NONLINEAR CONTROLLABILITY OF VERY FLEXIBLE AIRCRAFT: ANALYSIS & IMPLEMENTATION

Leonardo Zolli*[1], Maciej Michałów[1], Leandro Ribeiro Lustosa[2]

[1]ISAE-SUPAERO, Université de Toulouse
10, avenue Marc Pélegrin, BP 54032
31055 Toulouse CEDEX 4 - France
leonardo.zolli@student.isae-supaero.fr
maciej.michalow@isae-supaero.fr

[2]Fédération ENAC ISAE-SUPAERO ONERA, Université de Toulouse
10, avenue Marc Pélegrin, BP 54032
31055 Toulouse CEDEX 4 - France
leandro.ribeiro-lustosa@isae-supaero.fr

ABSTRACT

High-aspect-ratio aircraft are inherently prone to dynamic instabilities due to strong aeroelastic coupling, making them particularly challenging to control using conventional piloting techniques. To ensure safe and stable operation in the presence of significant structural flexibility, the adoption of a Stability Augmentation System (SAS) becomes essential. Accurate, real-time measurements of structural deformations are therefore required to feed into the SAS in order to control the deflection of the wing. In this context, several studies have explored vision-based wing shape estimation using LED markers, demonstrating the feasibility of optically tracking structural deformations with lightweight and non-intrusive sensing solutions. Kurita et al. [1], Pang et al. [2] have shown that one of the main limitations of this approach is the high sensitivity to varying lighting conditions; others such as Burners et al. [3] at NASA's Dryden Flight Research Center or Liu et al. [4] introduced a videogrammetry approach, that allows to reconstruct a 3D shape but comes with the disadvantage of needing more than one camera. Moreover, all these approaches required the algorithm to be ran offline. Finally, [5] introduced the Camera-Aided Rate Gyro Wing Shape Estimator (CRG-WSE), an algorithm capable of estimating wing deformation throughout the mission by relying on low-cost inertial measurement units (IMUs) and a single onboard camera and that, with proper hardware and a properly optimized software, is capable of running online.

Past applications of CRG-WSE [6] have used the Channel and Spatial Reliability Tracker (CSRT) algorithm to implement a robust tracking system for the LED markers; however, this required a relatively high computational complexity, which required the use of a parallel computing platform such as CUDA (Compute Unified Device Architecture) and therefore a device equipped with a GPU capable of running the required libraries, specifically the *NVidia Jetson Nano*. Moreover, despite the parallel computing techniques used, the algorithm could run at a maximum of 10 frames per second (fps).

The work illustrated in this paper presents a new approach that has the objective of maintaining an equally robust and reliable LED tracking, while at the same time increasing the bandwidth of the system.

The technique proposed in this paper adopts a simplified color-based detection framework augmented with a Kalman filter to improve tracking robustness. Compared to the method presented in [6], the proposed approach exhibits significantly lower computational complexity, while achieving substantially higher robustness than systems relying exclusively on color detection.

Additional robustness at low computational cost is obtained by enforcing a non-self-intersecting polygon constraint on the detected LED positions, allowing the system to detect and reject marker swapping and other geometrically inconsistent configurations.

The reduced computational burden eliminates the need for parallel computing strategies and enables deployment on low-cost, resource-constrained hardware platforms that do not require GPU acceleration. In its current implementation, the algorithm operates without parallelization at frame rates at least 50% higher than the one presented in [6], as demonstrated experimentally. Finally, different approaches to the filtering part are presented, specifically using a Kalman filter and a particle filter in order to predict the position of the markers in case of false detections and temporary occlusion, comparing their experimental performance in terms of precision, bandwidth and robustness to adverse conditions.

1 REFERENCES

[1] Kurita, M., Koike, S., Nakakita, K., et al. (2013). In-flight wing deformation measurement. In *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*. p. 967.

[2] Pang, Z. Y. and Cesnik, C. E. (2016). Flight shape estimation of very flexible unmanned aerial vehicle. In *57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. p. 1955.

[3] Burner, A. W., Lokos, W. A., and Barrows, D. A. (2003). In-flight aeroelastic measurement technique development. In *Optical diagnostics for fluids, solids, and combustion II*, vol. 5191. SPIE, pp. 186–199.

[4] DeAngelis, V. M. (1982). In-flight deflection measurement of the himat aeroelastically tailored wing. *Journal of Aircraft*, 19(12), 1088–1094.

[5] Lustosa, L. R., Kolmanovsky, I., Cesnik, C. E., et al. (2021). Aided inertial estimation of wing shape. *Journal of Guidance, Control, and Dynamics*, 44(2), 210–219.

[6] Srikanth, R., Afonso, I. M., and Lustosa, L. R. (2022). Experimental aided inertial estimation of wing shape for flexible aircraft control. In *CEAS EuroGNC 2024*.