Optimization of robot configurations for motion planning in industrial riveting

Hakan Girgin[1,2], Teguh Lembono [1,2], Radu Cirligeanu [3], Sylvain Calinon [1,2]
[1]Idiap Research Institute, [2]Ecole Polytechnique Fédérale de Lausanne (EPFL), [3]ROMAERO

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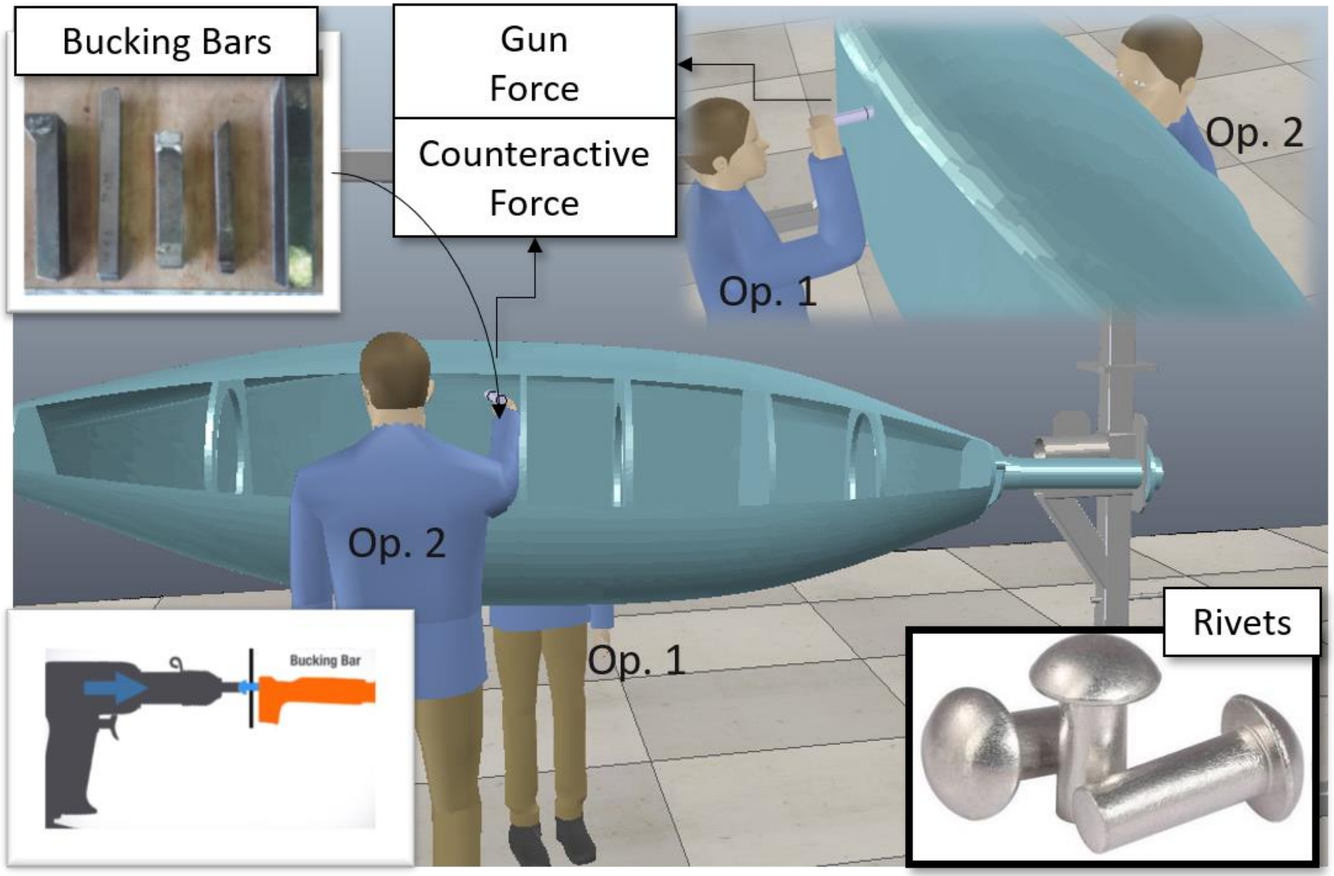
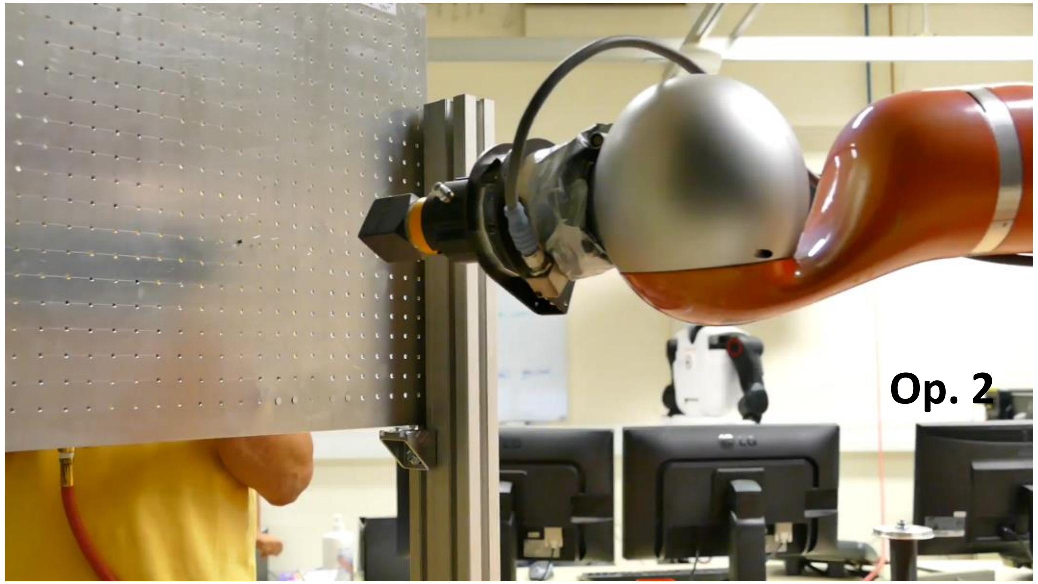
Percussive Riveting in Aerospace Industry

