Dr. Tamim Asfour, Professor
Editor-in-Chief
IEEE Robotics & Automation Letters
Institute for Anthropomatics and Robotics
Karlsruhe Institute of Technology

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Dear Prof Tamim Asfour,

We would like to thank you, the editors, and the reviewers for the helpful feedback on the revision of our manuscript. As instructed, we are now submitting a revised version of our paper (IEEE Robotics & Automation Letters: 21-0690)[1]. The paper has been modified according to your feedback and the Reviewers' comments. Please find our detailed responses in the following pages.

All authors have read and approved this submission for publication. This work is original and has not been published, or is being considered for publication, elsewhere in any language.

Once again, thank you for your time and kind consideration.

Sincerely,

Tong Yang
Jaime Valls Miro
Yue Wang
Rong Xiong[2]

[1] "Optimal Task-space Tracking with Minimum Manipulator Reconfiguration" by Tong Yang (255613), Jaime Valls Miro (106478), Yue Wang (156231) and Rong Xiong (113216)

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Response to the Editors

Please find our responses to the point raised by the editors below. In the following sections, we answer the individual reviewers' questions in detail (R1 and R2).

I.

The reviewers thought the work was good and interesting, but there were some gaps in the experiments that should be resolved before the final version.

We added more experiments and included further metrics to the analysis of the results as suggested by both reviewers.

Response to Reviewer 1

We thank Reviewer 1 for the careful examination of the manuscript and the helpful feedback and suggestions. Please see our detailed responses below.

I.

One major issue I found with this paper is that the proposed solution does not account for the path taken by the RRT during the switches. This could lead to sub-par performance, affecting the cycle time and the total path length which were the initial motivations for the paper as mentioned in the introduction. I think incorporating the RRT-path in the algorithm is non trivial and could in itself be a research paper.

The reviewer is correct in his observation that the actual RRT planner adopted during the switches is not specifically accounted for in the algorithm. This would indeed call for a new research paper in itself, and we thank the Reviewer for the pointer that we leave for future work. Yet this being the case for any of the reconfigurations motions adopted by any of the planners, optimal or sampled, it is felt the comparison and advantage of the proposed scheme with respect to minimal reconfigurations remain validated.

II.

For this submission, it would be good to run some experiments in highly constrained environments to see if the total path length (joint-space) is different across many optimal solutions produced by the proposed method. Specifically reporting the path length during the task-space tracking and rrt-path for switching separately will be very insightful.

(This query is also somewhat related to R2.I and R2.II, albeit not specifically for the optimal solutions as hinted by Reviewer I. The Reviewer is referred to the answer thereby provided also).

We have added a new simulated comparison (case 4) with more clutter in the environment. We have added and reported on new metrics as suggested by the Reviewer, where the length traversed for all testings cases is considered, including separately reporting on the final relative lengths of the EE with respect to the desired task-space tracking paths, thus accounting for EE deviations during reconfigurations (with the RRT implementation adopted). This is extended not only to the optimal solutions, but also to all the comparative cases. The metric is reported both in task- and joint-space lengths for completeness. It is seen how when it comes to the number of reconfigurations, the proposed scheme solves for the optimal solution, yet total lengths do not necessarily remain shorter in those cases, as was not regarded in the optimisation factor. They often do though. This is now even more apparent when looking at the numbers reported in the table and the added discussions to Section V.B.

We are showing in a new table (II) two sampling-based resulting motions for each comparative case (random 1-8). Moreover, as pointed by the Reviewer, there may be more than one optimal solution when it comes to the number of reconfigurations, and have added that as well to the table. Not all solutions are shown for brevity: two optimal solutions are shown for cases 2 and 4, where more than one solution exists (case 1 and case 3 have a singular optimal solution). The number of optimal solutions has also been incorporated into the table for added clarity. All these results are compiled in the new, much expanded Table II (Table I in our initial submission).

It is noteworthy (stated in the manuscript) that we adopted a constant joint-space velocity model, so that the comparison between execution time is equivalent to the comparison between joint-space travelling distance.

III.

> *Additionally reporting time taken on the real robot will help show the improvement with the proposed method.*

The execution times of the real-world robot had been shown in the supplemented video in our initial submission, but have now also been added to the revised paper as advised (Section V.B). Moreover, we have also added the metric to all the simulation cases in Table II.

IV.

