Reference Number JSCE1691

Dear Helen:

On behalf of my colleagues I would like to thank you and the reviewers for the time they devoted to reading the manuscript and pointing out issues that needed clarification.

In response to your and their comments we have introduced the following modifications:

1. The introduction has been modified to specify the scope of the work more precisely.
2. A new short subsection "II.C. Multicriteria Optimization Framework" has been added to justify the choice of the optimization method and to present a high level overview of the optimization framework.
3. A new result addressing the robustness properties of the optimal control system design has been included in Section IV.B.
4. All references along the text have been revised to represent the latest developments in the field.
5. Most of the figures have been significantly modified to improve the clarity. Furthermore, three new figures have been added to support the discussion in Subsection II.C. (one figure) and the new results of Section IV.B (two figures).

In what follows we attach our response to each of the reviewers. Thank you for your consideration of our work.

Sincerely,
Vladimir Dobrokhodov

1. Response to the first reviewer

1. *The authors should give the control schemes and MatLab design diagrams in "IV. Solutions and Analysis".*

RE: The diagram in Figure 2 presents a simplified version of the controller implemented in Simulink. It provides sufficient details on the implementation of the longitudinal controller. The paper provides complete references to the previous works, where more details are described in details. We think that including complete implementation details in this paper will hurt the readability of the paper.
In response to the reviewer’s request, we included a separate section “II.C. Multicriteria Optimization Framework” in the revised paper, where we justify the choice of the optimization method and present a high level architecture that illustrates the interaction between the AirSTAR simulation environment, L1 adaptive controller and the PSI method. A short overview accompanies the diagram as follows:

> The architecture of the developed optimization framework is presented in Figure 4. The framework integrates the GTM model and the L1 adaptive controller (both implemented in Simulink), the criteria calculating scripts (implemented in MatLab), and the PSI method (implemented by the MOVI software). This setup allows integrating the capabilities of a high-fidelity simulation environment with the vast set of features of the MOVI package.

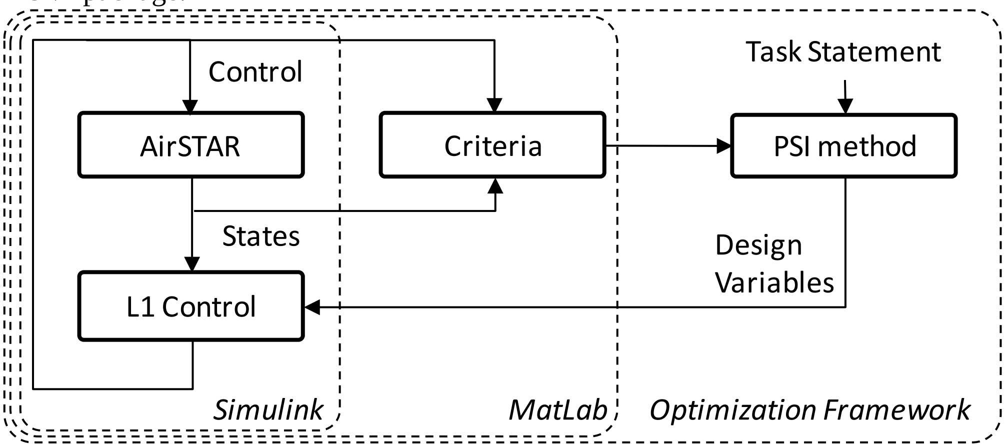

Figure 1. Optimization framework

2. *In 21 papers of "Bibliography", there are 7 papers written by the authors of Dr. Hovakimyan and Dr. Cao even though they have been focusing on the development and the application of L1 adaptive control for many years.*

RE: We revised all references of the paper with the objective of keeping only the key publications relevant to the points of discussion along the entire text of the paper. As per the references to the works of Professors Hovakimyan and Cao the following considerations are important:
Ref [2] - retained in the revised manuscript - the work provides a general overview of the safety critical control problems in aerospace engineering that specifically call for adaptive control approaches; in essence this work frames the scope of issues in the area.
Ref [4] - retained in the revised manuscript - is the monograph that represents the most comprehensive description of the L1 theory of adaptive control.
Ref [5] - retained in the revised manuscript – while the monograph Ref.[4] discusses the issues associated with the choice of the controller design, the work in Ref.[5] provides an

approach to solving the problems associated with non-convex optimization in a multidimensional design space. Thus, Reference [5] not only acknowledges an existing work in the field but also builds a motivated transition to the employment of the PSI method, where the same design optimization problem is solved in multicriteria space.
Ref [15] – updated to the most recent work - presents the L1 control architecture that was implemented on the GTM aircraft and provides the theoretical guarantees for its performance.
Ref [16-17,21] – deleted and substituted by single most recent publication [1] containing the most up to date material.