Manual riveting → collaborative riveting





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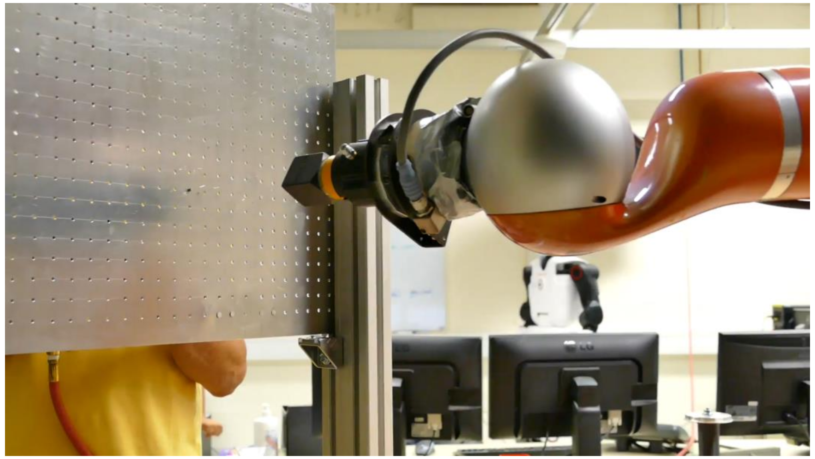
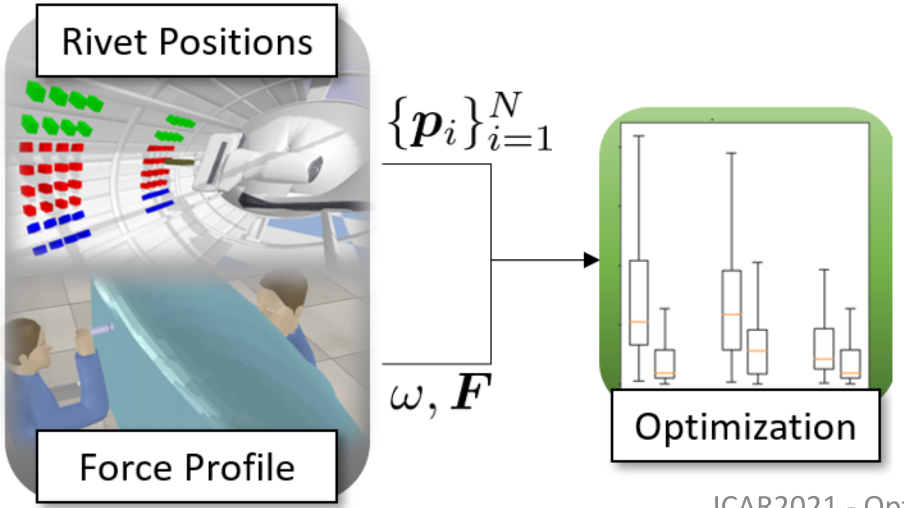
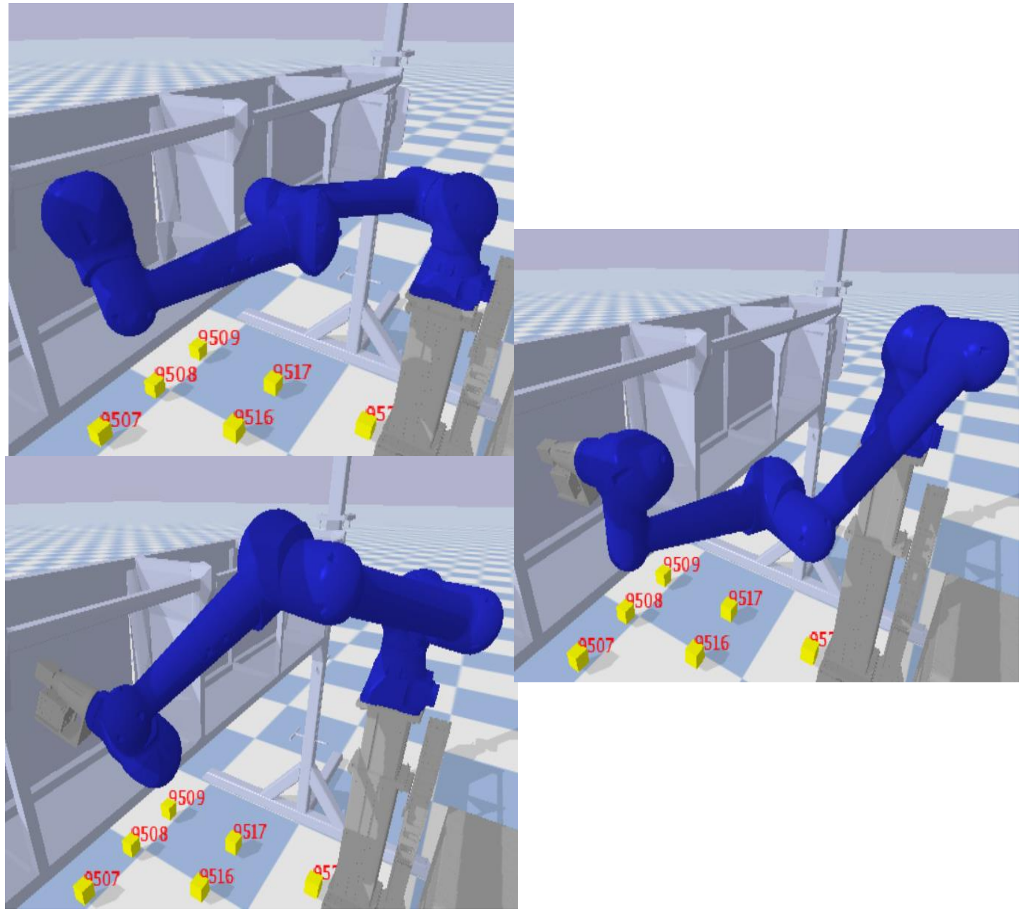
Challenges in Collaborative Riveting (1)

