Ottawa, October 27th, 2020

Mohammad Ayoubi, PhD
Associate Editor
Journal of Spacecraft and Rockets

Dear Associate Editor,

On behalf of Mr. Justin Kernot and myself, I would like to thank you and the reviewers for the time you have dedicated to review our paper. All comments were welcomed and have helped to significantly improve the quality of our manuscript. In the following, we provide detailed responses to each of the reviewers' comments.

We sincerely hope this version of our manuscript meets the high standards of the *Journal of Spacecraft and Rockets*.

The revised version of the manuscript titled "Adaptive Control of a Tendon-Driven Manipulator for Capturing Non-Cooperative Space Targets," and has been submitted via ScholarOne as a revision with manuscript ID 2020-06-A34881.R1.

Best regards,

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Reviewer 1

The paper studies a robotic mechanism for non-cooperative capture and active servicing mission, where the authors apply two adaptive control strategies (indirect adaptive control, and L1 adaptive control) to handle uncertainties. The simulation compares the performance of the two adaptive controllers with that of PID. The paper well formulates the problem of interest as an adaptive control problem, but there are several comments to be addressed.

The L1 literature review and cooperative control literature review are not up to date.

The following was added to the literature review in reference to the cooperative spacecraft capture portion of the introduction:

Medina, A., Tomassini, A., Suatoni, M., Avilés, M., Solway, N., Coxhill, I., Paraskevas, I. S., Rekleitis, G., Papadopoulos, E.,Krenn, R., et al., "Towards a standardized grasping and refuelling on-orbit servicing for geo spacecraft," Acta Astronautica, Vol. 134, 2017, pp. 1–10. doi:10.1016/j.actaastro.2017.01.022

Virgili-Llop, J., Drew, J. V., Zappulla II, R., and Romano, M., "Laboratory experiments of resident space object capture by a spacecraft–manipulator system," *Aerospace Science and Technology*, Vol. 71, 2017, pp. 530–545. doi:10.1016/j.ast.2017.09.043

Benavides, J. V., and Bualat, M. G., "SPHERES: Synchronized, Position, Hold, Engage, Reorient, Experimental Satellites," 2018. URL https://ntrs.nasa.gov/citations/20180007934.

With regards to including more works on L1 control, the following has been added to the literature review:

Yousef, H. A., Hamdy, M., and Nashed, K., "L1 Adaptive fuzzy controller for a class of nonlinear systems with unknown backlash-like hysteresis," *International Journal of Systems Science*, Vol. 48, No. 12, 2017, pp. 2522–2533. doi:10.1080/00207721.2017.1324065

The way the literature review is written shows the development of various control strategies applied specifically to CSTMs and systems with hysteresis throughout time, eventually guiding the reader to the selection of L1 for our gripper. Since most of the recent work on L1 control has been towards other unrelated systems/applications, the authors have opted to include these references to the beginning of Section III as "other L1 literature" since they fall outside the scope of the literature review presented in Section I. The References added include:

Dodenhöft, J., Choe, R., Ackerman, K., Holzapfel, F., and Hovakimyan, N., "Design and Evaluation of an L1 Adaptive Controller for NASA's Transport Class Model," *AIAA Guidance, Navigation, and Control Conference*, 2017. doi:10.2514/6.2017-1250

Jafarnejadsani, H., Lee, H., and Hovakimyan, N., "L1 adaptive sampled-data control for uncertain multi-input multi-output systems," *Automatica*, Vol. 103, 2019, pp. 346–353.
doi:10.1016/j.automatica.2019.01.007

Nayyeri, P., Mohammadi, A., and Zakerzadeh, M. R., "Optimal-tuned Parameters for L1Adaptive Control," *7th IEEE International Conference on Robotics and Mechatronics*, 2019, pp. 13–16.
doi:10.1109/ICRoM48714.2019.9071843

In section 3, \bar{u}_1 and \bar{u}_2 are independently controlled, albeit u_1 in (12) and u_2 in (13) are dependent on each other. For example, \bar{u}_2 in (21) may have a unique solution given by (20), (23), (24), and (25), which will subsequently uniquely define u_1, making it impossible to control independently. This point needs clarification.

