Haptic-guided Needle Grasping in Minimally Invasive Robotic Surgery

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Problem

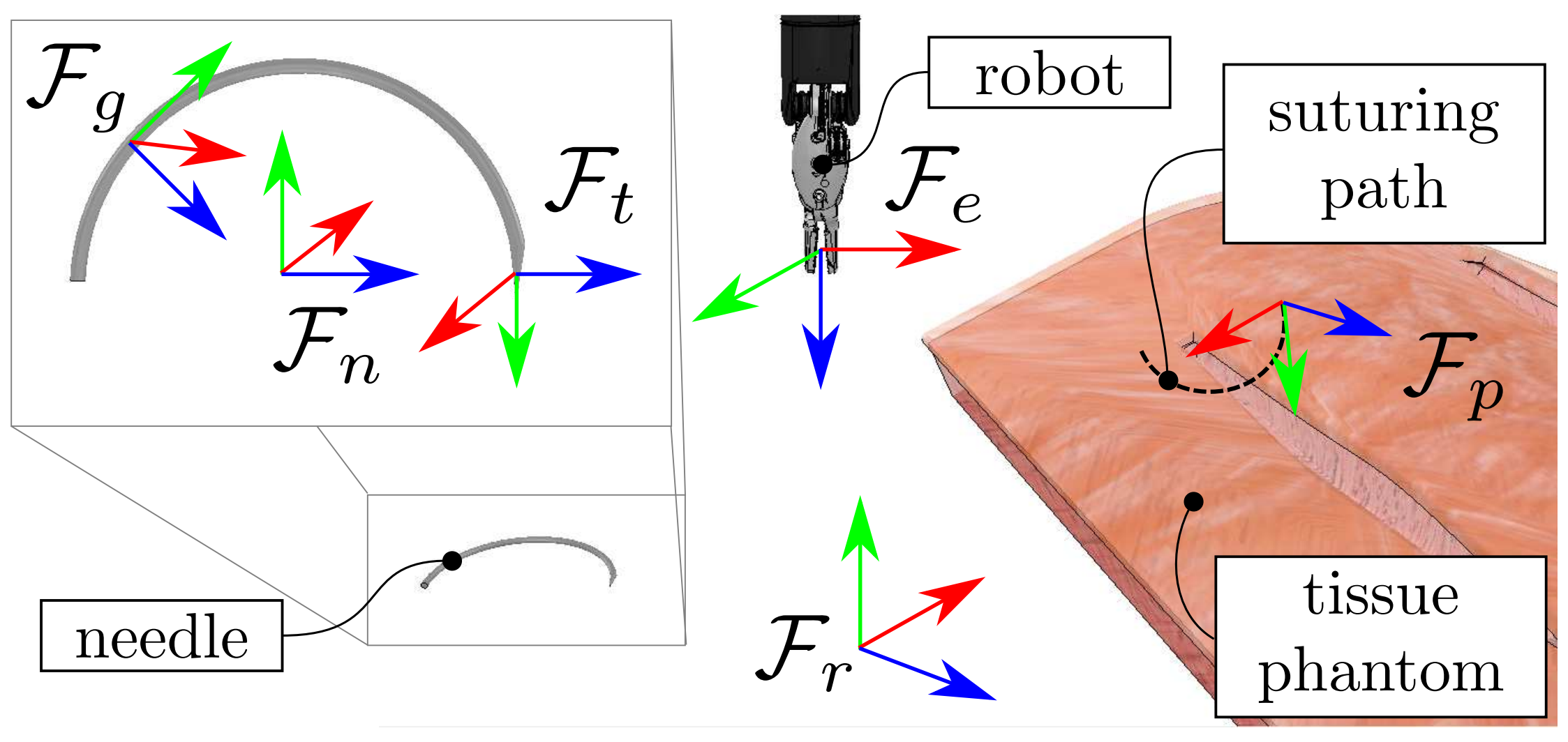
Robot **joint limits** and **singularities** are **constraints** that cause the surgeon to re-grasp the needle in the middle of suturing using complex dual-arm hand-off movements [1]. This increases the surgeon's **cognitive workload** and causes severe fatigue and degeneration in performance.