1) <u>Undesired vibrational end-effector displacements</u>

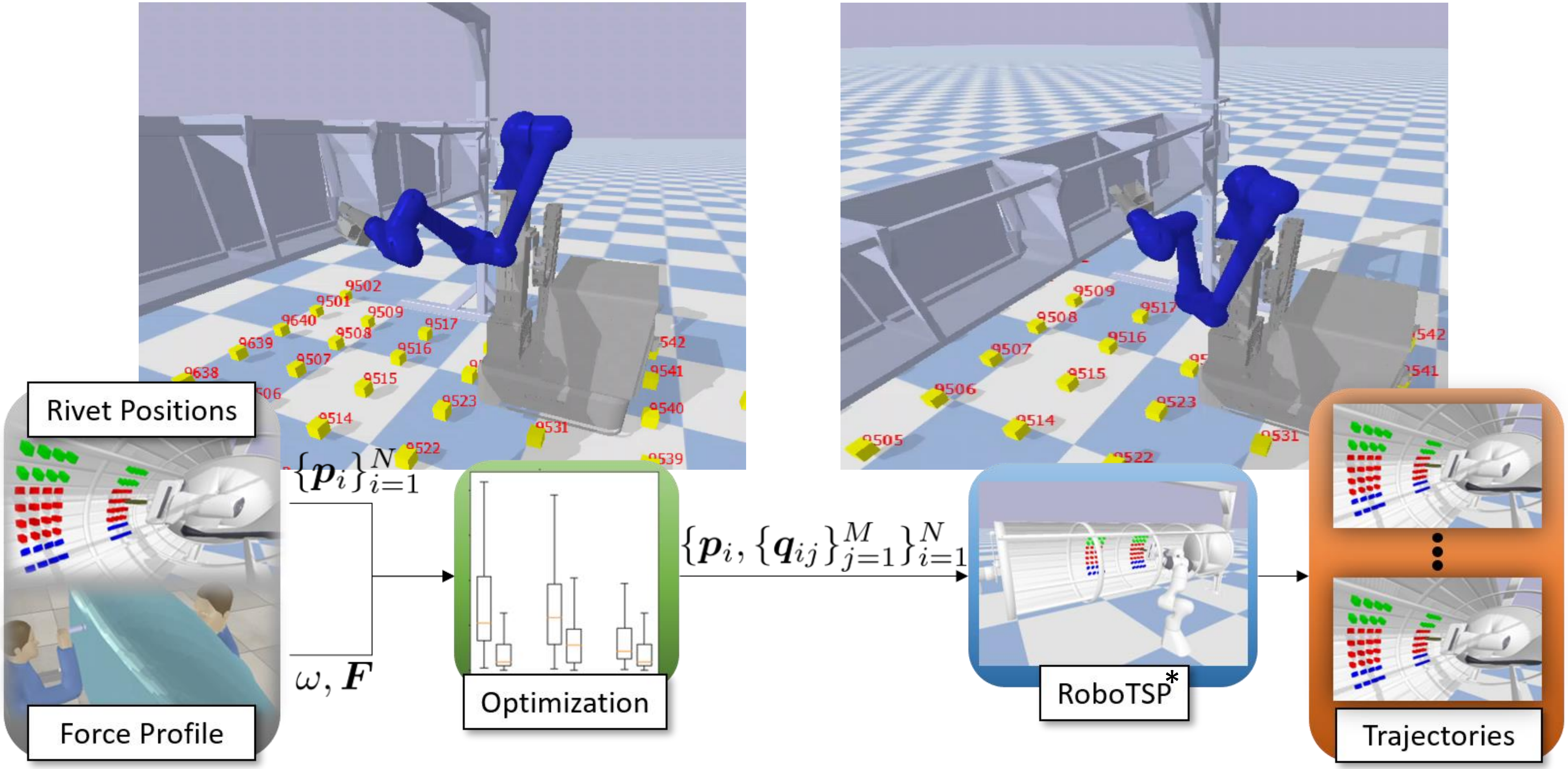






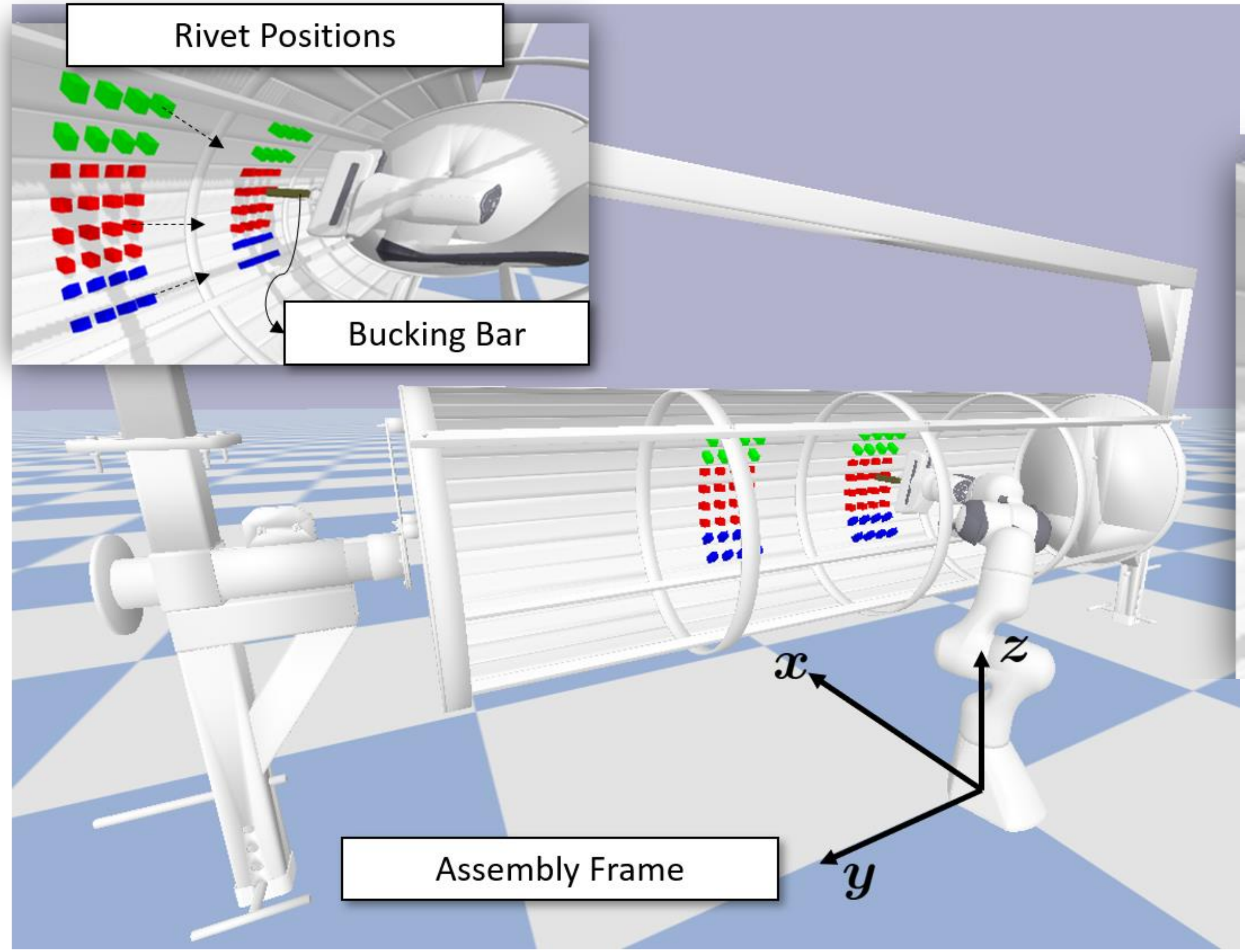
Challenges in Collaborative Riveting (2)

