Authors' response to reports on submission for Paper Ms. No. auto-2024-0166

Lea Bold, Lukas Lanza, Karl Worthmann

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We thank the AE and the reviewers for their careful reading of our manuscript and their helpful comments. Please find below a detailed response to the AE's and the reviewers' comments. Based on the comments provided by the Editor and the reviewers, we have thoroughly revised our manuscript to meet the high standards of at - Automatisierungstechnik publications. Changes in the revised version of the manuscript are highlighted in blue color.

Reviewer 2

The articles under review presents a two-component control architecture to enable safe data-driven control of nonlinear systems. The first component is a model-free funnel controller that ensures safe operation by enforcing potentially time-varying output constraints, the second component a learning-based predictive controller for stabilization and tracking. Moreover, the articles proposes a scheme for safe date collection using funnel control based on recent results on the approximation error of the Koopman operator for nonlinear systems (which, however, is not applied in the numerical example of Section 5). This results in a control scheme that can stabilize and track a desired reference with limited a priori model knowledge while maintaining constraints on the plant output.

Overall, the article is well written and easy to follow. Its theoretical contribution is minor but it is presenting an interesting and novel combination of recent results on Koopman operator theory and funnel control to provide a controller architecture for safe data-driven control. There are no major issues with the article content or its presentation, but the following minor aspects should be addressed.

We thank the reviewer for the careful reading and positive assessment of our paper. In the following we answer the comments and questions raised by the reviewer.

The activation function α contains two parameters, both of which are insufficiently discussed. On the one hand, there is the activation threshold λ whose influence is visualized in Fig. 1b), and on the other the dwell-time τ. In both cases, it would be nice to discuss the effect of choosing any specific value, e.g. on Theorem 1 (if any) or the numerical simulations of Section 5. So far, the article does not offer guidance in tuning these parameters.

We thank the reviewer for the comment and have taken the opportunity to add clarifying words in Section 3 after equation (6).

While the article discusses output constraint satisfaction in detail, the input constraints enforced by the predictive component are only mentioned in passing. It would be interesting to discuss whether asymptotic input constraint satisfaction as shown in Section 5.2 is guaranteed even though the constraint can be violated temporarily due to the funnel controller.

We thank the reviewer for this comment which addresses a very interesting point in current research. While there exists a natural conflict between arbitrary input constraints and arbitrary output constraints (funnel control), the question of satisfying input constraints asymptotically if only the learned model for EDMD-based MPC is sufficiently good will be topic of future research.

> *The least-squares problem of EDMD above (8) is not properly stated. I would appreciate to state the formal minimization problem once there, especially since it is matrix-valued. Furthermore, I would check the involved matrix norm, since I believe that the provided normal equation solution minimizes the Frobenius norm.*

We thank the reviewer for the careful reading. We have corrected it.

> *The second paragraph of Section 2.2 contains multiple forward references to concepts to be defined in Section 3, which is hurting its readability.*

We thank the reviewer for the comment. We have revised this section to ease the natural conflict between precise definitions and a brief explanation of the overall concept.

> *Finally, a few typos: Section 3, last paragraph: guarante'es' Definition 1: duplicated i=1 (?) Section 5, first paragraph: constrain't'*

Again, we thank the reviewer for the careful reading which helps us a lot to improve the quality of the manuscript.

Reviewer 3

> *The paper provides a tutorial on a two-component controller design approach for data-driven predictive control. The two-component controller combines a funnel controller and a data-driven predictive controller (here, Koopman-based MPC via EDMD). The funnel controller serves as a safeguard, enabling both safe exploration to gather data for the data-driven predictive controller as well as guaranteeing a certain prescribed tracking performance when the data-driven predictive controller falls short. Overall, the paper is well-written, clearly outlines its objectives, and may serve as a good tutorial introduction to integrating funnel control with Koopman-based MPC. I recommend accepting the paper.*

We would like to thank the reviewer for taking the time to read our manuscript carefully and evaluate it positively. Please find below our detailed reply.