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



Constraints
Cost functions accounting for joint limits and singularities (Task-oriented Velocity manipulability)

$$h_j\left(\hat{\boldsymbol{q}}_g(t)\right)=\sum_{i=1}^{n}\frac{1}{\lambda}\frac{\left(\hat{q}_{g,i}^{+}-\hat{q}_{g,i}^{-}\right)^2}{\left(\hat{q}_{g,i}^{+}-\hat{q}_{g,i}(t)\right)\left(\hat{q}_{g,i}(t)-\hat{q}_{g,i}^{-}\right)}$$

$$h_s\left(\hat{\boldsymbol{q}}_g(t)\right)=\dot{\hat{x}}^T\left(\boldsymbol{J}_s(\hat{\boldsymbol{q}}_g(t))\boldsymbol{J}_s(\hat{\boldsymbol{q}}_g(t))^T\right)^{-1}\dot{\hat{x}}$$

The total cost function along the suturing trajectory is

$$\mathcal{H}(\boldsymbol{z})=\int_0^{s^\star}h\left(\hat{\boldsymbol{q}}_g(s,\boldsymbol{z})\right)\mathrm{d}s$$

$$h\left(\hat{\boldsymbol{q}}_g\right)=h_j\left(\hat{\boldsymbol{q}}_g\right)+h_s\left(\hat{\boldsymbol{q}}_g\right).$$

Acknowledgements

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References

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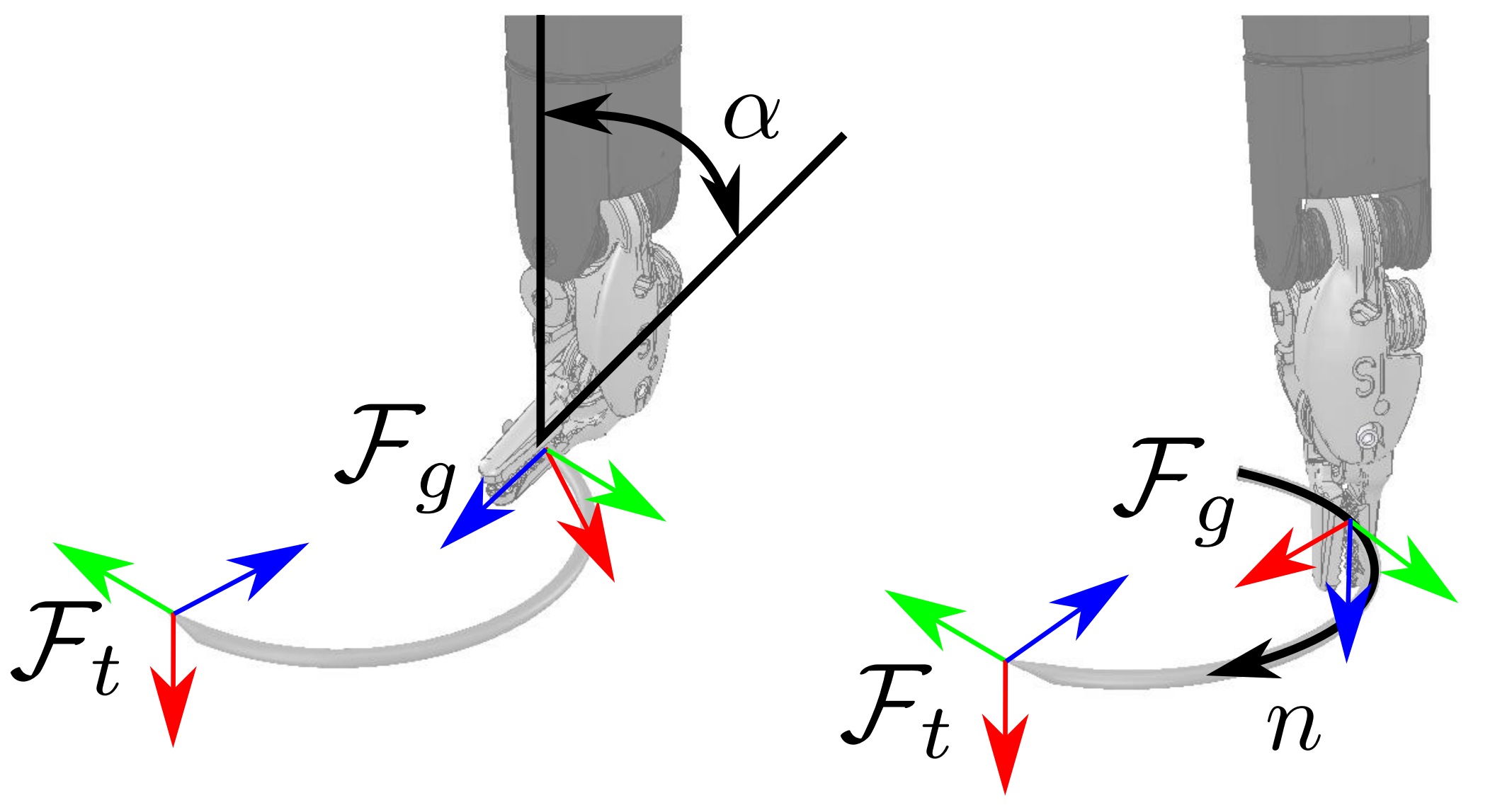
[3] T. Liu and M. C. Cavusoglu, "Needle grasp and entry port selection for automatic execution of suturing tasks in robotic minimally invasive surgery," *IEEE Transactions on Automation Science and Engineering*, vol. 13, no. 2, pp. 552–563, 2016.