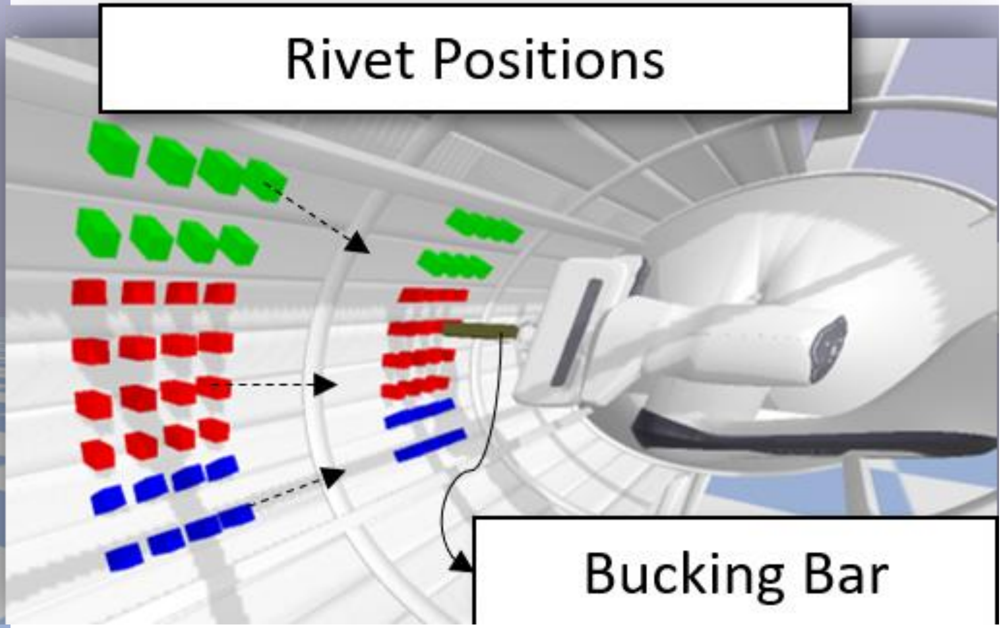
2) Motion planning in cluttered environments for redundant tasks



*F. Suarez-Ruiz, T. S. Lembono, and Q.-C. Pham, "RoboTSP–a fast solution to the robotic task sequencing problem," in Proc. IEEE Intl Conf. on Robotics and Automation (ICRA), 2018.

Simulation Setup

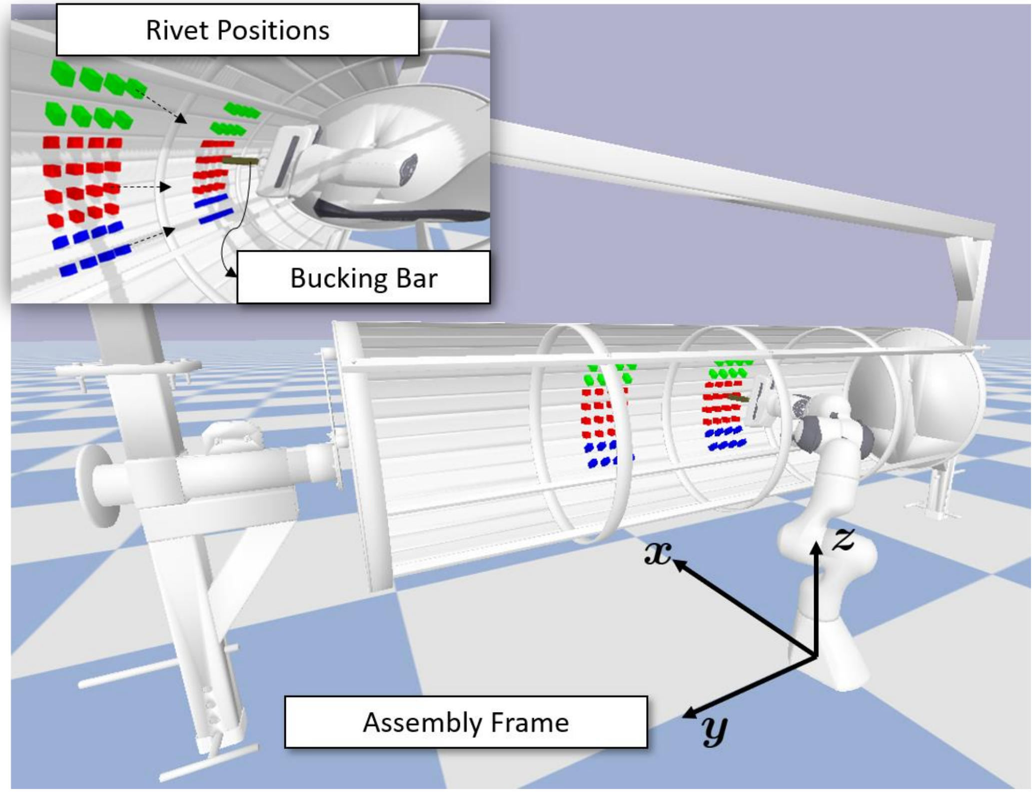




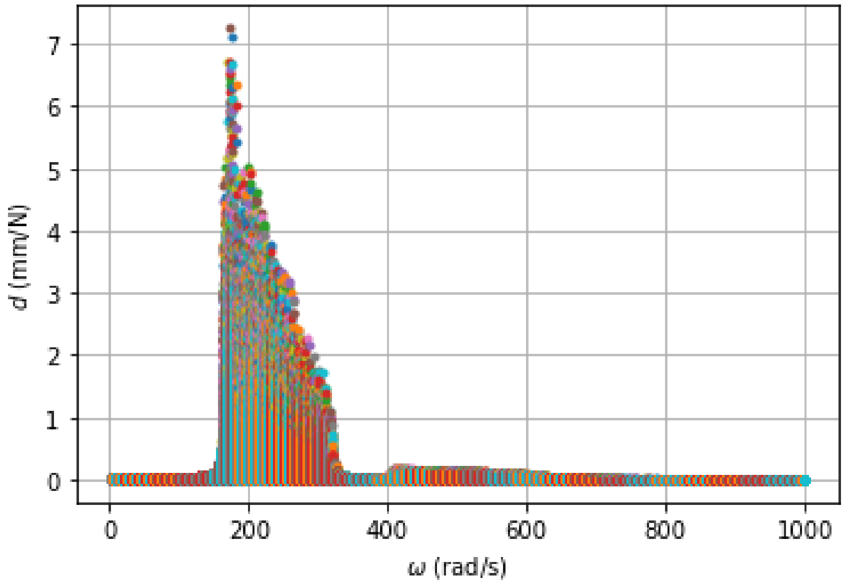
The task requires 5 DoF and the robot has 7 DoF which makes the task a redundant task.