> *The paper mentions a supplementary video which was not submitted.*

There was a mistake in the embedded http reference in the latex code, our apologies for the oversight. While the video http address stated was correct and could be copied and pasted to visualise the video, the embedded link was not. This has now been fixed. The video in our initial submission can still be found at:

`https://github.com/ZJUTongYang/min_reconfig_taskspace_tracking_video`

The video has been further edited to add enhancements as suggested by the reviewers with additional experimental examples and modifications to the actual visualisations to add clarity in some of the simulations (See R1.VI reviewer comment below). The improved version, directly hyperreferenced in the manuscript, can be found at:

`https://youtu.be/HHqGBk9_3x8`

V.

Having a table for different variables used will be helpful.

We have incorporated Table I listing the notation for the most repeatedly-used variables.

VI.

In Fig.5 and 6, the grey trajectory (rrt path) could be shown with a dotted line to improve visual clarity.

We have shown the reconfiguration motions as dotted curves, and also further reduced the width of the curves during the reconfiguration phases. We thank the reviewer as it indeed increases the clarity of the visualisation.

Response to Reviewer 2

We thank Reviewer 2 for the careful examination of the manuscript and the helpful feedback and suggestions. Please see our detailed responses below.

I.

The authors develop an algorithm for globally minimizing the number of reconfigurations during pose trajectory following as a way of improving behavior during these unavoidable maneuvers. The authors test on a few cases showing how the optimization process does indeed reduce the number of configurations as opposed to a randomly selection baseline.

The main question I have regarding the approach is whether solving for the minimum number of reconfigurations actually guarantees improvement over the performance metrics cited, i.e., reducing workspace volume requirements, reducing motion times and energy cost. It is true that their approach reduces the number of reconfigurations, but the results also show that the random baseline can produce more reconfigurations with less workspace volume (see Case 2). I also found the execution times for maneuvers of the random baseline to be competitive at times with the optimized solution.

The Reviewer's appreciation is correct in that optimality of the proposed work is prescribed to the minimum number of EE deviations from the pre-defined path, and that indeed does not guarantee optimality with respect to other parameters. The goal seeks to minimise the need to adopt reconfigurations for specific tasks where that discontinuity is notably undesirable, e.g. welding or painting. When extending to other metrics, optimal minimum reconfiguration paths might not translate into shortest or fastest paths (albeit they often do). The fact that the result of case 2 (in our initial submission manuscript and video) showed a solution that exhibits a smaller bounding box and a shorter joint-space travelling distance than the minimum reconfiguration optimal path is testament to the objective of the authors to show the results in full light, whilst the key objective remains to reveal the optimality of the solutions found with respect to arm reconfigurations.

Having said that, we concur with Reviewer 2 - which also follows from a similar comment from Reviewer 1 - that a broader set of metrics and test cases will aid in providing a fuller picture of the capabilities of the proposed planner in terms of motion planning in general. In that regard, and following the advice (also from Reviewer 1), Table II incorporates a more extensive set of metrics that make this manifest, and the extended discussion in Section V.B further reveals the scenarios raised by the Reviewer. All the joint- and task-space path lengths for all motions are reported, as well as execution times, thus extending the analysis of the test cases beyond the pure number of reconfigurations that is core to the manuscript. Besides, the distribution of the number of reconfigurations in all possible greedy solutions is visualised as a bin histogram chart in Table II. It can be seen that for example, in case 2, a solution with 11 pose reconfigurations has the highest probability to be constructed by sampling-based strategies; the proposed algorithm is able to solve for the solutions with 1, the minimum.

II.

To address the above issue, I would recommend evaluating across a much larger number of cases, where the 3D convex hull of motion, execution time, etc., are reported and compared between the proposed solution and the baseline random one.

We have extended the analysis with a more complex case (4), where more clutter has been added to the environment. New metrics have been added, including a bounding box for the resulting motion, execution times, and lengths relative to the desired path to track (please refer to response R1.II). All test cases have been evaluated exhaustively, with the full results gathered in Table II, and extended examples included in the adjoining video. Moreover, we have incorporated two solutions generated by the random sampling-based strategies for each testing case, also visualised in the video for better context and clarity. We have also added values for 2 optimal solutions each for cases 2 and 4, further drawing attention via the example studied to the fact that more than one solution may exist.

III.

There are spelling errors throughout that need to be fixed.

We have fixed all the grammatical omissions we could identify, and believe to be free of any misspellings.