Grasp Parametrization

The grasping manifold is parameterized by α (angle around the needle tangent) and n (needle curvilinear abscissa) [2, 3]



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

$$\dot{\boldsymbol{q}}_s=\boldsymbol{J}_s^{\dagger}(\boldsymbol{q}_s)^r\bar{\boldsymbol{R}}_n\boldsymbol{J}_g(\boldsymbol{z})\dot{\boldsymbol{z}}$$

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

Optimization

Mathematically, the problem writes as follows

$$\begin{aligned}&\underset{\boldsymbol{z}}{\text{minimize}} && \mathcal{H}\left(\hat{\boldsymbol{q}}_g(\boldsymbol{z})\right)\\ &\text{subject to} && \boldsymbol{z}^-\leq\boldsymbol{z}\leq\boldsymbol{z}^+\end{aligned}$$

Newton-Raphson method is used to solve the optimization problem. At each step $\boldsymbol{z}$ is updated as $\boldsymbol{z}_{n+1}=\boldsymbol{z}_n-\gamma\nabla_{\boldsymbol{z}}\mathcal{H}$ where

$$\nabla_{\boldsymbol{z}}\mathcal{H}=\frac{\partial\mathcal{H}}{\partial\boldsymbol{z}}=\int_0^{s^\star}\frac{\partial h}{\partial\boldsymbol{z}}\mathrm{d}s,\qquad\frac{\partial h}{\partial\boldsymbol{z}}=\frac{\partial h}{\partial\boldsymbol{q}_s}\frac{\partial\boldsymbol{q}_s}{\partial\boldsymbol{z}}$$

$$\frac{\partial h}{\partial\boldsymbol{q}_s}\rightarrow\text{analytical}$$

$$\frac{\partial\boldsymbol{q}_s}{\partial\boldsymbol{z}}=\boldsymbol{J}_s^{\dagger}(\boldsymbol{q}_s)^r\bar{\boldsymbol{R}}_n\boldsymbol{J}_g(\boldsymbol{z})$$

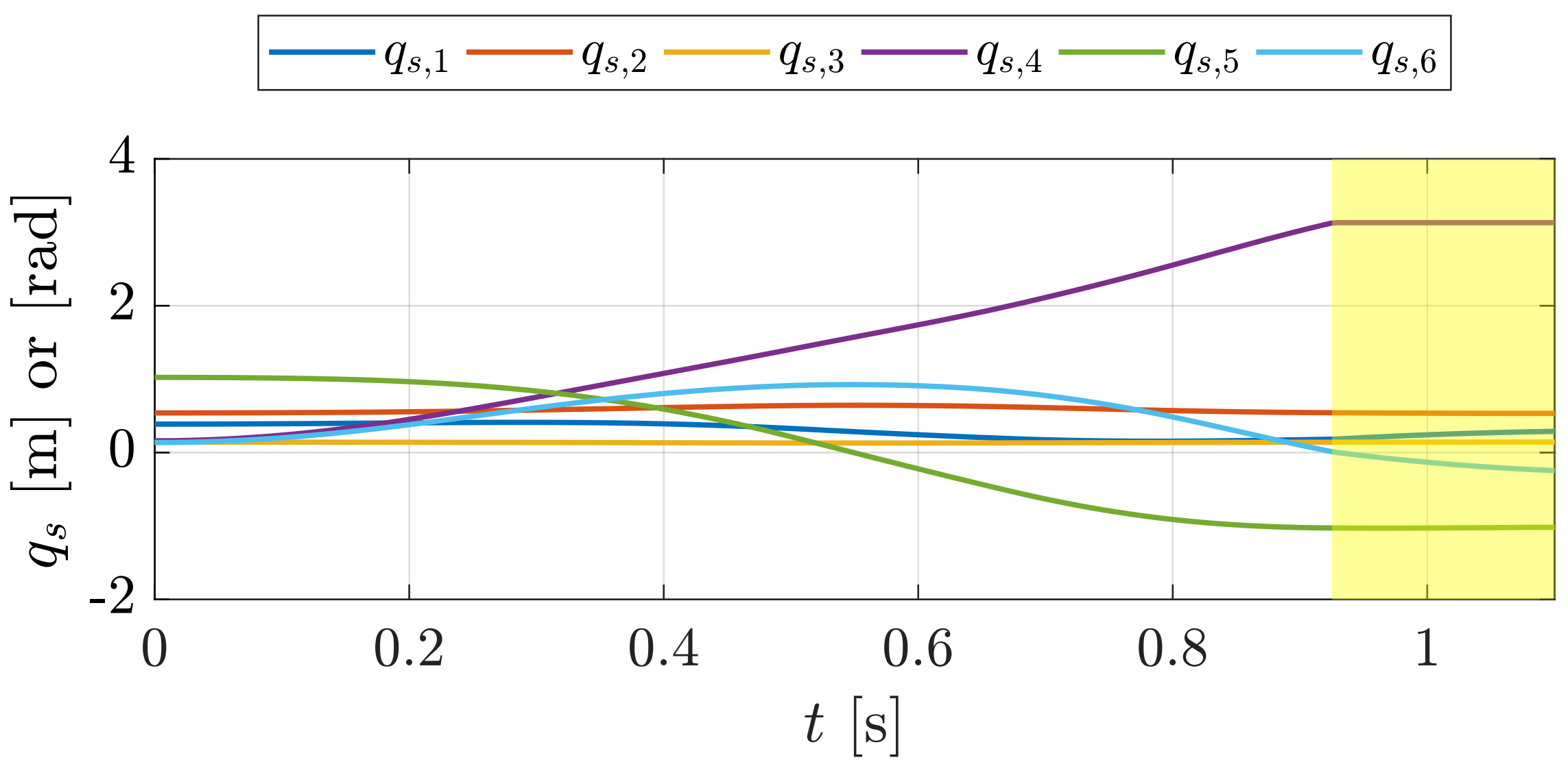
$$\frac{\partial h}{\partial\boldsymbol{z}}=\frac{\partial h}{\partial\boldsymbol{q}_s}\boldsymbol{J}_s^{\dagger}(\boldsymbol{q}_s)^r\bar{\boldsymbol{R}}_n\boldsymbol{J}_g(\boldsymbol{z})$$