Optimization of robot configurations (methods)

$$c(\boldsymbol{q}) = c_{\text{pos}}(\boldsymbol{q}) + c_{\text{orn}}(\boldsymbol{q}) + \beta c_{\text{disp}}(\boldsymbol{q}, \omega)$$

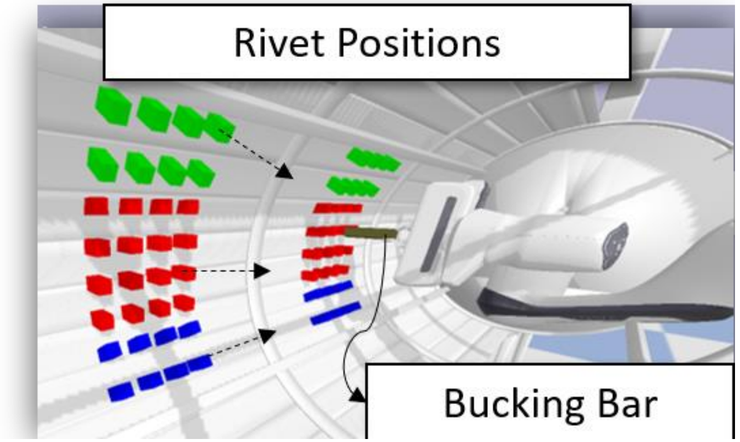


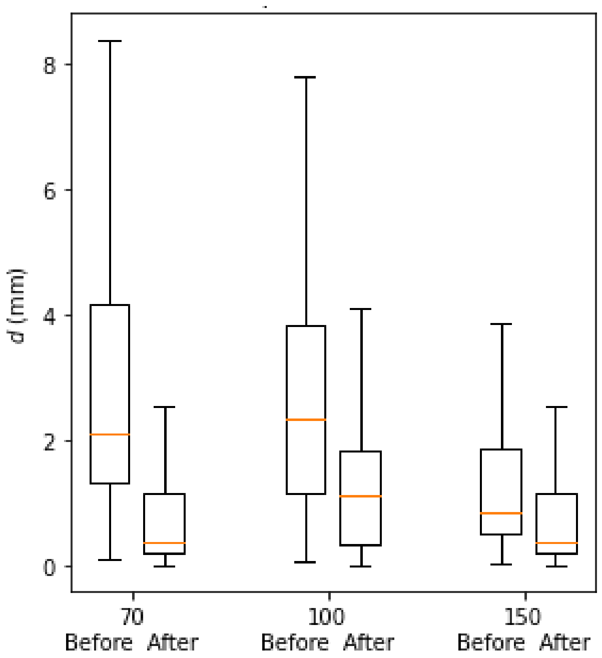
$$||\underbrace{\Delta \boldsymbol{x}(\boldsymbol{q}, \omega)}_{d}||_2^2 \qquad \Delta \boldsymbol{x} = \boldsymbol{H}(\boldsymbol{q}, \omega)\bar{\boldsymbol{F}}$$



Optimization of robot configurations (results)

$$c(\boldsymbol{q}) = c_{\mathrm{pos}}(\boldsymbol{q}) + c_{\mathrm{orn}}(\boldsymbol{q}) + \beta c_{\mathrm{disp}}(\boldsymbol{q}, \omega)$$





Percentage reduction of vibrational displacement

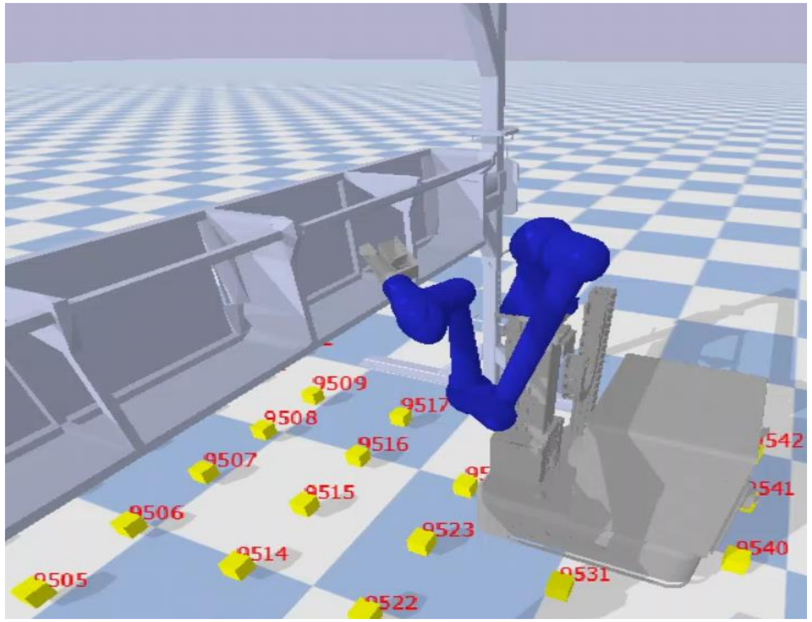
Frequency (rad/s)	Top	Middle	Bottom
70	82.9	67.79	78.17
100	51.8	54.94	56.4
150	62.52	50.98	50.74

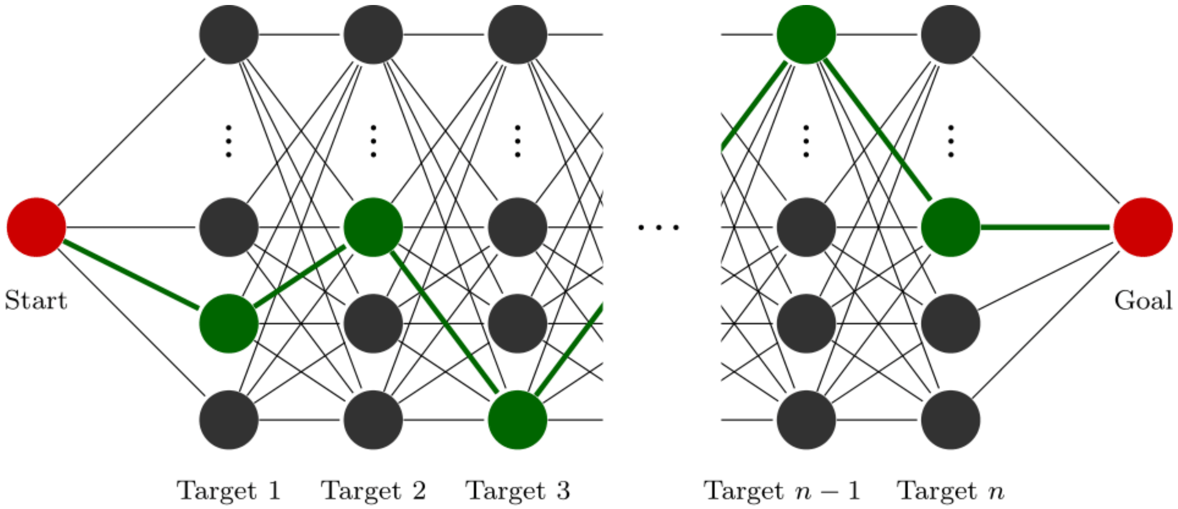
→ The output of this first part is 500 configurations for each rivet position on the structure (minimizing vibrational displacements).