The indirect adaptive controller presented in Section III was originally developed by Do et al. (https://doi.org/10.1109/TASE.2015.2438319). As it is shown in the original work, the assumption made by the reviewer "*making it impossible to control independently"* is incorrect, since u_1 and u_2 are not dependent upon one another. The statement "Note that Eq. (12) and Eq. (13) do not depend on one another." was added to Section III

In section 4, the authors should show how to transform the system (1) to the system (26) and (27). The relationship between the states/parameters in (1) with those in (26), (27) is unclear.

The LTI model in (26) and (27) used for CMAC is not obtained through the linearization of the nonlinear hysteresis model presented in (1). The decoupling process shown in Sec. IV-A demonstrates how to generalize a system with hysteresis to into the expected LTI form of (26) and (27). The non-linear kinematic model in (1) was solely used by Do et al. to develop the indirect adaptive controller presented in (22), which is described in Sec II-B.

In the simulation of the L1 adaptive controller, the adaptation gain for L1 is too low. Because of the advantage of L1 (decoupled fast adaptation and robustness), the gain is usually chosen very high.

The reviewer is right; the adaptation gain is indeed typically selected relatively high. However, due to the large time scale of the experiment, the adaptation gain was intentionally set low to see the transient phase of the controller adaptation more clearly. This clarification was added to the paper.

Also, the paper did not give any information about the low pass filter, which is an important part of the L1 control design.

Good point. Details about the filter were added to the paper. Specifically, the low pass filter used in experiment was $D(s)=1/s$, as it is commonly used in practice and is shown to provide a simple, yet effective, solution for these first-order experiments.

Equation (11) is wrong.

Eq. (11) is correct, as shown by Do et al. (https://doi.org/10.1109/TASE.2015.2438319) in Eq. (9) of their paper. To further this point, let us examine the following proof:

As a reference, the Eq. (11) stated incorrect by Reviewer 1 is below

$$u = u_1 + u_2 \tag*{Eq. (11)}$$

The following equations are the definitions of variables u_1 and u_2

$$u_1 \triangleq \frac{ue^{2\dot{u}}}{e^{2\dot{u}} + 1} \tag*{Eq. (12)}$$

$$u_2 \triangleq \frac{u}{e^{2\dot{u}} + 1} \tag*{Eq. (13)}$$

Substituting Eqs. (12) and (13) into Eq. (11) gives

$$u = \frac{ue^{2\dot{u}}}{e^{2\dot{u}} + 1} + \frac{u}{e^{2\dot{u}} + 1}$$

$$u = \frac{ue^{2\dot{u}} + u}{e^{2\dot{u}} + 1}$$

$$u = u\frac{e^{2\dot{u}} + 1}{e^{2\dot{u}} + 1}$$

$$\therefore u = u$$

Equation (12) has a problem with the position of the dot.

Good point. We modified the position of the dot to the correct position in Eq. (12).

There are question marks in line 44 on page 21.

Sorry. The broken reference within LaTeX has been addressed.

Since the simulation plots are similar to each other, it would be better to put them in the same plot to compare the performance easily.

While combining plots on the graph is often beneficial, the authors have nevertheless opted not to combine the experimental results to a single plot for the following reasons:

1. There are 3-sigma error bars on each plot the reader would be unable to distinguish them if the results were overlaid.

2. It would be difficult to read for a reader without colour print since the data is noisy, so “dashes” and “dots” etc. would look too similar in an overlay plot

Theorem 2 may also mention the guaranteed transient performance of the L1 adaptive controller. This will help the authors to justify why L1 performs fine in the simulation.

