Dr. Kevin Lynch, Professor
Editor-in-Chief
IEEE Transactions on Robotics
Center for Robotics and Biosystems
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November 15, 2021

Dear Prof Kevin Lynch,

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 Transactions on Robotics: 21-0448)[1]. The paper has been modified according to your feedback and the Reviewers' comments. Please find our detailed responses in the following pages. In addition, we have also highlighted the changes in the revised version of our manuscript in blue.

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[2]
Rong Xiong

[1] "An Improved Maximal Continuity Graph Solver for Non-repetitive Manipulator Coverage Path Planning" by Tong Yang (255613), Jaime Valls Miro (106478), Yue Wang (156231) and Rong Xiong (113216)

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Response to the Editors

We would like to thank the editors for the helpful suggestions on the revised manuscript. Please find our responses to the points raised by the editors, below, followed by a summary of changes in our revised manuscript. In the following sections, we answer the individual reviewers' questions in detail (R1, R3 and R3).

I.

> *On the basis of the reviewers' ratings and comments, we regret to inform you that your paper in the present form cannot be published in the Transactions. However, you are encouraged to submit a revised version of your work addressing the reviewers concerns. The revised paper will be handled as a new submission that will be reviewed accordingly while keeping track of the previous review material.*
>
> *The revised manuscript should be formatted so that any changes can be easily identified by the reviewers, by using, e.g., coloured or bold text to indicate revised passages.*

II.

> *This paper is about non-repetitive coverage planning with maximal continuity performed by a non-redundant manipulator. The approach is based on graph colouring, with a reduction in complexity by accounting for certain topological invariants. Though the reviews note certain merit of the paper, particularly with regard to the overall approach, they also call attention to serious issues with the manuscript. Thus, a thorough revision is needed for the paper to have a chance of being a suitable for publication in the Transactions on Robotics. Most importantly, the reviews note that the organization and presentation of the paper can often be difficult to follow, to an extent that the technical content is challenging to understand to evaluate. Thus, the authors are encouraged to:*
>
> *(a) Ensure that the manuscript is self-contained, particularly in the sense of being intelligible for readers that have not read the authors' prior work in reference 23. This will require, among other things, a precise statement of the problem to be solved in terms of its inputs and outputs, and clear and precise definitions of all of the relevant terminology within the main text of this paper.*
>
> *(b) Deeply revise the technical exposition, particularly with an eye toward ensuring that the definitions, lemmas, theorems, and other elements are precise, mathematical statements.*
>
> *(c) Restructure the introduction, to ensure that the motivation for the work is persuasively presented, that contributions of the paper are directly stated, and that the*

structure of the introduction is clearly discernible.

(d) Expand the evaluation to include more complex objects that more clearly demonstrate the effectiveness of the approach.

(e) Update the references to include more recent results on coverage path planning, and to refer to the latest versions of work that has appeared in journals.

In addition, the reviews provide a number of specific suggestions for additional clarification and correction that the authors should address.

We carefully addressed the issues raised by the reviewers regarding details of the proposed algorithms, clarity of presentation and further experimental results. These changes are listed in the summary of changes as well as in our detailed response to the reviewers as follow. Thank you for the feedback and consideration.

Summary of Changes:

- Based on the editorial and reviewers' comments, we have addressed presentation issues to increase clarity (R1, R2, R3).
- We fixed, improved, and where possible simplified notation and language throughout the paper (R1, R2, R3).
- We significantly expanded the experimental section with examples of arbitrary shape objects, and added further comparative metrics (R1, R3).
- We added more explanations in the accompanying video regarding details of the proposed algorithms and the inclusion of additional experiments (R1, R2).
- We decide to opensource our implementations to help the reviewers validate the proposed algorithm.

Response to Reviewer 1

We thank the Reviewer for his/her positive review. Please see our detailed responses below.

I.

> *A paragraph on the original NCPP would be a nice addition to this section.*

Thank you. We have added separate sections, formally defining the problem of optimal non-revisiting coverage path planning problem (in Section 3), and re-stating the existing solution of NCPP (in Section 4).

II.

> *The experimental results are based on the simulation on a hat-like concave hemisphere and a saddle surface. It looks like though from the perspective of segmentation the manipulator motion is not very intuitive. Maybe a more complex object would have been more beneficial to consider in this case, since the hat-like shape for example intuitively could probably be painted with only one colour with circular motion. But if it is not the case, it would be great to elaborate on why those shapes are good test sample examples.*

Thank you. The simulation cases on the hat-like surface and a saddle surface are actually non-trivial. The coverable region of valid configurations (represented by different colours) were calculated pointwise based on the collision-checking module and the manipulability-calculating module, which were highly non-linear. Thus the resulting distribution of colours are not simple as we can easily imagine. The reasons that we choose such examples are:

(a) The cases were neither too complicated (it is computationally affordable using the proposed algorithm) nor too simple (it should be not computationally efficient using previous solutions),

(b) The designing of geometric coverage paths is not our focus, so the mesh surfaces were regularly parameterized so that geometric coverage paths (e.g., the boustrophedon motion) can be easily designed.