Integration with RoboTSP (methods)

- Need to choose one configuration out of 500 for each rivet and plan the trajectory.
- One naïve way is to choose the configurations with the smallest displacements for each rivet hole.

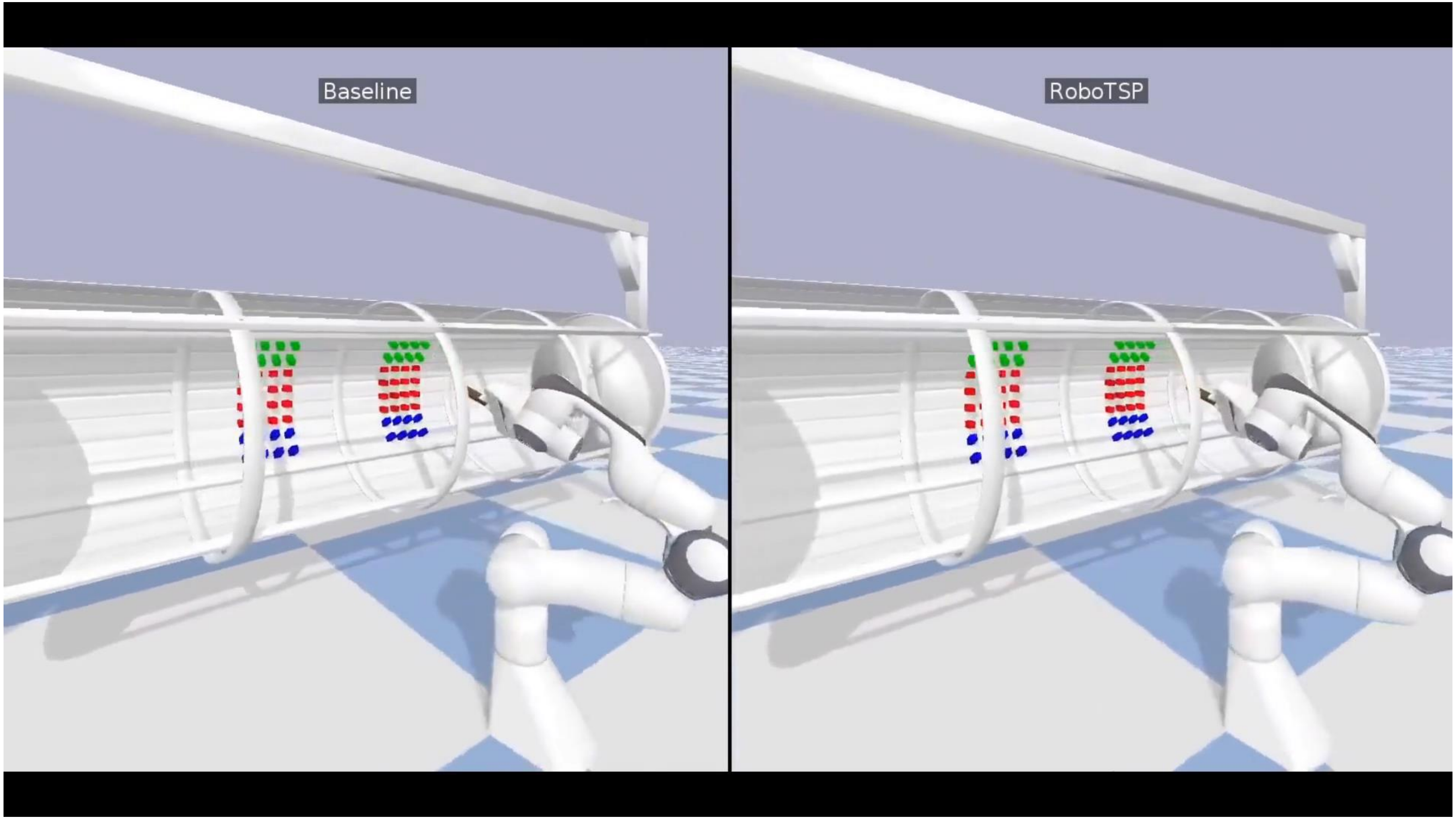
-> **Baseline**





- We propose to use RoboTSP, an optimal task and motion planner.
- The planner can select the optimal configuration at each position/hole such that it minimizes the total length of the trajectory and the displacements.

