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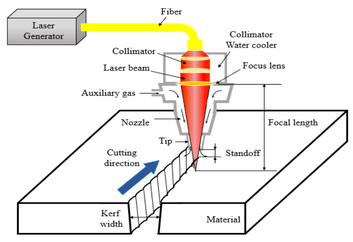
37th Cycle

Analysis, planning and control of complex redundant manipulators

Zhipeng Ding
Supervisor: Prof. Marina Indri, Prof. Alessandro Rizzo

Research context and motivation

- In the field of robotics, the concept of redundancy refers to providing a robot with more degrees of freedom(DOF) than are strictly necessary for completing a given task. This approach, often employed in the design of redundant robots, offers several advantages and is a subject of keen interest, including robot manipulation in complex and constrained environment more effectively and enhanced dexterous performance and precision. However, managing the additional DOF in an advanced way necessitates sophisticated control algorithms and strategies.

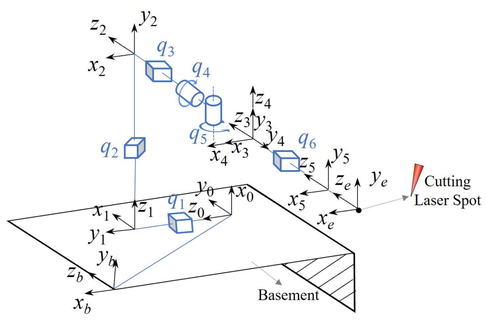


- An innovative redundant manipulator structure in 3D laser cutting of car-bodies is the core of a joint research project between Politecnico di Torino and EFORT.. This robotic system's distinguishing feature is the additional DOF that allows for movement along the tool direction at its end-effector. Our research is driven by the imperative to enhance the 3D laser cutting of high-strength steel, a critical process in the automotive parts manufacturing. The primary focus is on developing and implementing optimized algorithms designed for the redundant kinematic structure of the manipulator. This optimization aims to strike a delicate balance between high precision and accelerated processing speeds, ultimately improving both the quality of the products and the efficiency of production.

Addressed research questions/problems

- **Problem 1**: ***Inverse Kinematics for Redundant Manipulator and Singularity Robustness***

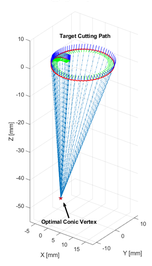
We tackle the task of establishing a kinematic model of redundant robots using the Denavit-Hartenberg (DH) method. To overcome the challenge of redundancy, we propose a novel approach that involves the decoupling of the kinematic chain into two distinct components: the Cartesian robot chain and the polar robot chain. This decomposition simplifies the inverse kinematic problem by breaking it down into 2 manageable sub-problems: finding the optimal wrist center position and resolve the rotatory axes considering the singularity avoidance.

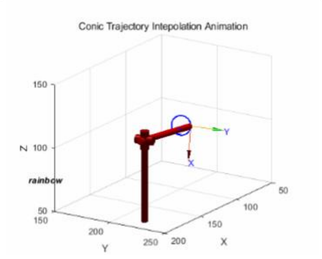


- **Problem 2**: ***Closed Through Holes Cutting Posture Optimization Modelling and Application***

In our research, we delve into the challenge of optimizing the cutting posture for closed through-hole operations in manufacturing. Achieving the ideal posture provides significant benefits for manufacturing dynamics, particularly in High Speed Machining (HSM) scenarios. The optimization model we developed incorporates the position of the cone vertex in $\mathbb{R}^3$ as the design variable, as it has a significant impact on the overall geometric shape of the cone. The joint variables $\boldsymbol{q}_i$ can be derived from the linearization of the trajectory in the task space. Additionally, evaluating the dynamics in the joint spaces allows for achieving a smoother state.