From $\boldsymbol{z}^\star\rightarrow\boldsymbol{x}_{s,d}$ optimal robot Cartesian pose.

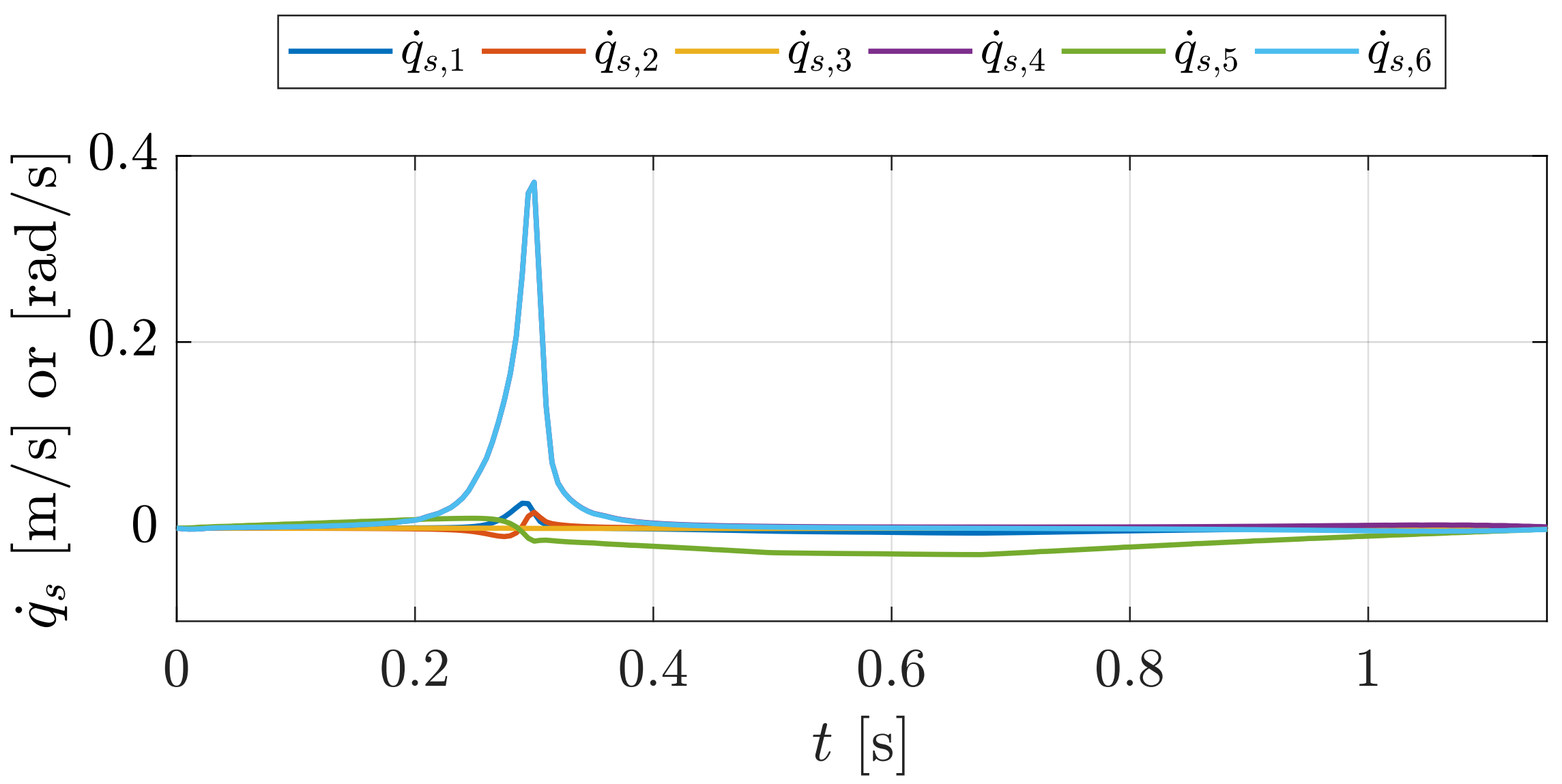
Experiments

Experiment 1: Simulated constraints occurrence

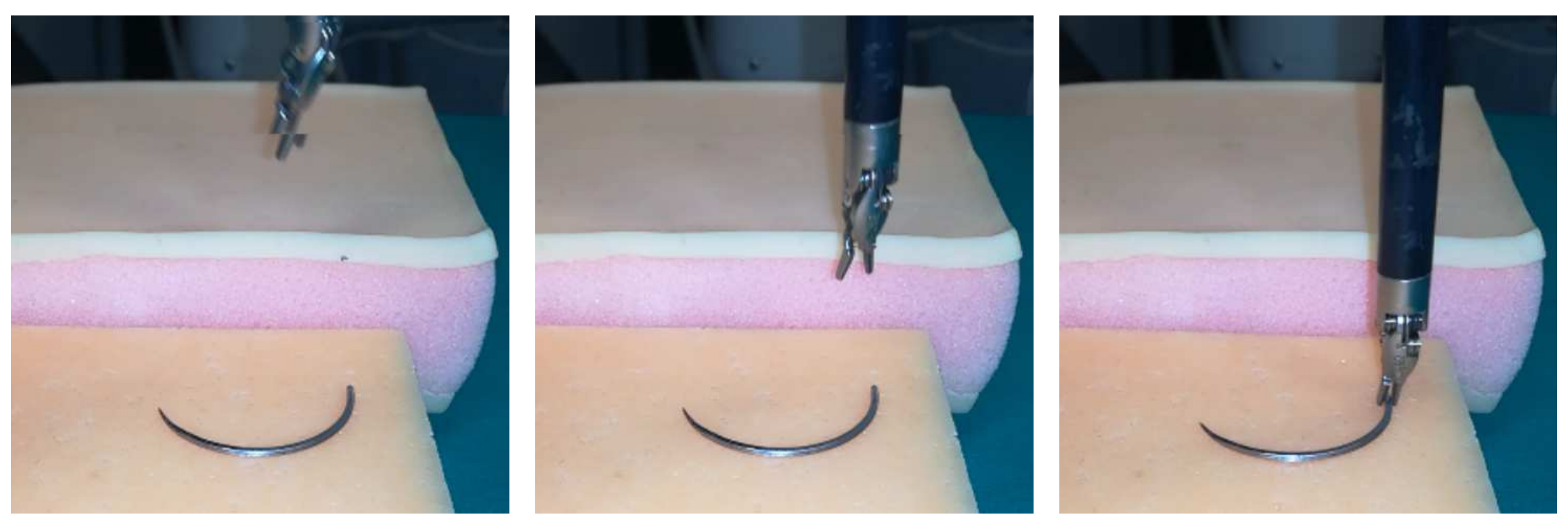
Joint Limits: deviation from desired path