Execution of baseline approach vs proposed approach



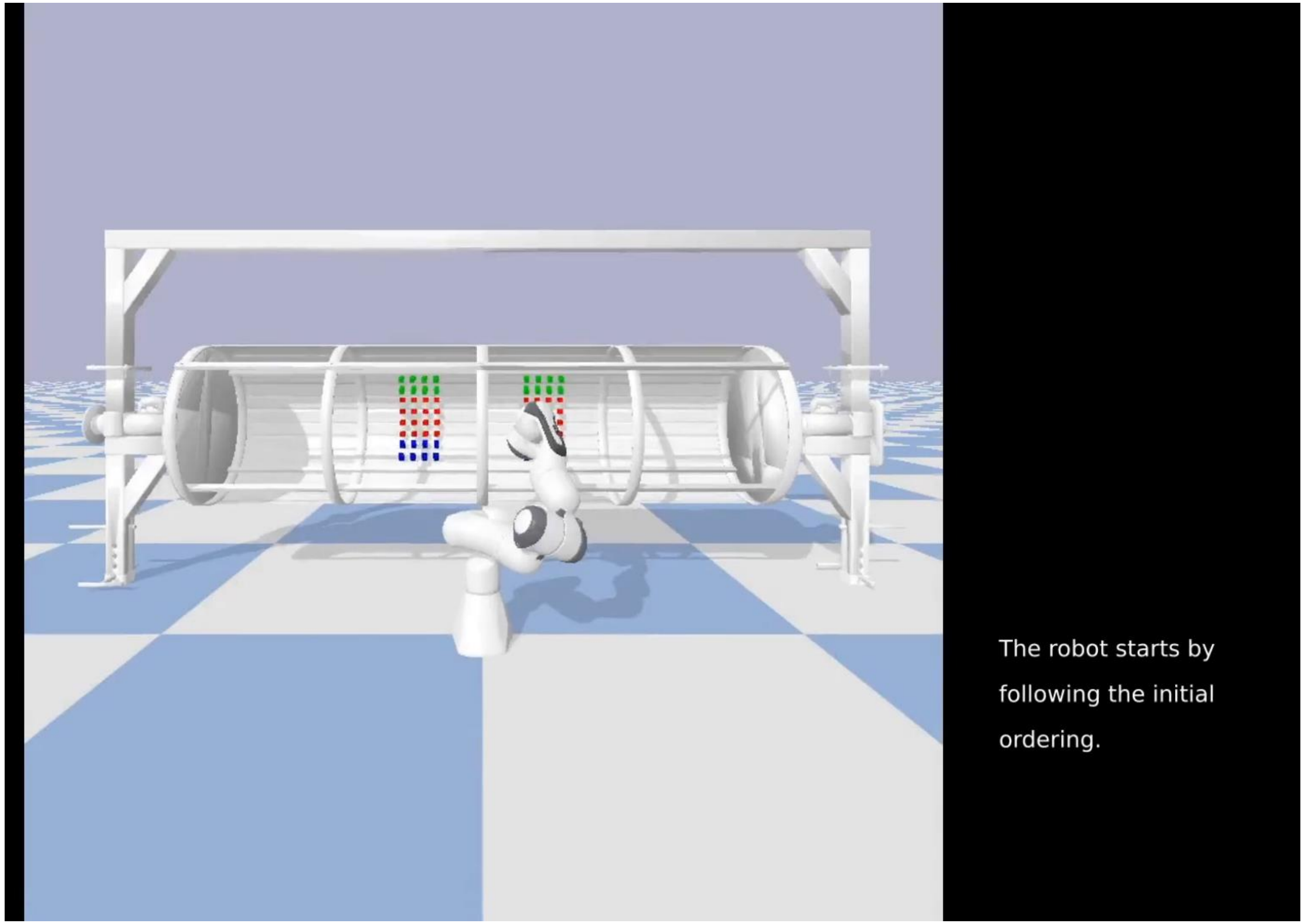
Integration with RoboTSP (results)

- Compared to baseline, RoboTSP achieves 10 times shorter trajectories with almost similar vibrational displacements.

- As RoboTSP chooses optimal configurations for each rivet hole, the computation time of the trajectory planning is significantly faster than baseline.

→ Can be used to replan on the fly

Online adaptation to riveting sequences

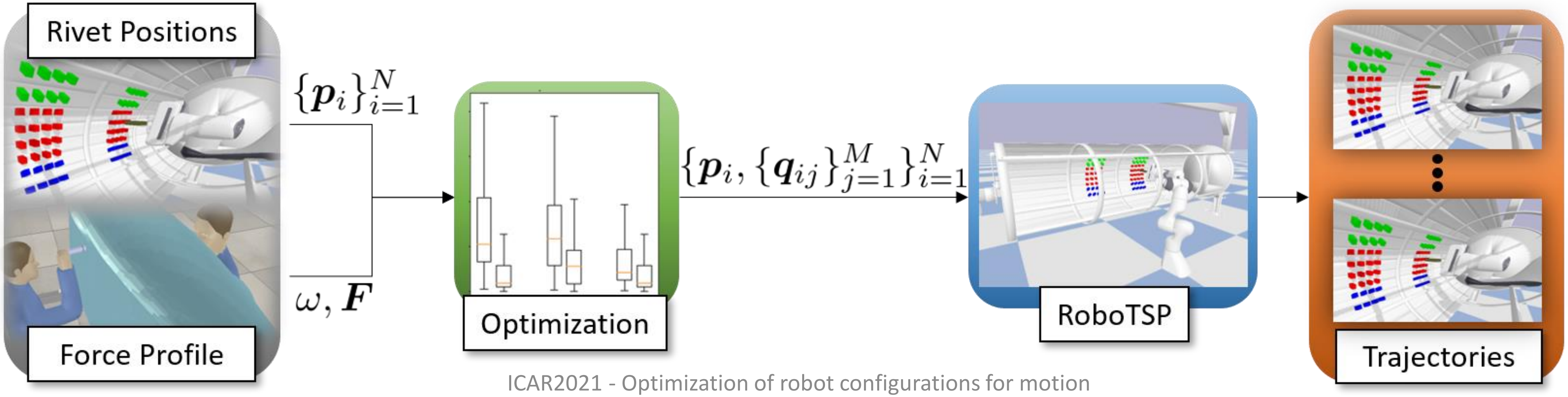


Conclusion

In this work, we addressed two major challenges in the automatization of **industrial riveting** with a **collaborative robot**:

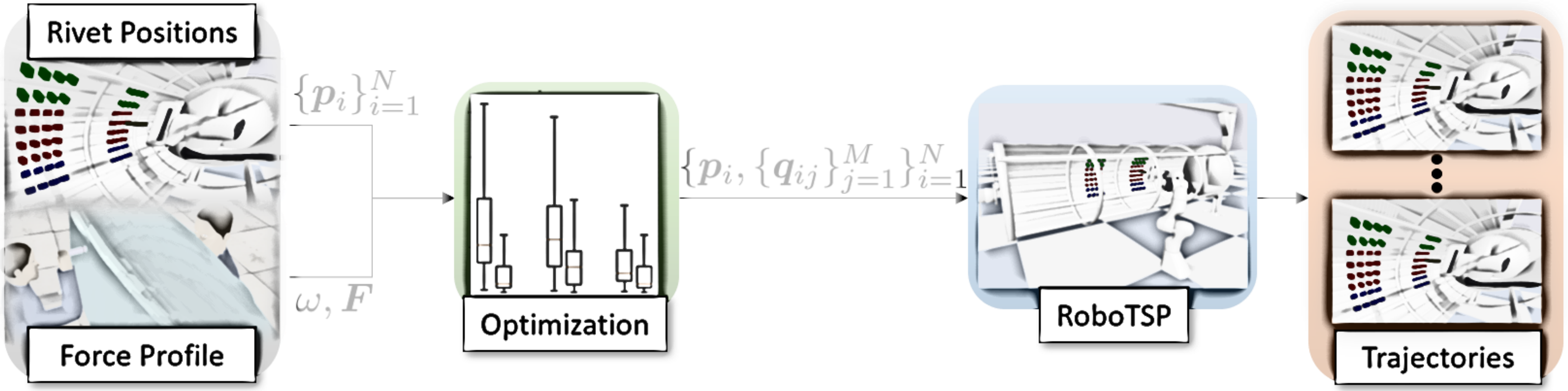
1) We proposed a principled way to **exploit kinematic redundancies** in the riveting task by determining configurations which result in **minimal vibrational displacement** of the end-effector when it is subject to percussive loading.

