Haptic Shared-Control Methods for Robotic Cutting

Rahaf Rahal
Univ Rennes, Inria,
CNRS, IRISA
Rennes, France
rahaf.rahal@irisa.fr

Firas Abi-Farraj
Engie, Lab Crigen
Paris, France
firas.abifarraj@gmail.com

Paolo Robuffo Giordano
CNRS, Univ Rennes,
Inria, IRISA
Rennes, France
prg@irisa.fr

Claudio Pacchierotti
CNRS, Univ Rennes,
Inria, IRISA
Rennes, France
claudio.pacchierotti@irisa.fr

I. INTRODUCTION

Shared control allows to *share* the available degrees of freedom of a robotic system between the operator and an autonomous controller, to facilitate the task and improve the efficiency of the system [1], [2], e.g., in robotic teleoperation [3]–[5]. Robotic cutting is particularly interesting for shared control, as it is employed in various sensitive applications which range from surgical cutting [6] to nuclear decommissioning [7] and disaster response [8]. Moreover, cutting applications feature a variety of constraints which can have a high impact on the task. For example, to avoid damaging the environment, the cutting tool should neither perform pure lateral motion nor rotate in place. Indeed, unicycle and car-like kinematic models have been used for modeling the cutting task to reflect its nonholonomic nature [9], [10].

Several shared-control architectures have been proposed in the literature to tackle different cutting applications [11]. One example is enforcing nonholonomic constraints on multi-purpose robots through control [12], [13]. In [13], Vozar et al. design four shared-control approaches for cutting straight lines into MLI blankets under a time delay. In all modes, the master interface was free to move in any direction, and the constraints were implemented only at the remote side.

This work targets the limitations of the above-described architectures. It presents the design and evaluation of two shared-control approaches for commanding a manipulator in a cutting scenario while enforcing constraints associated with the task itself, e.g., limiting lateral motions, rotations in place, and sharp turns of the tool. The user is provided with information about the enforced nonholonomic constraints (alongside contact forces) via haptic feedback on the master device.

II. METHODS

The robotic system is composed of a master 6-DoF haptic interface and a remote 7-DoF torque-controlled manipulator, equipped with a scalpel. A planar object to cut is placed on a table in front of the robot (see Fig. 1). The scalpel and the end-effector of the master device can move along the three translational directions but their orientation is constrained via control to only rotate around the vertical axis $\boldsymbol{z}_b$.

We present three different control approaches which are shown in Fig. 2. More details on the methods are given in [14] and in the video available as supplemental material and at https://youtu.be/DkW4OcjgX9M.

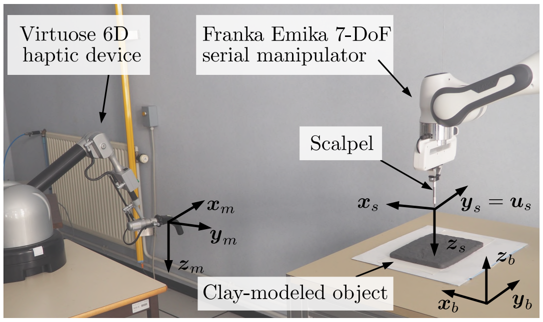


Fig. 1. Experimental setup and frames used for the shared-control methods that enforced various nonholonomic-inspired constraints.

A. *Standard haptic teleoperation (condition T)*

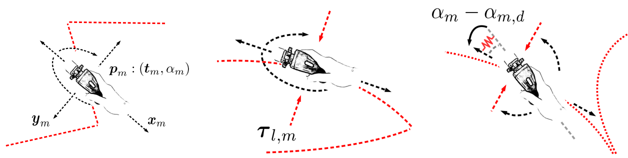
This mode is a simple teleoperation, with no added constraints related to the cutting task. The manipulator receives torque commands based on impedance control, relating the pose of the remote robot to the pose of the master.

The external forces applied by the environment on the remote robot are fed back to the user through the master interface, such that $\boldsymbol{\tau}_m = \boldsymbol{\tau}_c + \boldsymbol{\tau}_{nc}$, where $\boldsymbol{\tau}_c$ represents the forces applied along the constrained directions, and $\boldsymbol{\tau}_{nc}$ the ones applied along the non-constrained directions. In this mode, nonholonomic constraints are not applied, so external forces are reflected on all directions controlled by the operator.