The first objective is to evaluate and mitigate angular deviations that occur along the cutting path of closed through holes. However, this limitation arises from the fact that a mere increase in the spatial separation between the vertex and the cutting plane could lead to reduced taper errors, driven by the inherent geometric characteristics of the cone. The second objective we introduced in the optimization model is the sum of weighted squared acceleration, which captures the magnitudes of the energy provided by the system and combining with the weight vector.





$$\min_{\mathbf{x}\in\mathbb{R}^3} \quad \mathbf{F}(\mathbf{x}) = \begin{cases} \frac{1}{N}\sum_{k=1}^{N} \arccos(\hat{\mathbf{v}}_n \cdot \hat{\mathbf{v}}_{k,z}) \\ \frac{1}{2}\mathbf{Q}^T\mathbf{U}\mathbf{Q} \end{cases}$$

$$\textbf{Subject to}$$

$$\mathbf{lb} \le \mathbf{x} \le \mathbf{ub}$$
$$0 \le \alpha_k \le \boldsymbol{\alpha}_{\max} \qquad \forall k \in 1,\dots,N$$
$$\mathbf{q}_{i,\min} \le q_{i,k} \le \mathbf{q}_{i,\max} \qquad \forall i \in 1,\dots,6$$
$$\mathbf{v}_{i,\min} \le \dot{q}_{i,k} \le \mathbf{v}_{i,\max}$$
$$\mathbf{a}_{i,\min} \le \ddot{q}_{i,k} \le \mathbf{a}_{i,\max}$$

- **Problem 3**: ***Advanced Trajectory Smoothness by Using Dual-quaternions Form***

$\mathrm{Q_r}$ and $\mathrm{Q_d}$ are quaternions corresponding to rotation and translation.

$$\widehat{\mathrm{Q}} = \mathrm{Q_r} + \epsilon \mathrm{Q_d}$$

Where,

$$\mathrm{Q}_r = [\cos\left(\frac{\theta}{2}\right), \mathrm{n}_x \sin\left(\frac{\theta}{2}\right), \mathrm{n}_y \sin\left(\frac{\theta}{2}\right), \mathrm{n}_z \sin\left(\frac{\theta}{2}\right)][0,0,0,0]$$

$$\mathrm{Q_d} = \frac{1}{2}\mathrm{D}\mathrm{Q_r} = [1,0,0,0][0, \frac{d_x}{2}, \frac{d_y}{2}, \frac{d_z}{2}]$$

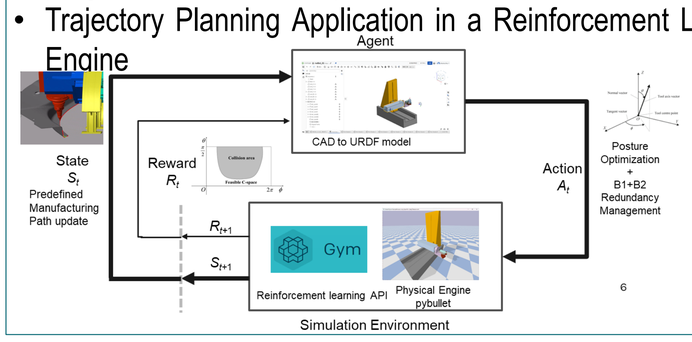
The spatial displacements $\acute{\mathrm{p}}$ of the point p will be given by:

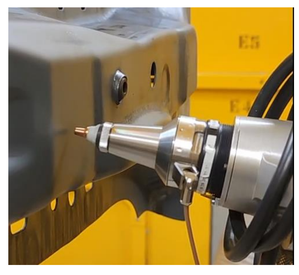
$$\hat{\mathrm{p}} = \overline{\widehat{\mathrm{Q}}}\hat{\mathrm{p}}\widehat{\mathrm{Q}}^*$$

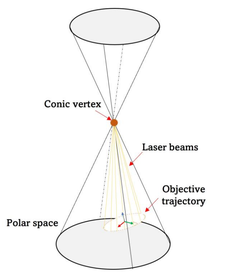
Dual-quaternions are interesting and important because they reduce the complexity of algebra. In fact, dual-quaternions give us a compact, unambiguous, singularity-free, and computationally minimalist rigid transform. The four alternative methods we mathematically and computationally compare to dual quaternions are Rotation Matrices, Axis-Angles, Euler-Angles, and Quaternions PLUS Translation. Each alternative method is used to represent both the orientation and translation

Novel contributions

- An Innovative Conic Posture Cutting Strategy with Inclined Angles
- A time minimization approach aimed at achieving the highest speed while adhering to the specified constraints. Post-processing of the workpiece manufacturing to export the correspond G-code program based on the optimization result.
- Trajectory Planning Application in a Reinforcement Learning Environment with a Robotics Physics Engine