2. Response to the third reviewer

1. *This paper addresses an important aspect of adaptive control using L1 criterion and applies the results to a real world problem at NASA.*

RE: N/A

3. Response to the forth reviewer

1. *This paper mainly focused on the application of the Parameter Space Investigation method for the multi-criteria design optimization of the L1 adaptive flight control system implemented on the two turbine powered dynamically-scaled GTM AirSTAR aircraft, experimental results are also given.*

   I believe the contents are not new, the innovative contents are not highlighted. The authors failed to compare the presented method with other current methods, and the feasibility and effectiveness, especially the advantages of the presented approach are not verified.

RE:
The Introduction section is modified to address the criticism by explicitly formulating the work objectives:

> The paper also illustrates the suitability of the PSI method (and the MOVI software package) as a tool for formulating and solving multicriteria optimization problems for design of adaptive flight control systems. The work reported here is not intended to compare the benefits and drawbacks of various optimization methods; instead it illustrates the complexity of multicriteria analysis and suggests a viable approach to the design of control systems for safety-critical control applications. An explicit comparison of various multicriteria analysis methods can be found in [7], which provides an essential overview of modern approaches to multicriteria decision making.

Benefits of the PSI method are further presented in Introduction by adding the following details:

> This method explicitly addresses the issues associated with high dimensionality of the criteria and the functional constraint spaces. It takes into account the complexity and the computational expenses of sampling the design space of high dimensionality by employing the quasi-random sampling (LP-tau sequences, see [6], [7]), which yield converging results by a factor of 4-8 smaller sample sizes compared to the other methods.
>
> The availability of an initial feasible solution may narrow the design variable space over which the search for feasible solutions should be performed. Furthermore, considering the benefits of sampling the multidimensional design variables space by the LP-tau quasi-random sequences, the number of trials required for the construction of the feasible set may be significantly reduced.

A new section "II.C. Multicriteria Optimization Framework." is included to justify the choice of the optimization method and to present a high level overview of the optimization framework. Please see the presentation in the manuscript.

To further support the claim of innovative results, sensitivity analysis of the optimal design was added to section IV.B. The result addresses the problem of robustness of the final design.

> As the last step, we verify the robustness of design #202 to small variations of the design variables by performing a sensitivity analysis. This analysis calculates a criterion response in the direction defined by a design variable in the neighborhood of the optimal solution (in our case, design #202). As an example of this sensitivity analysis, Figure 10 shows the dependence of criterion FQ1 and desired-model tracking performance P2 on the design variables DV1 and DV3 respectively; each figure represents the case where only one design variable is varied while the remaining design variables are kept fixed at the optimal value defined by design #202. Compact distribution of the Pareto solutions and smoothness of the criteria confirm the robustness of design #202.

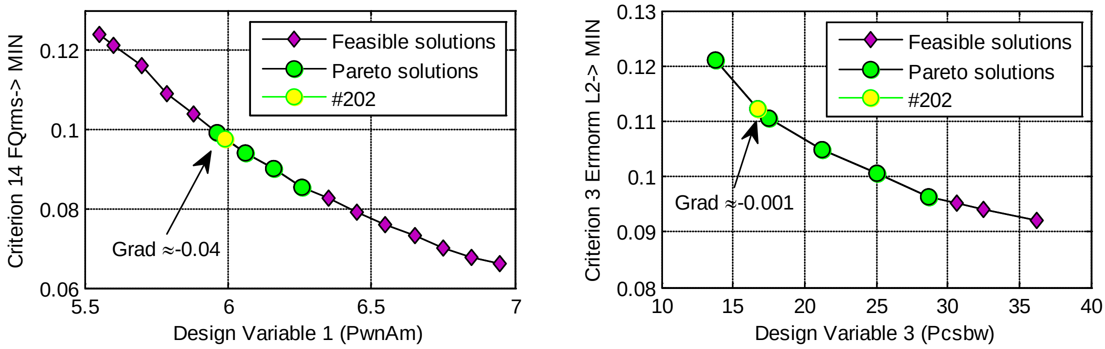

Figure 10. Sensitivity plots.