B. *Unicycle approach (condition U)*

While T guarantees high flexibility, the cutting scenario enables us to introduce additional constraints which can make the teleoperation easier and safer. In particular, any lateral motion of the scalpel during cutting can induce significant damage on the material (and even on the scalpel itself). We thus impose nonholonomic constraints on the robot motion, such that the scalpel can only move along two translational directions: its cutting direction $\boldsymbol{u}_s$, and its vertical direction $\boldsymbol{z}_b$; however, it cannot translate laterally. The scalpel can always rotate around its axis $\boldsymbol{z}_s$.

To achieve this desired behavior, we also constrain the master device such that the user is allowed to move along $\boldsymbol{x}_m$ and $\boldsymbol{z}_m$ in translation, as well as to rotate around $\boldsymbol{z}_m$. The motion around $\boldsymbol{y}_m$ is, however, blocked. In addition to the forces imposing the constraints on the master interface, the user also receives haptic feedback $\boldsymbol{\tau}_{nc}$ from the environment along the directions not constrained by the control.



(a) Teleoperation. (b) Unicycle. (c) Car-like.

Fig. 2. Summary of the shared control modes. Black arrows are directions the user is allowed to control, red arrows directions which are blocked, dashed red lines sample trajectories. **(T) Teleoperation.** The user has control over all planar motions and the vertical movement. **(U) Unicycle.** Pure lateral motions are blocked. **(C) Car-like.** In addition to blocking the lateral motion, rotations in place and sharp turns are also avoided. The user controls the radius of curvature of the steering. A spring informs the user about the master position corresponding to a zero radius of curvature.

C. Car-like approach (condition C)

The previous approach prevents the user from moving the scalpel laterally. However, it does not prevent rotation in place or sharp turns. To limit these undesired behaviors, we impose additional constraints executing rotations only if the scalpel moves along $\boldsymbol{u}_s$. Moreover, the user is given control over the radius of curvature of the trajectory, R_d. Similarly to driving a car, the user does not directly control the angular velocity of the remote robot but rather the steering angle.

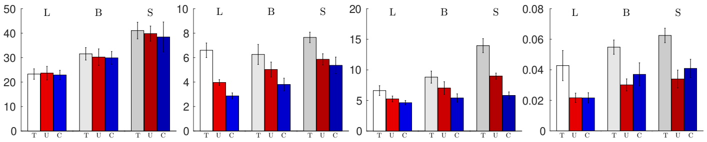
As in Sec. II-B, we constrain the master interface with a hard spring blocking any lateral motion. A soft spring is applied around $\boldsymbol{z}_m$ to fix the orientation of the master device at a particular pivot angle, which ensures that the master and the robot are aligned at all times. As before, the user also receives $\boldsymbol{\tau}_{nc}$ along the directions not constrained by the control.

III. EXPERIMENTS AND RESULTS

To evaluate the effectiveness of our shared-control approaches, we carried out a human subject experiment with twelve participants. Participants used the master device to control the robot and cut a target shape in the modeling clay. The three modes T, U and C were considered. For each mode, participants were asked to carve three different shapes: a straight line (L), a bent line (B), and a sinusoidal shape (S).

The different metrics and results are summarized in Fig. 3. A questionnaire also showed that eight subjects found condition U to be the most effective for the cutting task. Three subjects preferred condition T while one preferred C.

Results show that the proposed shared-control approaches C and U outperform standard teleoperation in all metrics but completion time. These results are sustained across the three considered shapes. This proves our hypothesis that shared control is an effective approach to improve currently-available teleoperation systems for cutting tasks, which is in agreement with previous results in the literature. Comparing performance between U and C, we can see that limiting the maximum radius of curvature and preventing rotations in place (C) significantly lowers the lateral forces w.r.t. U, where these constraints were not enforced. Moreover, the error metric shows significant differences among all pairs, ranking C first (lowest error), followed by U and T (highest error). Finally, comparing performance among the target shapes, we can see that, as the shapes become more complex, their performance degrades. For most metrics, as the shapes become more complex, the difference of T vs. U and C increases. This is quite expected, as users need more help when cutting more complex shapes.



