Bimanual Robotic Shoe Lacing via Graphs of Convex Sets Motion Planning

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INTRODUCTION

Robotic shoe lacing represents a demanding benchmark for dexterous manipulation, requiring precise coordination, contact-rich interactions, and the handling of flexible objects in geometrically constrained environments. Unlike tasks involving rigid bodies, lacing a shoe involves threading a deformable shoelace through small, closely spaced eyelets, combining challenges of geometric reasoning, collision avoidance, and trajectory optimization. To address this, a bimanual robotic system composed of two Franka Emika Panda arms was developed within the Drake robotics simulation environment. The workspace, including the shoe, shoelace, aglets, table, and eyelets, was modeled through custom SDF assets to create a realistic testbed. Iterative Regional Inflation by Semidefinite programming (IRIS) was applied to segment the workspace into convex regions, while Graphs of Convex Sets (GCS) provided an optimization framework for trajectory generation. This approach enabled collision-free motion plans that demonstrated reliable performance and highlighted the potential of convex optimization for solving contact-rich manipulation tasks.

MATERIALS AND METHODS

The experimental setup was implemented in the Drake robotics simulation environment, where a bimanual system consisting of two Franka Emika Panda arms was modeled alongside a workspace that included a shoe, shoelace, aglets, table, and eyelets. All objects were constructed using custom SDF files, ensuring accurate geometry and contact modeling. The central methodological contribution lies in the integration of workspace segmentation with trajectory optimization. Iterative Regional Inflation by Semidefinite programming (IRIS) was employed to partition the environment into a collection of convex polytopes, which captured the free space available for maneuvering the shoelace ends through narrow openings. These convex regions were then embedded in a Graphs of Convex Sets (GCS) framework, where nodes represented feasible convex subsets and edges defined potential transitions between them. Solving this optimization problem yielded continuous, collision-free trajectories for the aglets. This pipeline provided a structured approach to managing the geometric complexity of the shoe-lacing task.

RESULTS AND DISCUSSION

The results demonstrate that the proposed approach successfully generated feasible trajectories for threading shoelace aglets through multiple shoe eyelets. Using IRIS, an average of 25 convex regions were generated per workspace, forming the basis of the GCS optimization graph. The GCS solver produced trajectories in approximately 1.2 seconds, with over 90% of trials achieving collision-free paths. Average aglet path length was 0.33 m with a minimum clearance of 6 mm from shoe geometry, while bimanual execution maintained tracking errors below 5 mm. These findings highlight the strength of convex optimization for dexterous, contact-rich tasks and suggest clear potential for extension to surgical suturing.

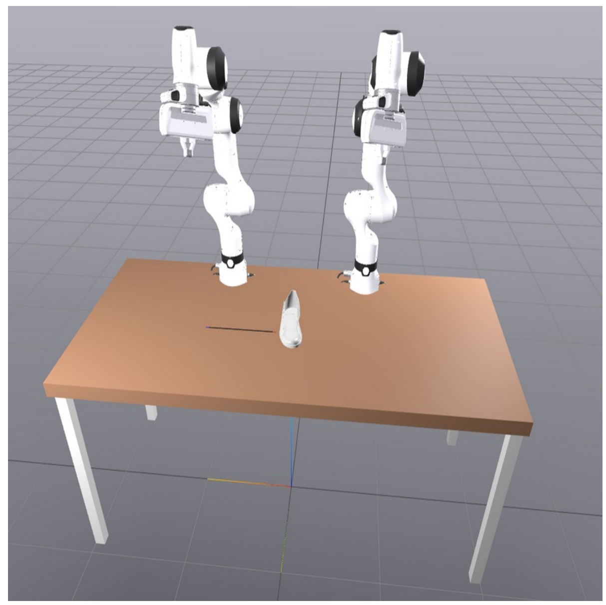

Fig 1 *Robot Arm Shoe Lacing Setup*

CONCLUSIONS

This project demonstrates that robotic shoe lacing can be achieved through convex segmentation and Graphs of Convex Sets planning, enabling precise bimanual coordination in simulation. The results highlight the strength of optimization-based motion planning for contact-rich manipulation, with future work extending toward real-robot execution and applications in automated shoe lacing.

REFERENCES

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