4. Response to the fifth reviewer

1. *My largest concern is that the response of the prototype (shown page 8) and case #202 (page 25) to a 3deg change in AoA for 4 seconds appears to be divergent if held longer than 4 sec. This might be due to changes in flight condition of an increase in climb angle. Would this occur on a linearization of the system? Include an analysis of what is happening and why we should not be concerned.*

RE: The solution is not divergent; the deviation with respect to the desired constant response is due to the phugoid mode [2], which is stable and under-damped, and appears as unmatched dynamics in the short-period dynamics. The L1 controller is able to partially compensate for this mode, but not able to completely cancel it. The same behavior is present in the linearized model of the aircraft that considers airspeed, AoA, pitch rate, and pitch angle as states. It is not present in the simplified linear model of the short-period dynamics (AoA and pitch rate).
This is a standard behavior, which also occurs when using conventional flight control systems based on PID control. This slow oscillation can be easily compensated for by the human pilot or an outer-loop autopilot, so it is of no concern. Below we attach the linearized model and the results illustrating this behavior:

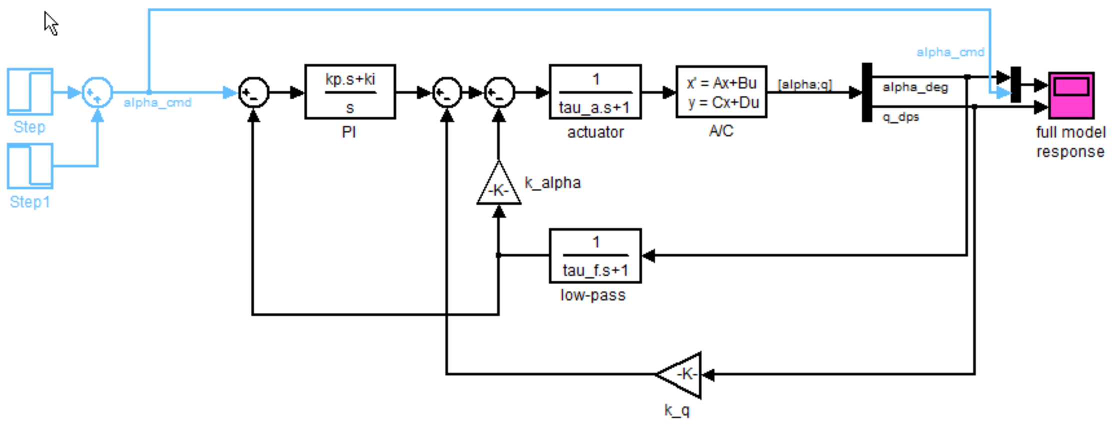

Figure. A linearized model that captures the phugoid mode.