(T) Completion time (s). (U) Error in carving the target shape (mm). (C) Max. lateral force (N). (?) Roughness of the cut profile (mm).

Fig. 3. Human subjects experiment. Objective metrics. Mean and standard error of the mean of (a) completion time, (b) error in carving the target shape, (c) mean lateral force, and (d) roughness of the cut profile for the three control conditions (T, U, C) and the three target shapes (L, B, S).

Surprisingly, the subjective metrics did not always agree with the above results. In fact, users preferred T and U over C, as many constraints imposed in the C modality created the impression of conditions difficult to use. These results might change in the presence of experienced users.

REFERENCES

[1] D. A. Abbink, M. Mulder, and E. R. Boer, "Haptic shared control: smoothly shifting control authority?" *Cognition, Technology & Work*, vol. 14, no. 1, pp. 19–28, 2012.

[2] T. B. Sheridan, "Human-robot interaction: Status and challenges," *Human Factors*, vol. 58, no. 4, pp. 525–532, 2016, pMID: 27098262.

[3] M. Selvaggio, F. Abi-Farraj, C. Pacchierotti, P. Robuffo Giordano, and B. Siciliano, "Haptic-based shared-control methods for a dual-arm system," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 4249–4256, 2018.

[4] F. Abi-Farraj, C. Pacchierotti, O. Arenz, G. Neumann, and P. R. Giordano, "A haptic shared-control architecture for guided multi-target robotic grasping," *IEEE transactions on haptics*, 2019.

[5] F. Abi-Farraj, C. Pacchierotti, and P. Robuffo Giordano, "User evaluation of a haptic-enabled shared-control approach for robotic telemanipulation," in *Proc. IEEE/RSJ Intl. Conf. Intell. Robots and Systems*, 2018, pp. 1–9.

[6] V. Patnaik, R. K. Singla, and V. Bansal, "Surgical incisionstheir anatomical basis part iv-abdomen," *Journal of the Anat. Soc. India*, vol. 50, no. 2, pp. 170–8, 2001.

[7] Y. S. Park, H. Kang, T. F. Ewing, E. L. Faulring, J. E. Colgate, and M. A. Peshkin, "Enhanced teleoperation for d and d," in *Proc. IEEE Int. Conf. Robotics and Automation*, vol. 4, 2004, pp. 3702–3707 Vol.4.

[8] F. Abi-Farraj, B. Henze, A. Werner, M. Panzirsch, C. Ott, and M. A. Roa, "Humanoid teleoperation using task-relevant haptic feedback," in *IEEE/RSJ Intl. Conf. Intell. Robots and Systems*, 2018, pp. 5010–5017.

[9] A. M. Bloch, M. Reyhanoglu, and N. H. McClamroch, "Control and stabilization of nonholonomic dynamic systems," *IEEE Trans. Automatic Control*, vol. 37, no. 11, pp. 1746–1757, 1992.

[10] H. McClamroch, M. Reyhanoglu, and M. Rehan, "Knife-edge motion on a surface as a nonholonomic control problem," *IEEE Control Systems Letters*, vol. 1, no. 1, pp. 26–31, 2017.

[11] R. Prada and S. Payandeh, "A study on design and analysis of virtual fixtures for cutting in training environments," in *Proc. World Haptics Conference*, March 2005, pp. 375–380.

[12] X. Li and P. Kazanzides, "Task frame estimation during model-based teleoperation for satellite servicing," in *Proc. IEEE Intl. Conf. Robotics and Automation*, 2016, pp. 2834–2839.

[13] S. Vozar, Z. Chen, P. Kazanzides, and L. L. Whitcomb, "Preliminary study of virtual nonholonomic constraints for time-delayed teleoperation," in *Proc. IEEE/RSJ Intl. Conf. Intell. Robots and Systems*, 2015, pp. 4244–4250.

[14] R. Rahal, F. Abi-Farraj, P. R. Giordano, and C. Pacchierotti, "Haptic shared-control methods for robotic cutting under nonholonomic constraints," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2019, pp. 8151–8157.