We have added a supplementary video that detailedly shows the reasonability of colour distributions and the motion of the manipulator. Also, as suggested by the reviewer, we have added a new test case in this revision.

III.

Throughout this paper the algorithm is referred to as NCPP, but at the beginning it was defined as the original version from paper [1]. Maybe it could be better to use different terms for the proposed approach in this paper?

Thanks for the advice. The problem that is to be solved is exactly the previous non-revisiting coverage path planning (NCPP) problem, so we keep the usage of abbreviation, NCPP. And we have given a new name to the proposed algorithm, "IMCGS".

(Here the reviewer gave a wrong citation [1], so I'm not sure what he was asking, whether removing the "NCPP" or adding a new name to the proposed algorithm.)

IV.

On page 10, when mentioning naïve enumeration proposed in the literature, please put a reference to that work.

Thanks for the advice. The naive enumeration approach was the previous work [23]. This work has been cited and detailedly re-stated (in Section 4) in this revision.

V.

On page 10, please elaborate in short what do you mean by minor abuse of notion in this context.

In this paper, we thought the most straightforward way to illustrate the algorithmic complexity improvement may be calculating the number of enumerations of different algorithms on a same test case. However, this will inevitably show the multiplication of numbers (i.e., Eqn. (11)∼(14) in our initial submission), instead of just the final number in the experiment section, which might be not succinct.

VI.

In the appendix, Lemma 22 is without proof. It will be useful to have reference to the proof if it is available in literature.

Thanks for the advice. Lemma 22 is part of the contributions in previous work [23]. This was not claimed as a contribution of this paper, but had significant effects in the proposed algorithm, so in the revised version we re-stated its proof in Section 4.

VII.

Grammar Issues:

(a) Page 2: posissible solutions − > possible solutions

(b) Page 8: Fig 13 is referencing to Fig 14 that comes after, possibly change the order.

(c) Page 10: results for the others − > results for the other

(d) Page 11 : Earlier work has proven that [23] the number − > Earlier work [23] has proven that the number

We have fixed all these grammatical ommisions. Also others picked by other reviewers. We thank the Reviewer for the time and detailed consideration.

Response to Reviewer 2

We thank the Reviewer for the careful examination of our response and the revised paper, and the helpful feedback and suggestions. Please see our detailed responses below.

I.

> *The manuscript is not self-contained in its current form. The paper cannot be understood fully without reading reference [23] which is authors previous work on the problem. The authors don't even include an explicit problem formulation in the paper. Important building blocks for the problem have been pushed to the appendix and should be included within the main text.*

Thanks for the advice. We have explicitly incorporated the problem statement and a detailed explanation of the existing solution in the main text (Section 3 and Section 4).

II.

> *It is hard to follow the flow of ideas in the current draft. The writing can be considerably improved to make it concise and highlight the creation of intersection free regions for cell decomposition and painting. Authors should consider moving most of the proofs to the appendix to avoid disrupting the flow.*

Thanks for the advice. We acknowledge that the most straightforward way to highlight the construction of intersection-free sub-graphs may be shortening the length of its motivation, i.e., Section 2 in our initial submission.

In this revision, we still think that reading the case studies before going into the algorithmic section helps the readers to understand the algorithm idea. Hence we move the explanations of the visual examples to their captions.

III.

> *The paper also has many grammatical errors and long unnecessarily complicated sentences, that make it hard to read and confuses a reader.*

We have fixed all these grammatical ommisions. ~~Also others picked up by Reviewer 1.~~ We thank the Reviewer for the time and detailed consideration.

IV.

Can the authors comment on the trade-offs to achieve this computationally efficient NCPP solution with minimal lift-offs. It will be interesting to see how the approach developed in this paper affects the path length as compared to other approaches to NCPP or that of [23]. An ideal solution should not affect the path length since the coverage is non-repetitive.

Thanks for the advice. The proposed algorithm is both globally optimal and complete, i.e., all solutions that collected by previous work [23] are also collected by the proposed algorithm, with an exponential improvement on the algorithmic complexity. Thus, there is no trade-off between the algorithmic efficiency and the quality of solutions. Picking up the same cellular decomposition solution to the given NCPP task generated by both algorithms, the geometric coverage path can be the same, and the path length of manipulator motion will also be the same.

V.

The introduction does not motivate the problem sufficiently. The text starting from "Given the object's surface, the manipulator, the surrounding ..." to "... critical such as painting [4], deburring [5], welding [6], scanning [7], etc" justifies why lifting is undesirable. However, it does not make it clear why non-repetitive coverage is useful in the given context.

Thanks for the advice. Finding a non-repetitive coverage path solution is essential when the object surface to be manipulated is sensitive to over-polishing or over-coverage. For instance, when the coverage task in robotic machining is carried out along a removal process of the surface material, then covering a part of the region for multiple times may over-removing the surface material, which influences the performance of the coverage task. We have added a separated paragraph that detailedly surveys the related applications in the introduction.

VI.