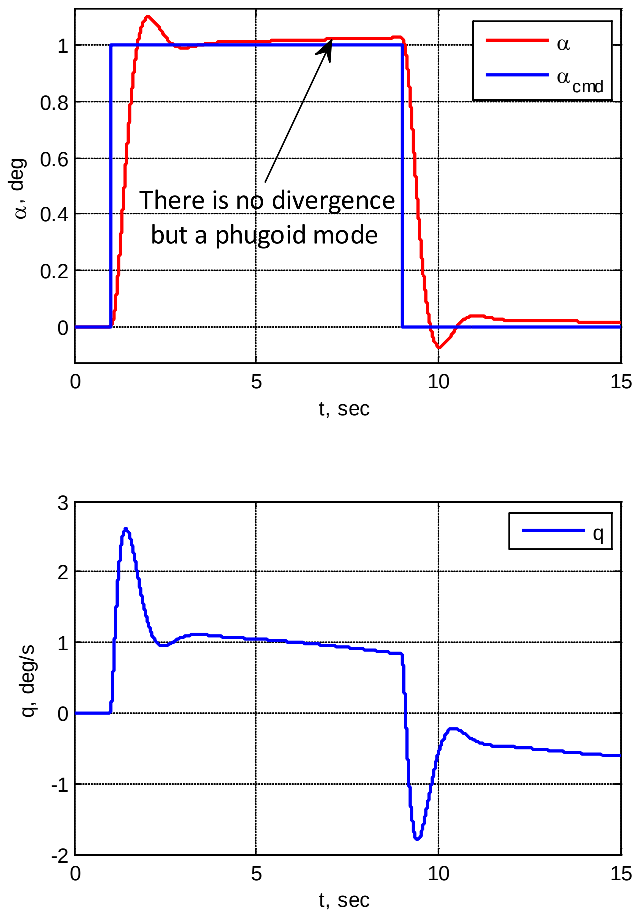

Figure. AOA and pitch rate responses of the linearized model.

To avoid the ambiguity in reading the data in Figure 3 the following comment is added when the nominal AoA response is described first time; see page 8:

> Page 8: This *prototype* design of the state predictor, the low-pass filters, the adaptation sampling rate, and the prefilter, delivers an AOA response similar to the desired one (α_{des}),

see Figure 3. The deviation of the AOA response from the commanded step is due to the phugoid mode of the aircraft, which is stable, oscillatory, and slow. This phugoid deviation appears when designing AOA and pitch-rate CASs, and can be easily compensated for by the pilot (or autopilot in the case of autonomous flight).

2. *On page 6, the longitudinal system is described as SISO, that uses AoA and pitch rate feedback. I understand the single output is intended to be the control variable AoA, but the system has two outputs being used in the control.*

RE: The comment is partially correct. Thorough explanation would require reproducing a significant portion of the control system design that takes into account matched and unmatched uncertainties. Instead, the description of both the longitudinal and lateral control systems is modified and an interested reader is referred to the theoretical material in references [15],[16]. The paper is modified accordingly:

> The implemented longitudinal L1 controller utilizes feedback in AOA and pitch rate to generate an elevator control signal in order to track AOA reference signals. The lateral/directional L1 controller uses feedback in AOSS, roll rate, and yaw rate to generate aileron and rudder commands in order to track sideslip-angle and roll-rate reference signals with reduced coupling.

3. *For P12 (page 13), it is unclear if the max includes the entire equation of just the delta e term. Although in P13 it is expressed more clearly that it should include the entire equation.*

RE: The equation defining the maximum deviation in cross-coupling dynamics is revised and presented in the following form:

$$P12 = \max_{t \in [t_0, t_f]} \left[\left| \delta_e(t) \right| ((\beta(t) - \beta_{des}(t))^2 + (p(t) - p_{des}(t))^2) \right]$$

4. *On page 15, 'a priory' should read 'a priori'.*

RE: corrected

5. *On page 17, 'useful inside' should read 'useful insight'.*

RE: corrected

6. *On page 24, the statement is made that smaller damping ratio results in reduced pilot compensation, but Figure 7 appears to show the opposite.*

RE: What we meant is that the new Pareto solutions achieve better flying qualities (smaller FQ1) for smaller values of the damping ratio of the state-predictor eigenvalues (smaller DV2). The revised conclusion is presented as follows:

> • Figure 7 shows the dependencies of the flying qualities criterion FQ1 on the design variable DV2. While the trend seems to indicate that a smaller damping ratio of the state predictor results in increased (lead) pilot compensation, the figure shows that the new Pareto solutions achieve a 20% reduction in criterion FQ1 with respect to the prototype design despite having a smaller damping ratio. A similar observation can be made for criterion *FQ2* when analyzed versus design variable *DV2*.

References

[1] E. Xargay, N. Hovakimyan, V. Dobrokhodov, I. Kaminer, C. Cao and I. M. Gregory, "L1 Adaptive Control in Flight," in *Intelligent Systems, Progress in Aeronautics and Astronautics Series*, American Institute of Aeronautics and Astronautics, 2012.

[2] B. Etkin and L. Reid, "Dynamics of Flight," Wiley, 1996.

List of key changes

1. Introduction section has been extended.

2. A new section “II.C. Multicriteria Optimization Framework” has been added.

3. Section IV.B has been extended with the results of sensitivity analysis.

4. References have been modified along the text.

5. Figures have been modified significantly to improve their clarity. Three new figures have been added to support a discussion in Subsection II.C. (one figure) and new results of Section IV.B (two figures).