2) We exploited these configurations in an **optimal motion planning algorithm** for **faster execution** of the task.



Thank you for listening!

Questions?



hakan.girgin@idiap.ch

hgirgin.github.io

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Vibration Model for a simple harmonic force

Rigid Body Dynamics: $\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau}_{\mathrm{m}} + \boldsymbol{\tau}_{\mathrm{ext}}$ (1)

Impedance Controller: $\boldsymbol{\tau}_{\mathrm{m}} = \boldsymbol{K}_d(\boldsymbol{q}_d - \boldsymbol{q}) + \boldsymbol{C}_d(\dot{\boldsymbol{q}}_d - \dot{\boldsymbol{q}}) + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q})$ (2)

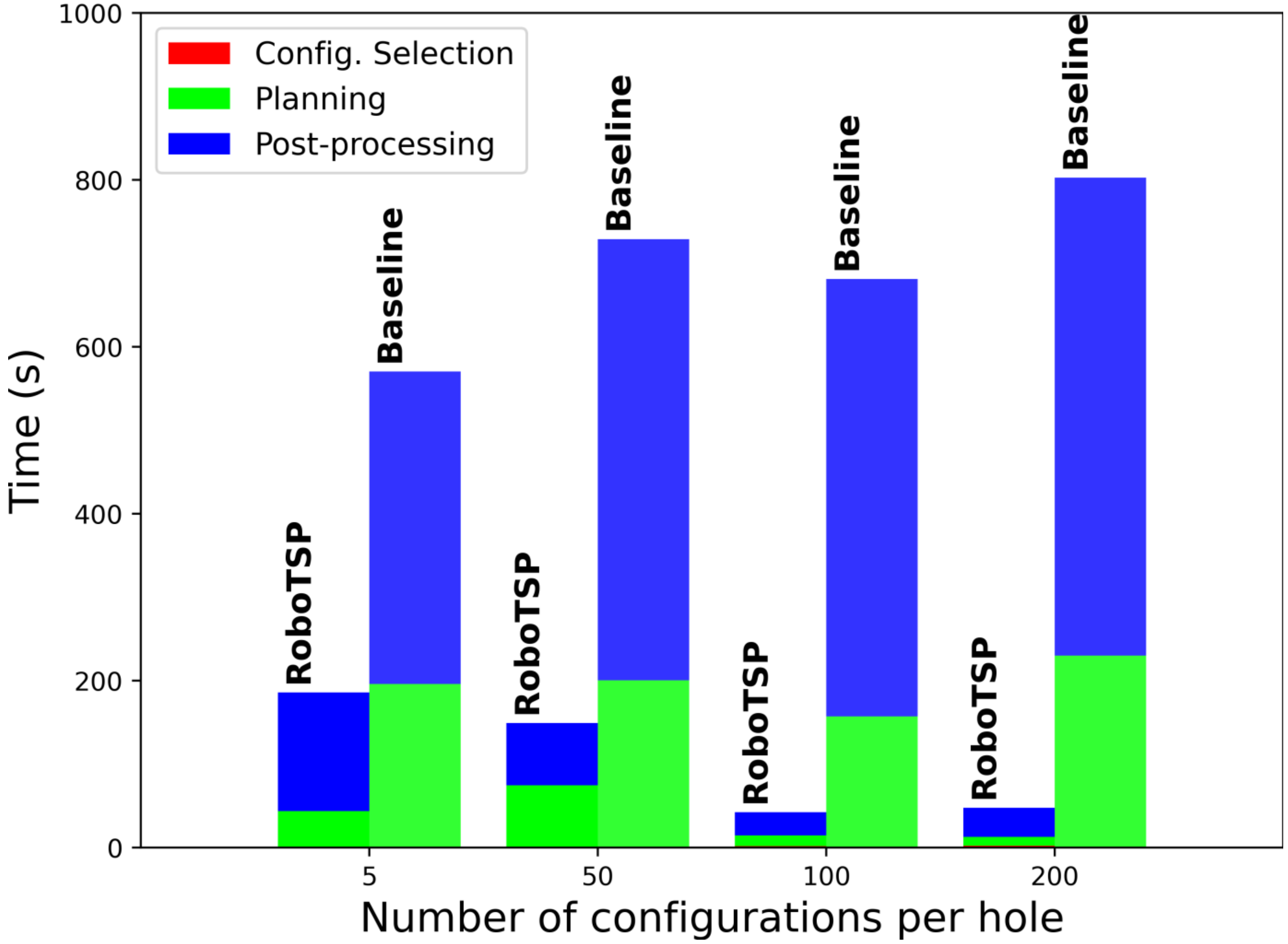
- We are interested in analyzing the deflections/perturbations from a desired configuration $\boldsymbol{\delta} = \boldsymbol{q} - \boldsymbol{q}_d$ when the manipulator is subject to external forces applied at the end-effector $\boldsymbol{\tau}_{\mathrm{ext}} = \boldsymbol{J}^{\top}\boldsymbol{F}(t)$
- Substitute (2) into (1) to get the deflection model $\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{\delta}} + \boldsymbol{C}_d\dot{\boldsymbol{\delta}} + \boldsymbol{K}_d\boldsymbol{\delta} = \boldsymbol{J}^{\top}\boldsymbol{F}(t)$

$$\boldsymbol{F}(t) = \bar{\boldsymbol{F}}\mathrm{e}^{j\omega t}$$

Deflection in joint space $\boldsymbol{\delta}(t) = \bar{\boldsymbol{\delta}}\mathrm{e}^{j\omega t}$ $\quad \bar{\boldsymbol{\delta}} = (-\omega^2\boldsymbol{M} + j\omega\boldsymbol{C} + \boldsymbol{K})^{-1}\boldsymbol{J}^{\top}\bar{\boldsymbol{F}}$

Deflection in task space $\Delta\boldsymbol{x} = \boldsymbol{J}^{\top}\bar{\boldsymbol{\delta}} = \boldsymbol{H}(\omega)\bar{\boldsymbol{F}}$ $\quad \boldsymbol{H}(\omega) = \boldsymbol{J}^{\top}(-\omega^2\boldsymbol{M} + j\omega\boldsymbol{C} + \boldsymbol{K})^{-1}\boldsymbol{J}^{\top}$

Computational time



Trajectory length and displacement plots