Singularities: high joint velocities

Acknowledgements

Problem

Robot joint limits and singularities are constraints that cause the surgeon to re-grasp the needle in the middle of suturing using complex dual-arm hand-off movements [1]. This increases the surgeon’s cognitive workload and causes severe fatigue and degeneration in performance.

Proposed Solution

Haptic-guided system that helps the surgeon to grasp the needle in an optimal configuration, which allows avoiding constraints along post-grasp suturing trajectories.

System Description

Kinematics

Suturing requires the surgeon to grasp the needle through the robot and deliver it along a predefined suturing path.

Grasp Parametrization

The grasping manifold is parameterized by \( \alpha \) (angle around the needle tangent) and \( \theta \) (needle curvilinear abscissa) [2, 3].

Optimization

Mathematically, the problem writes as follows:

\[
\begin{align*}
\text{minimize} & \quad \mathcal{H}(q_\theta(z)) \\
\text{subject to} & \quad z^- \leq z \leq z^+ \\
& \quad \frac{\partial h}{\partial q_\theta}(z) - \lambda = 0
\end{align*}
\]

Newton-Raphson method is used to solve the optimization problem. At each step \( z \) is updated as \( z_{n+1} = z_n - \gamma \nabla_z \mathcal{H} \)

\[
\nabla_z \mathcal{H} = \int_0^s \frac{\partial h}{\partial q_\theta} \, ds,
\]

\[
\frac{\partial h}{\partial q_\theta} \rightarrow \text{analytical}
\]

Grasp Parametrization

The vector \( z = [n, \theta]^T \) identifies any point in the grasp subspace \( Z \subseteq \mathbb{R}^2 \). The differential mapping to the robot configuration space is

\[
q_\theta = J_\theta(q_\theta) R_n J_g(z) \hat{z}
\]

where \( J_\theta(z) \in \mathbb{R}^{6 \times 2} \) is the grasp Jacobian specific to the object shape and the choice of grasping parameters.

Results

The proposed method

- Guides the surgeon towards the optimal needle grasping configuration through haptic forces while leaving her/him in control of the surgical system;
- Allows following the desired suturing path, thus avoiding joint limits (path deviation) and singularities (high joint velocities).

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