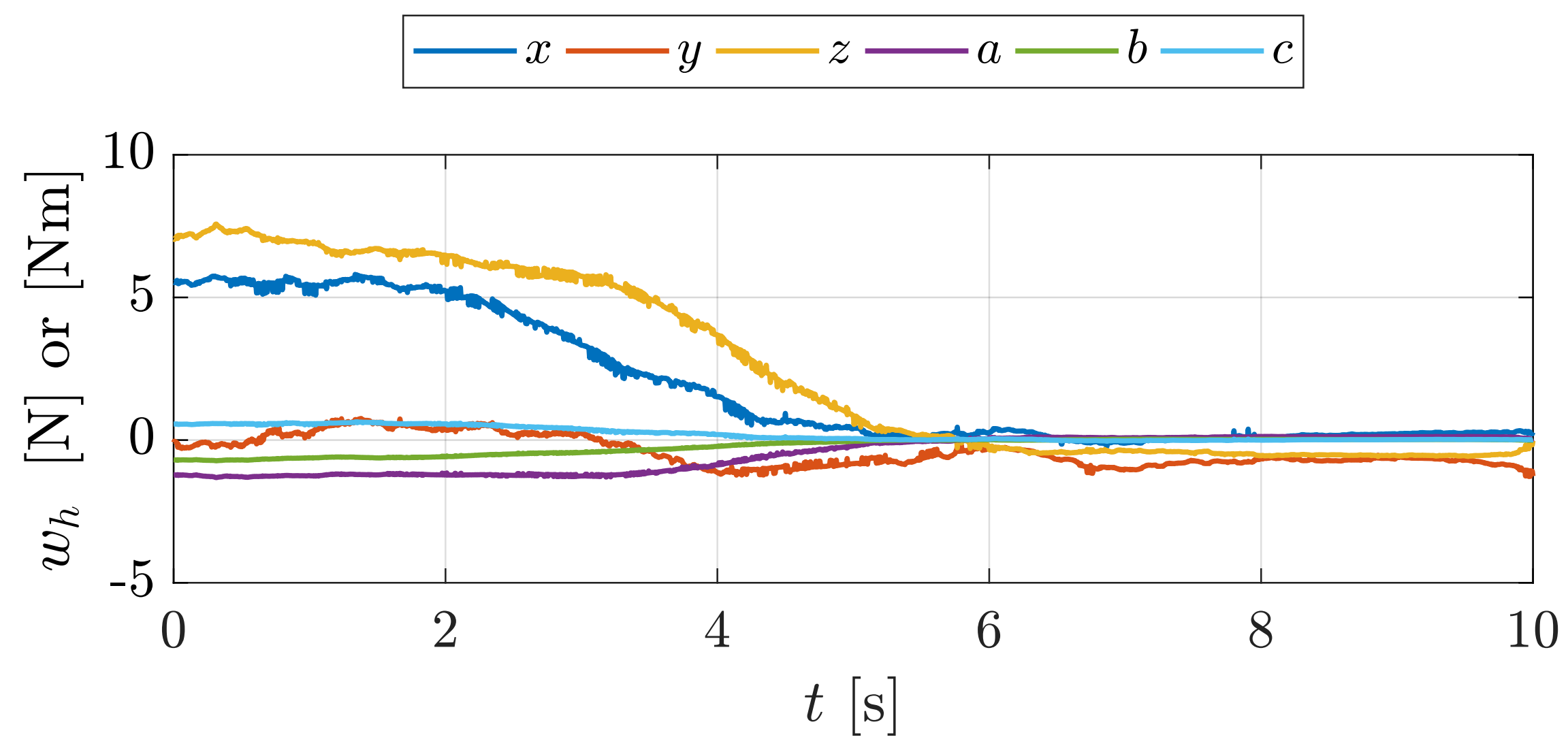


Singularities: high joint velocities