Good point. Theorem 2 has therefore been updated to include the guaranteed transient performance of the L1 adaptive controller.

Reviewer 2

The paper is very interesting and providing complete description of the tendon driven manipulator dedicated to capturing maneuver. In my opinion it is very valuable that besides the theoretical works the extensive testing campaign was executed to proof controller algorithm operation. Nevertheless there is few minor points which I suggest to clarify prior publication.

I suggest to add reference to other grippers developed in ESA programs – at least two of them (developed by OHB and Piap-Space) were described in ASTRA conference:

Jaworski et al, Grippers for Launch Adapter Rings of Non-Cooperative Satellites Capture for Active Debris Removal, Space Tug and Onorbit Satellite Servicing Applications, , Proceedings of 14th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2017), 2017

Oles et al., Testing and simulation of contact during on-orbit operations, Proceedings of 14th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2017), 2017

Thank you for the suggestions. These papers have been added to the literature review in the introduction.

In my opinion there is inconsistency between title, fig. 1 and fig 7. The title cover information about tendon driven manipulator (which suggest that all joints in manipulator are tendon driven). On figure 1 only manipulator gripper (or end effector EE) is presented with tendon joints – which might suggest that rest of joints in manipulator are standard one. On figure 7 the free floating base together with arm and gripper is presented. However there is no clear information if all joints (on gripper and on manipulator) are tendon driven.

Only the gripper is equipped with a CSTM; the arm uses standard servomotors to drive the links. Since the focus of this work is on the gripper, several modifications have been made to clarify this terminology issue:

1. Objective 3 in the second last paragraph of the Introduction changed the word “manipulator” to “gripper”

2. First sentence of Section V-A-1, the word “manipulator” has been changed to “gripper”

3. In the same sentence as above, changed “the capture mechanism must interface with the wrist joint of the 3-link manipulator” to “the capture mechanism must interface with the wrist joint of the **servo-driven** 3-link manipulator” (boldface is not included in main document).

In context of previous point, if the CSTM are used only in EE I suggest to clarify the benefit of using free floating platform instead of using fixed base manipulator. Especially having in mind that in the testing scenario the gripper not enter into contact with target S/C.

> The statement "*The purpose for developing the capture mechanism to function on the SPOT platform is to enable the capability of future experiments in a free-floating environment*" has been added to the second last paragraph of the Introduction. Additionally, the statement "*Since this paper is isolating the performance of the controllers, the initial experiments were performed while the SPOT platform was inertially fixed*" was added to Section V. to highlight the justification for implementing it onto a free-floating platform, despite the initial experiments being fixed-base.

I would suggest to clarify that proposed case studies (page 23, Table 2) are relevant for capturing non cooperative space target (which was promised in the title).

> The statement "*Note that the joint angles selected for these manoeuvres reflect a corner capture of a non-cooperative rectangular free-floating target, which is a proposed future experiment with the SPOT platforms*." Has been added to the first paragraph of Section V-B-1.

I suggest to add on figure 1 information where the xin and xout is defined (or can be measured). This should allow reader to easily understand the kinematic model provided in eq. 1

> The labels "x_in" and "x_out" have been added to Fig. 1.

Could you clarify which of provided parameters in simulated example (fig. 1) describe the stiffness of torsional spring.

> The simulated example is a pure simulation of the CSTM output position in response to a sinusoidal input signal to showcase that indeed, the model characterizes hysteresis. The model itself does not depend on the presence of springs. However, it does assume that the cable remains in tension (i.e. does not slacken). This was mentioned in the second paragraph of Section III. That being said, to address the Reviewer's comment, the statement "*Note that the model presented by Eq. 1 to Eq. 3 assumes that the cable remains in tension at all times (i.e. it does not slacken).*" has been added to Section II-B

On page 22 there is incorrect reference to figure on line 44.

> Sorry. The broken reference within LaTeX has been addressed.