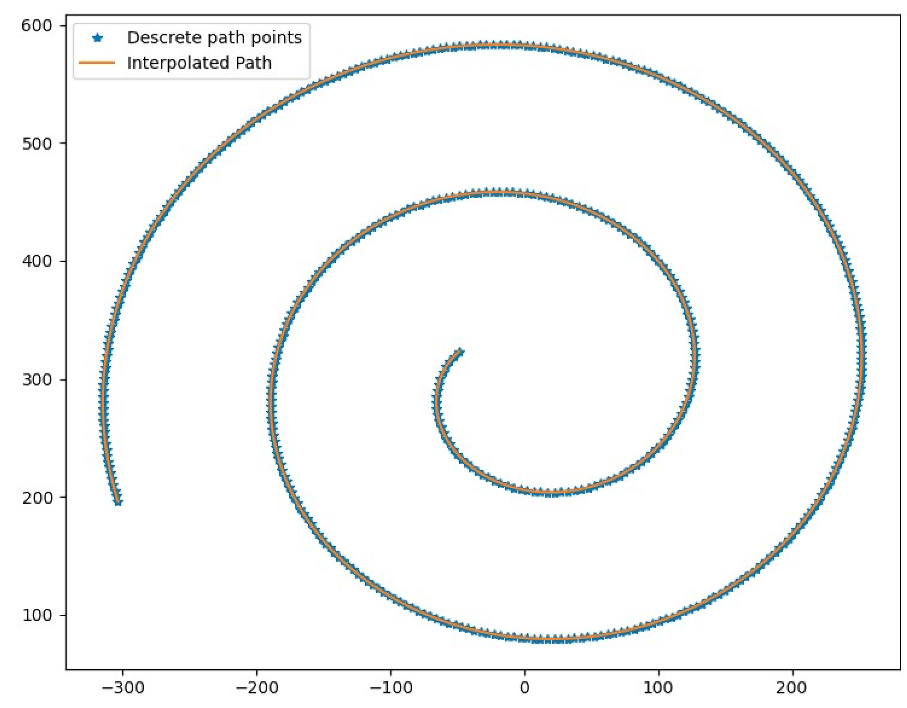
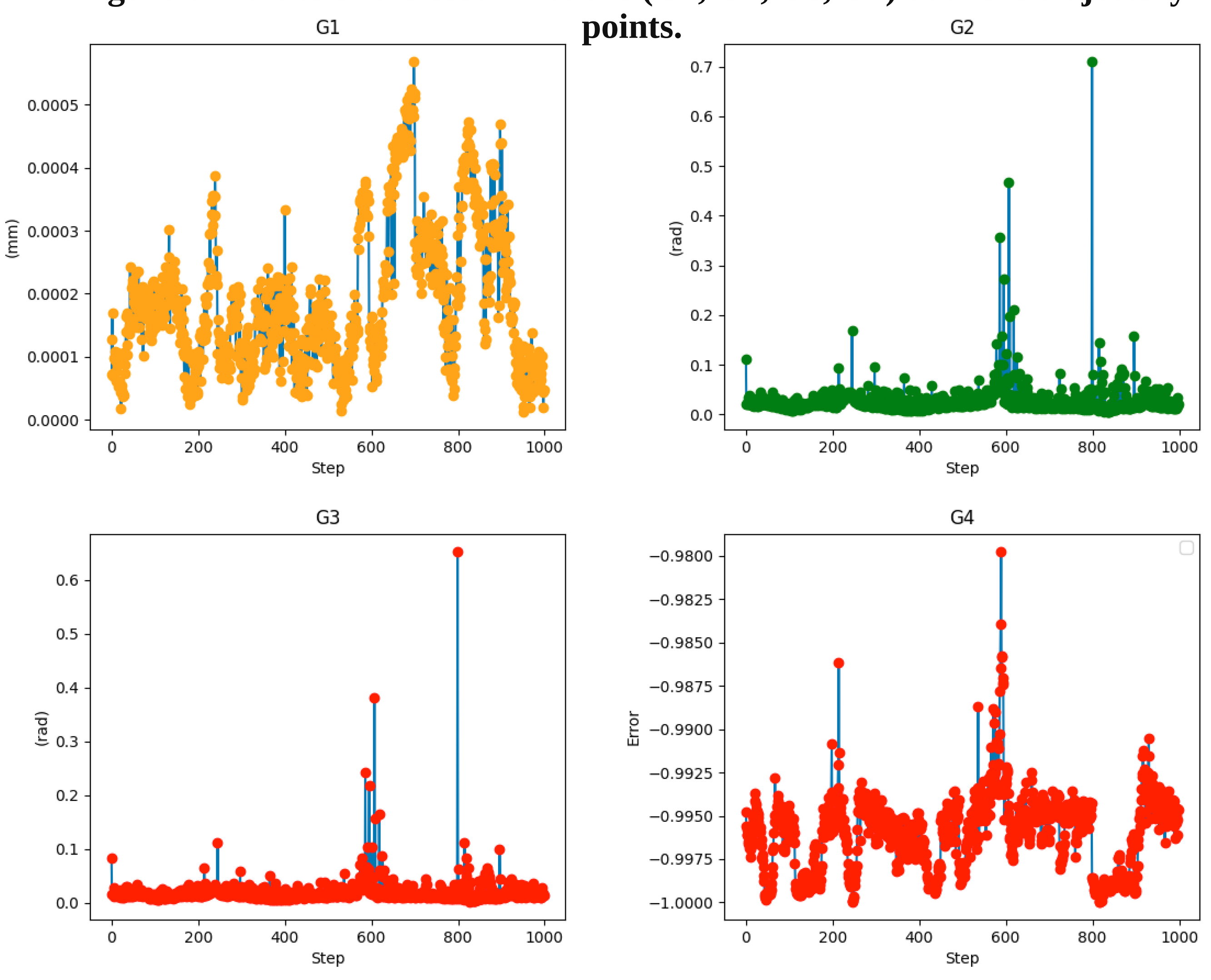


Figure 6: Values of the cost functions (G1, G2, G3, G4) over the trajectory points.



Conclusions

- This study successfully developed and validated an innovative optimal control framework for redundant robotic manipulators
- By formulating the trajectory planning as a MOO problem, the research provides a balance of the cost functions.
- The results pave the way for advanced control strategies in robotic systems where redundancy and precision are critical.

Acknowledgement

The work is sponsored by the Russian Science Foundation, Grant 23-29-0051 of Jan.13, 2023.