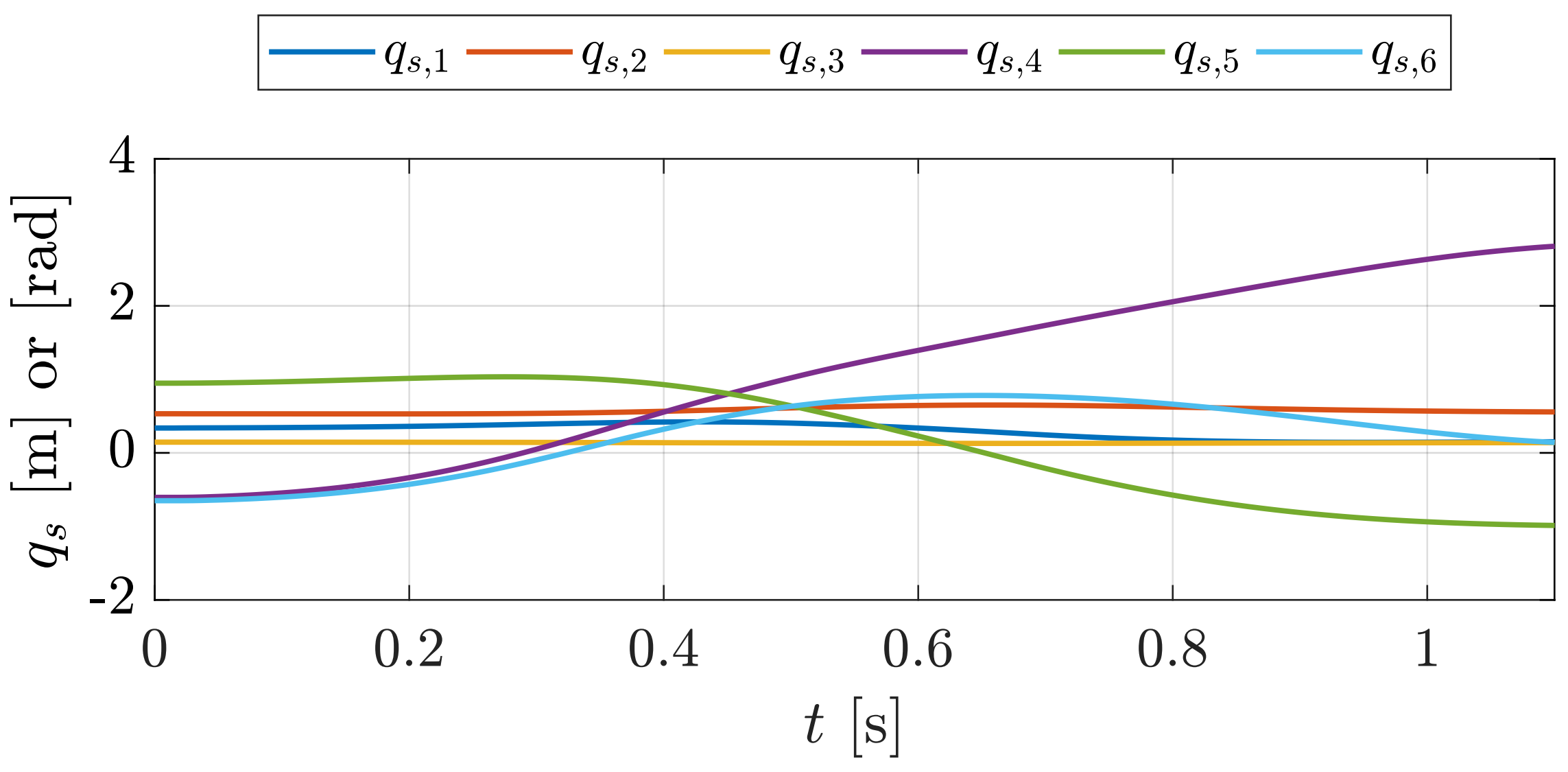


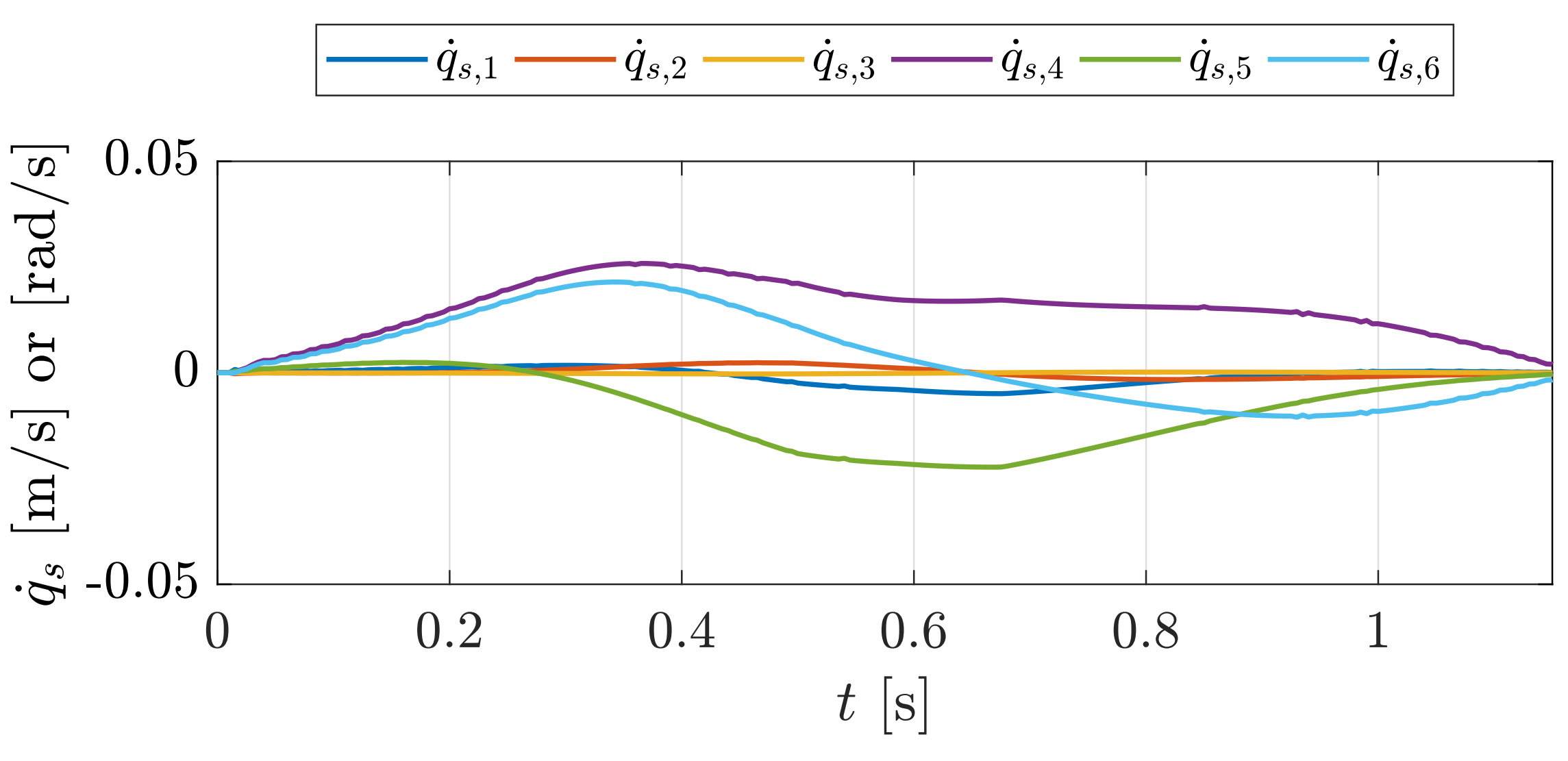
Experiment 2: Optimization and haptic-guided grasping