> *However, my main critique, detailed below, is that the paper's focus is somewhat unclear: Is it intended as a general tutorial on safeguarding arbitrary data-driven predictive control schemes, or as a work advancing results specific to Koopman-based MPC?*

We thank the reviewer for this comment. Based on this, we have revised our manuscript thoroughly. To emphasize the tutorial character of the paper, we have included a second learning scheme, namely Data-enabled predictive control (DeePC) based on the fundamental lemma by Willems and coauthors. To further specify a roadmap for future research, we have restructured Section 4 and included recent results on approximation results in Koopman theory.

> *Main Comment: The paper emphasizes that Koopman-based MPC via EDMD is used merely as an example, and its main aim is to introduce the concept of safeguarding generic data-driven predictive control schemes through funnel control. Yet, the theory underlying Koopman-based MPC is discussed in considerable depth—perhaps too much for a tutorial intended to highlight it as an example. Conversely, one of the two stated goals—"achieving a prescribed fill distance"—is very specific to Koopman-based MPC, necessitating this depth of discussion but somewhat misaligning with the paper's intended generality. Personally, I find*

the concept of using funnel control to ensure exploration with a predefined fill distance to be the paper's most intriguing contribution. However, this idea, while noted as a key contribution, is only briefly sketched in Section 4.2, which concludes quite abruptly.

Based on the reviewer's comment we have thoroughly revised the manuscript; in particular, Section 4. On the one hand, we have added another learning-based control scheme to maintain the tutorial character of the note. On the other hand, the revised version now contains a clearer presentation of the idea of "predefined fill distance", see Section 4.2.3

Furthermore, this idea seems to be absent from the numerical experiments, which instead use an alternation between mu(t)=1 and mu(t)=0 for exploration. Moreover, the second stated goal—"Learning-based predictive control without offline training"—is not demonstrated in the numerical section either. Both experiments begin with d=10 data samples, which appears unnecessary for the presented scheme and undermines this goal. Therefore, my main recommendations are as follows: Sharpen the paper's focus, either emphasizing its general tutorial purpose or centering on the specific application of Koopman-based MPC and exploration for a predefined fill distance. Provide demonstrations of both stated goals in the numerical section. (Or clarify why d=10 data samples are needed initially).

In the revised version we provide a simulation where we start with 1 data point (to avoid issues concerning the initialization of the algorithm, we use 1 data point). Since the technical details of "prescribed fill distance" are topic of near future research, we cannot provide numerical results on that yet.

Minor Comments

- *"the recent survey [42]" -¿ I'm not familiar with [42], but from a quick glance, it does not seem like a survey. Perhaps the authors intended to cite a different reference?*
- *"the underlying reproducible kernel Hilbert space (RKHS)" -¿ "reproducing"?*
- *"This paper is organized as follows.Section 2.1 [. . .]" -¿ Missing space.*
- *"there we describe the combination of any [. . .]" -¿ Consider adding a comma after the leading word for clarity. This issue appears multiple times; I recommend using a grammar tool to ensure proper punctuation throughout.*
- *"which enhance the performance of a safety-ensuring controller" -¿ "enhances"*
- *"We assume that the system has the following form, which represents many mechanical systems" -¿ Would be nice to give some examples/references.*
- *"W.l.o.g. we assume positive definiteness" -¿ For a tutorial, an intuitive explanation of why this holds w.l.o.g. would be helpful.*
- *In Remark 1, the notation "$y|_{[-\sigma,0]}$" is used without prior introduction.*
- *"To safe notation, we use alpha tau(t,e2) in the following." -¿ Likely "save"? Even then, the phrasing is a little strange.*
- *The concept of fill distance is mentioned very early but defined only on page 7. It would be nice to include the definition earlier or reference Definition 1 when fill distance is first mentioned.*
- *"starting the control task with a small prediction horizon and depending on the amount of data, the prediction horizon" -¿ Is this even relevant for EDMD? EDMD estimates a one-step prediction model used for (potentially arbitrarily long) multi-step predictions. This seems more applicable to methods like DeePC, which require more data for longer prediction horizons.*

We thank the reviewer for the careful reading of our manuscript. Based on the valuable comments we have revised the manuscript and have added several passages addressing your questions and remarks.