Switched Control Barrier Functions-based Safe Docking Control Strategy for a Planar Floating Platform

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***Abstract*— In this work, we design and experimentally validate a safe docking control strategy for an experimental planar floating platform, called the Slider. Three degrees-of-freedom (DOF) platforms like the Slider are used extensively in space industry and academia to emulate micro-gravity conditions on Earth, for validating in-plane Guidance, Navigation and Control (GNC) algorithms. The proposed docking control strategy is based on the Control Barrier Functions (CBF) approach, where a safe set (a Cardioid), capturing the clearance and direction-of-approach constraints, is rendered positively forward invariant. In the approach phase, the positive contour of the Cardioid function smoothly steers the Slider platform into the neighborhood of a deadlock point, which is designed to be at a safe distance from the docking port. In the neighborhood of the deadlock point, Slider corrects its proximity and heading until its configuration is well-suited to enter the docking phase. The docking maneuver is initiated by the CBF switching mechanism (positive to zero contour), which expands the safe zone to include the final docking configuration. Both the approach and docking phases are validated through experimentation on the Slider platform, in the presence of tether-induced disturbances and drifts induced by the non-ideal floating surface. Link to the video of experimental demonstration: https://youtu.be/eBiWvnKtG7U?si=QFPD-vm11wydyZSd.**

A. Introduction

In this work, we design and experimentally validate a novel safe docking strategy, designed for a planar floating platform, referred to as Slider in the rest of the article ([1]). The Slider is a Hardware-in-Loop (HIL) test-bed facility that has been designed to emulate in-plane zero-gravity motion of a spacecraft, for the validation of GNC algorithms. The Slider platform is supported by three air bearings, which release compressed air to form an air cushion (micrometers) that allows Slider to levitate over a smooth surface. This air cushion provides frictionless translational and rotational motion on a relatively flat surface, thus emulating space-like zero-gravity conditions. In orbital space missions such as rendezvous and docking, in-plane maneuvers are preferred, as they are significantly less fuel-intensive than maneuvers requiring both in-plane and out-of-plane motion. In applications such as docking for orbital refueling, spacecraft rendezvous and robotic capture control etc., planar floating platforms provide near-ideal micro-gravity conditions and aid in accurate HIL testing of GNC algorithms ([2]).

In this article, we propose a control strategy based on the control barrier functions (CBF) approach ([3]). In this technique, barrier functions are constructed such that their super-level sets capture safe regions, which are then rendered robustly forward invariant throughout the control execution.

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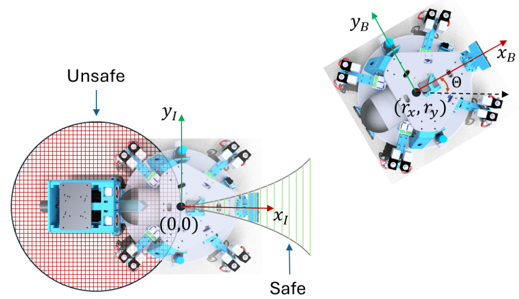

Fig. 1: The area around the docking station (in red) is unsafe. The area inside the tapering funnel (in green) is a safe region to approach the docking port.

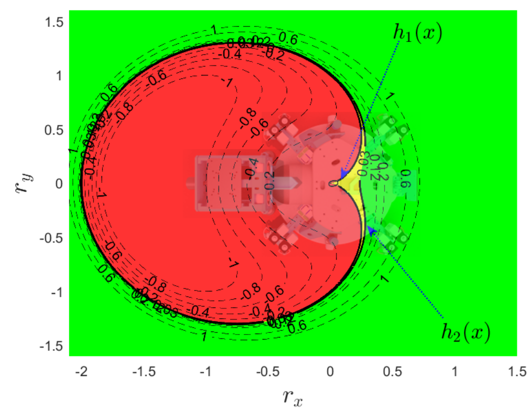

Fig. 2: The contours of a Cardioid function.