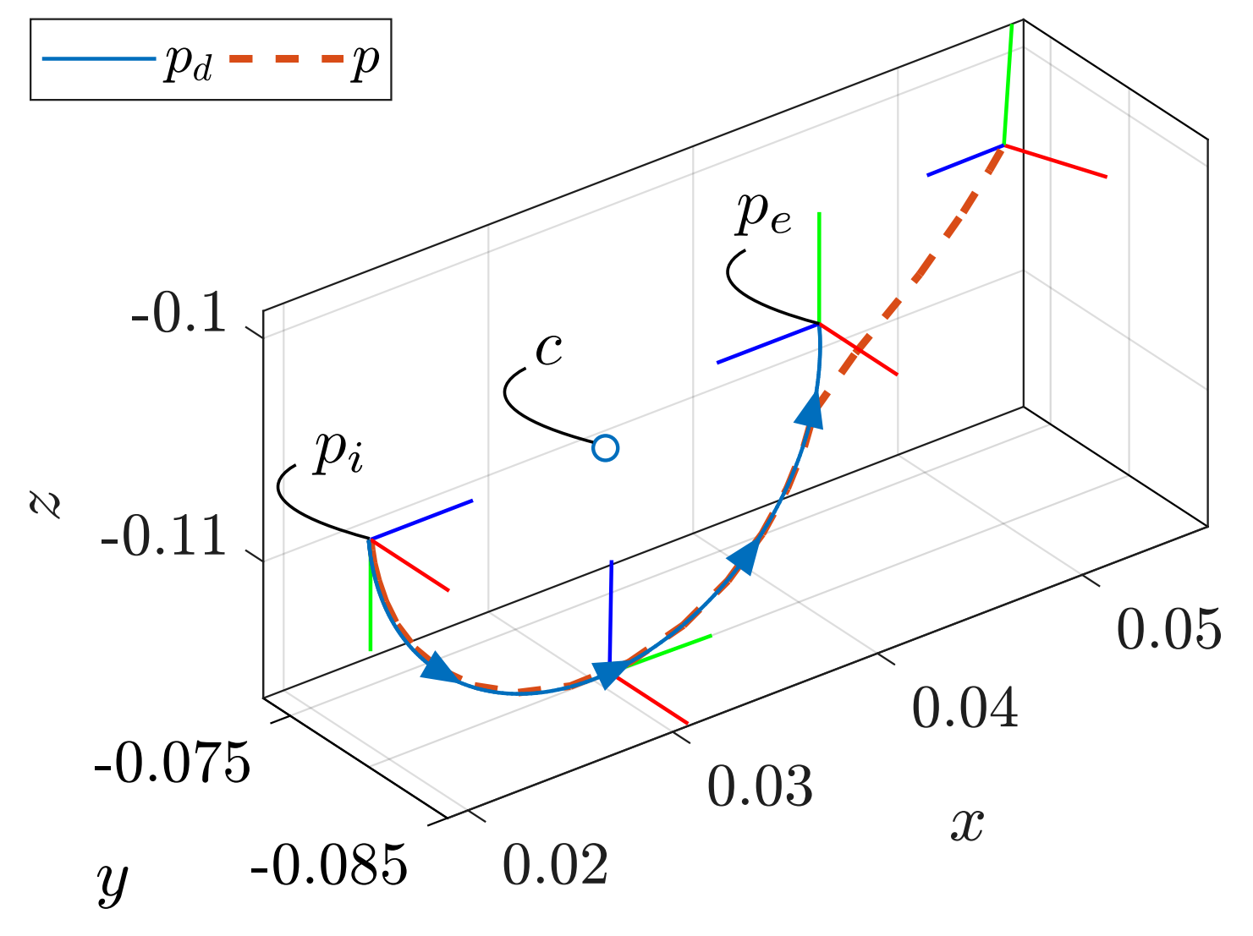


Experiment 3: Simulated optimal solution





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).