UNIVERSITY of HOUSTON
CULLEN COLLEGE of ENGINEERING

Aaron T. Becker
Department of Electrical Engineering
University of Houston
Houston, TX 77004, USA
Email: atbecker@central.uh.edu
Web: youTube.com/aabecker5
December 11, 2018

Exploiting Non-Slip Wall Contacts to Position Two Particles Using The Same Control Input

Dear IEEE Transactions on Robotics Editorial Office,

Please find attached the revised paper, *Exploiting Non-Slip Wall Contacts to Position Two Particles Using The Same Control Input*, of the conditionally accepted paper, along with the document containing a response to the reviewers. We are grateful to the reviewers for helping us improve our manuscript through their comments and questions. Please let us know if further information is required. This work extends the preliminary conference paper, "*Algorithms for shaping a particle swarm with a shared input by exploiting non-slip wall contacts*", presented at the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). The conference paper considered only square workspaces. This work extends the analysis to convex workspaces and 3D positioning. This paper also implements the algorithms using a hardware setup inspired by the anatomy of the gastrointestinal tract.

The new revision of our paper includes multi-media so that others can build on our results. These include illustrative videos for the simulations and experiments:

- Video *01Model.mov* animates the concepts of uniform control inputs and non-slip boundary contacts.
- Video *02DeltaConfigurationSpace.mp4* demonstrates how the Δ configuration space (the configuration space showing the difference in position for two particles) is constructed for a variety of workspaces.
- Video *03SimulationWorkSpaces.mp4* shows demonstrations of motion planning in square and disc-shaped workspaces.
- Video *04Hardware Experiments.mp4* shows an experiment trial moving two particles to goal positions in a small intestine phantom, then an experiment trial using cow stomach tissue.

We also include four Mathematica Notebooks (.nb files) containing the simulation code. This code generates plots for the paper and animates the path planner algorithm for arbitrary inputs.

- *SquareWorkSpace.nb* generates paths in a square workspace for two particles.
- *CircularWorkSpace.nb* generates paths in a circular workspace for two particles.
- *DeltaConfigurationSpacePolygon.nb* generates the Δ configuration space for convex polygons
- *ShortestPathForADisk.nb* analytical solution for shortest path that touches a boundary from one position to another position in a circular workspace.

Sincerely,

Aaron T. Becker

Aaron T. Becker (on behalf of all the authors)

Response to Reviewers

In the following document, we have provided detailed responses to the comments and questions of the reviewers. Comments and questions by reviewers are in red, our responses are in black.

Comments by Associate Editor

[R 0.1] "Both reviewers were pleased with the authors' revised manuscript. It is the opinion of the Associate Editor that this paper will be publishable in T-RO in some form. However, both reviewers have lingering concerns about discrepancies between the purported contribution of the paper and what is actually demonstrated. In the next draft of the manuscript, the authors are encouraged to be explicit in making sure that the stated contributions match what has been shown. This could involve removing or softening certain claims, or adding new material to strengthen certain claims."

Thank you for this opportunity! In addition to the changes listed below, we used this opportunity to remove a few typos and clean up several figures.

Comments by Reviewer #1

[R 1.1] "In the revised version most of my previous concerns have been addressed. I think with minor revisions the manuscript could be suitable for publication. The remaining issue still comes back to whether the iterative procedure is able to reach all target configurations. The new manuscript shows numerically that the accessible space approaches the entire space for a circular 2D domain. The paper, however, is meant to also cover any convex domains. Can the authors also prove that the accessible space approaches the entire domain for any convex domain? Or at least other polygonal cases? I see that on p4 in the last paragraph of section C, there is a statement that particles can be steered to arbitrary positions, but without an explanation of how that result is obtained, which should be included. I also think that paragraph should be highlighted a little more by a section title (to be parallel with the development of the circular workspace). Assuming this can be explained then I would be satisfied with the manuscript. "

Thank you! This was a fun extension to work on. In a similar form to the work with circular domain we now show that the accessible space rapidly grows to include the entire Δ configuration space. For finite-sided polygons, this convergence requires finite time (assuming the particles have at least ϵ separation). We have augmented Fig. 4 to show (as needed) the 4, 6, and 8-move reachable sets for polygons up to 10 sides. These sets reach the entire Δ configuration space.

[R 1.2] "I also think that paragraph should be highlighted a little more by a section title (to be parallel with the development of the circular workspace). Assuming this can be explained then I would be satisfied with the manuscript."

Great idea! We added Section IV.-D Convex Workspaces: Accessible Region.
This section includes the new text:
"As the corner angles increase, the number of moves required to access the entire configuration space increases. As shown in Fig. 4, four moves are sufficient for 3-sided regular polygons, and six moves accesses the entire Δ configuration space for up to 8-sided regular polygons. Eight moves is sufficient for polygons with less than 14-sides, but we have not checked polygons with more sides. For a circular workspace, with corner angles of 180°, the worst-case configuration can only be approached asymptotically, as explained in Section VI. If the polygon is irregular, more moves may be required. The entire configuration space is reachable in four moves for an acute triangle, but obtuse triangles require six moves. "

Comments by Reviewer #2

[R 2.1] "The authors did a great job in addressing my and the other reviewer's comments in a set of meaningful changes to the manuscript, including new analysis to investigate many of the questions. The only remaining comment is that the abstract and introduction imply that 3D results are obtained in this work. While this is shown theoretically, no 3D experimental results are shown. The abstract and introduction should state this explicitly as this is viewed as a notable limitation in what is actually demonstrated. "

Thank you. This has been a fun paper to work on. You are correct that no 3D experiments were performed. We corrected the abstract and introduction as follows:
"**Because *in vivo* environments are usually not square, this paper extends the previous work to all convex workspaces, and shows how this could be extended to 3D positioning of neutrally buoyant particles. We investigate analytically an idealized variant of this problem with non-slip boundaries and control inputs that are applied uniformly to all particles in the workspace. This paper also implements the algorithms in 2D using a hardware setup inspired by the gastrointestinal tract.**"
and at the end of the introduction: "This work extends the analysis to convex workspaces and 3D positioning. This paper also implements the algorithms in 2D using a hardware setup inspired by the anatomy of the gastrointestinal tract."
We hope in the future to use our new magnetic manipulator to test 3D movement, but are not yet ready for these experiments (and S. Shahrokhi, J. Shi, and B. Isichei have all graduated!)