The last few paragraphs of Section I should preferably be moved to a different section on problem formulation and the problem construction must be explicitly defined. Without a problem formulation and motivation for the problem, the paper is difficult to understand.

Thanks for the advice. As also required by other reviewers, we have moved the surveying of related works, problem statement, and explanation of existing algorithms into different sections.

VII.

Additionally, the authors should also add a list of contributions to the paper.

Thanks for the advice. We have listed the contribution of this paper in introduction in this revision. Besides, we additionally decided to opensource our C++ implementation to the proposed algorithm, which might be inspirational to the community.

VIII.

Last paragraph, page 2: The authors motivate and justify their solution strategy as a betterment of the cell-division and enumeration strategy that developed in [23]. What is that cell division? Authors use that cell division in figure 2 and it is not apparent to a reader without reading [23], what exactly is happening in figure 2.

Thanks for the advice. We have explicitly re-stated the basic idea in [23] in Section 4 in this revision.

IX.

It is not clear from the text if lemma 22 is a contribution of this paper. If it is , then the authors must give a proof. If not, then the authors must make it apparent in the text in the appendix. In the current form it is not clear. Also, the text of the lemma is grammatically incorrect as pointed above.

Thanks for the advice. Lemma 22 is a part of the contributions in previous work [23]. This was not claimed as a contribution of this paper, but had significant effects in the proposed algorithm, so in the revised version we re-stated its proof in Section 4.

Response to Reviewer 3

We thank the Reviewer for the careful examination of our response and the revised paper, and the helpful feedback and suggestions. Please see our detailed responses below.

I.

> *Introduction is too long and confusing. It is suggested to create multiple subsections in the introduction: Motivation, Challenges, Relevant Work, Proposed Method, Contributions, Paper Organization.*

Thanks for the advice. We have splitted the introduction into multiple sections: related works in Section 2, problem statement in Section 3, and detailed restatement and calculation of the existing solution in Section 4.

II.

> *The paper cites very old papers for CPP. Many new papers are missing.*
>
> *I wonder why so many conference papers are cited while their journal versions exist.*

Thanks for the advice. We have added more recent references, and checked all the conference papers. One conference paper ([19] in our initial submission) is now switched to its journal version ([22] in this revision).

III.

> *Issues on mathematical statements:*
>
> *(a) Section 2: Please define topological invariant variable in your problem context. "A topological invariant variable ... altogether" is vague and high level. Please given precise definitions as needed.*
>
> *(b) Definition 1: What class of distribution? Moreover the definition itself is confusing.*
>
> *(c) Proposition 2: What graph? What cell? Homotopic cutting paths? Please define them before using them.*
>
> *(d) Lemma 4: This does not sound like a mathematical statement. More like a fact.*
>
> *(e) Corollary 5: This does not sound like a mathematical statement. Also, the proof is long and unclear.*
>
> *(f) Lemma 6: what 0 and 1? I know they are discussed before but never defined. Also, what do you mean by "not countable"? Do you mean uncountable infinite? That is not true.*

(g) Corollary 7: This does not sound like a mathematical statement.

(h) Definition 9: What is "boundary of the graph"?

(i) Theorem 11: This does not sound like a mathematical statement with a mathematical proof.

In our initial submission, we aimed to intuitively introduce the difficulties in solving a topological graph by the mutual interruption of colours in Section 2, and then propose the algorithm in Section 3. However, it seems that the intuitive analysis brought unnecessary vagueness. Hence, we have switched the definitions of "intersection" from a global topological invariant to a property of a sub-graph, which we believe have made the paper easier to follow and comprehend.

Concretely,

(a) We have removed the terminology "topological invariant variable" to avoid vagueness.

(b) We have re-defined the definition "intersection" in Definition 10.

(c) We have provided all preliminarial definitions in Section 4.

(d) Lemma 4 is indeed a fact, while we still think it is noteworthy. So we have moved Lemma 4 to pure text.

(e) We have removed the claims in Corollary 5, while the case studies in its proof has been preserved for comprehensive understanding of the solving process of a graph with intersections.

(f) We have removed the analysis about a possible graph solver that can explicitly decrease the number of intersections in a graph. This did not directly contribute to the proposed graph solver.

(g) Same as above, we have removed Corollary 7 for clarity.

(h) We have formally defined the "sub-graph" in Definition 9, as a part of the region on the task-space surface, so the boundary of a sub-graph is now well-defined.

(i) In this revision, we have re-defined the "intersection" as the property of multiplicity of optimal cellular decompositions in a sub-graph, the claim in Theorem 11 (in our initial submission, 14 in the revision) should now be a precise statement.

IV.

I didn't see any section with the title "Proposed Method".

Thanks for the advice. We have re-named the algorithm section from "Graph Separation" to "Proposed Algorithm: Graph Pre-separation" to make it apparent .

V.

The experimental results doesn't show any performance measures such as total time? Only number of iterations are shown.

Thanks for the advice. We have shown the computational time of the case studies in Table 1 in Section V. In addition, another case study has been provided for further validation of the proposed algorithm. Besides, an opensource implementation has been provided.