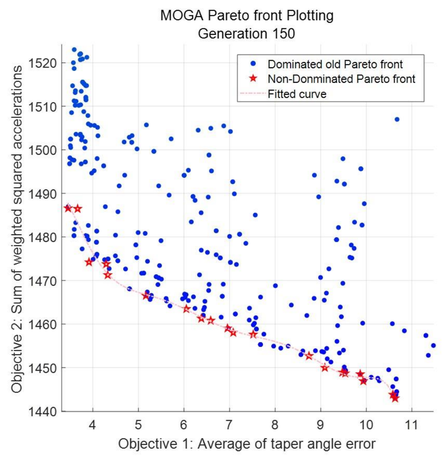






Adopted methodologies

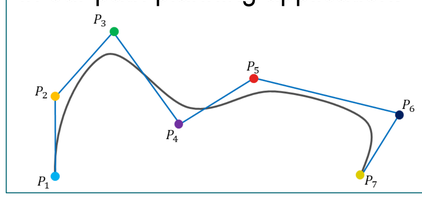
- ***Multi-Objective Genetic Algorithm***

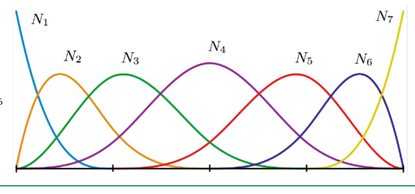


We employed an elitist genetic algorithm to address the conic posture optimization problem. During the evolution process, lower rank individuals are preferable to be selected as the parents considering crowding distance. The newly created population is again passed through the mechanism of genetic operators to generate another new offspring population. The Pareto Front is generated to obtain the set of optimal solutions

- ***Non-Uniform Rational B-Spline***

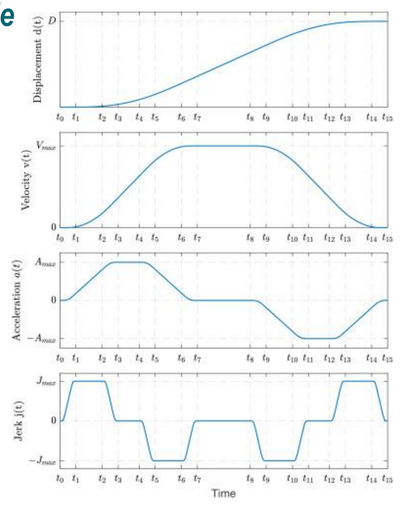
NURBS technique is adopted when require dealing with geometric elements for trajectory generation and smoothing in our path planning application.





S-shaped Ramped Profile

The S-shaped ramped profile method is adopted to outcome the C^2 continuity and smoothness at the level of acceleration of the parameterized curves.



Future work

- ***Advanced Dual NURBS Interpolator with the collision avoidance and orientation optimization***

Computer Numerical Control (CNC) machining has become an essential method for efficiently machining complex surface parts. It enhances tool accessibility and prevents interference between the tool and the workpiece by adjusting the cutter orientation. The advanced Dual NURBS interpolator algorithm synchronizes two parametric curves to achieve greater precision and smoothness.

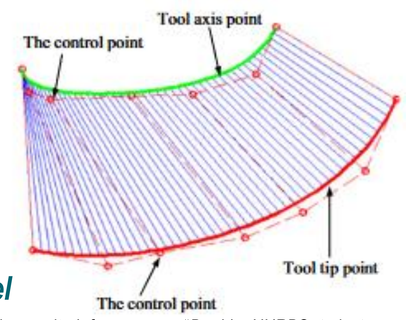


Figure cited from paper "*Double NURBS trajectory generation and synchronous interpolation for five-axis machining based on dual quaternion algorithm.*"

- ***Redundancy management of dual-arc-motor in dynamic model***

the objective manipulator possesses a well-optimized mechanical structure, wherein the arc-motor functions as a rotary axis.

The dynamic modeling of the head assumes great importance in servo torque control, employing a feedforward control strategy. This dynamic modeling allows for the pre-calculation of interactive torque, external nonlinear force, and centrifugal force originating from the system, thereby enabling superior control capabilities.

Publications

- Submitted works: 1 journal
- Through holes-cutting conic posture optimization based on multi-objective genetic algorithm for a redundant 3D laser cutting machine. *Journal of intelligent & robotic systems*

Politecnico di Torino
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PhD program in
Electrical, Electronics and Communications Engineering