B. Safety constraints in autonomous docking

In Figure 1, the two main constraints involved in autonomous docking are illustrated. We identify a region around the docking station (indicated in red, in Figure 1) into which the Slider must not enter. That Slider must also approach the docking port through a tapering funnel, shown in green in Figure 1, while maintaining perfect alignment between the two narrow ports. In Figure 2, the zero and positive contours of a Cardioid, $h_1(x) = 0$ and $h_2(x) = 0$, centered at the tip of the docking port are shown, where

$$h_1(x) = (r_x^2 + r_y^2)^2 + 4ar_x(r_x^2 + r_y^2) - 4a^2 r_y^2 \quad (1)$$

$$h_2(x) = h_1(x) - c, \ c > 0. \quad (2)$$

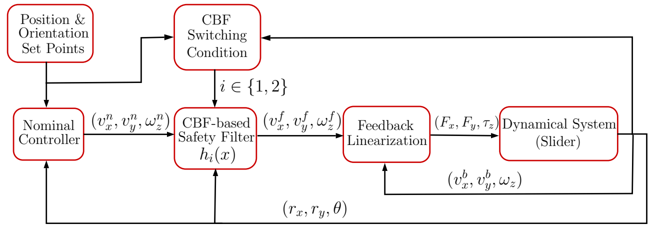

Fig. 3: Two-loop control setup for the Slider platform, with a feedback linearization-based velocity-tracking inner-loop.

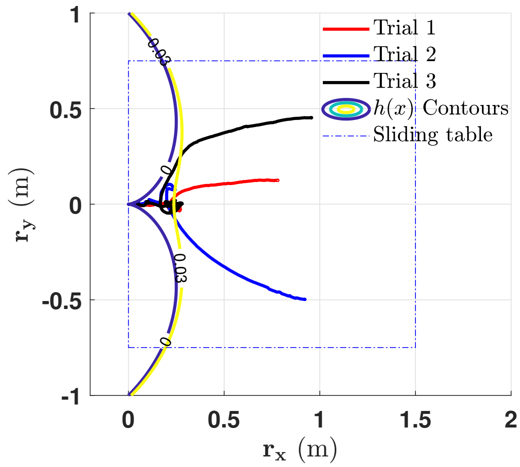

Fig. 4: Experimental results from three trials, showing successful docking and the positive invariance of the safe set throughout the docking maneuver.

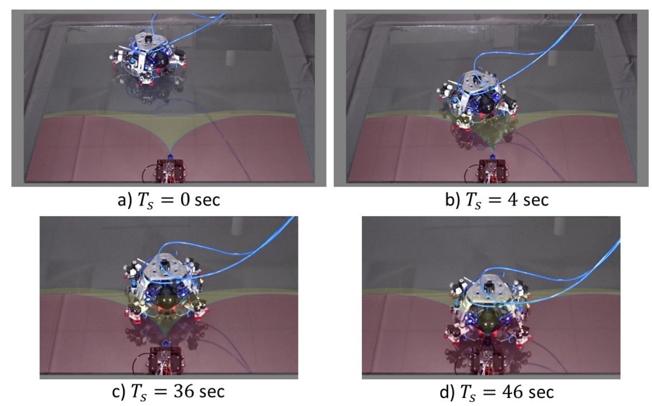

Fig. 5: Snapshots from an experimental trial.

By defining the region outside (inside) the Cardioid as safe (unsafe), the safe clearance constraint, shown in red in Figure 1 is incorporated. The zero-contour of the Cardioid has a cusp at the origin, thus satisfying the direction-of-approach constraint shown in green in Figure 1. If it is ensured that the Slider remains outside the Cardioid throughout the docking maneuver, we indirectly ensure in one shot, that both constraints are satisfied. In this work, we consider the Control Barrier Functions approach to impose state constraints, as this approach allows for systematic characterization of safe and unsafe zones for docking and results in an optimization-based control law which is computationally light (Section -C) in comparison with iterative trajectory reshaping.

C. CBF-based Quadratic program for safety guarantees

In the CBF approach, a control filter is designed, which takes a nominal controller $u_{\text{nom}}(x)$ as input (in this work a PI controller) and yields a minimally deviating filtered control input $u^*(x)$ that enforces the safety constraints. $u^*(x)$ is derived by solving the following Quadratic program

$$\begin{aligned} u^*(x) &= \underset{u \in \mathcal{U}}{\arg\min} \, ||u - u_{\text{nom}}(x)||^2 \\ \text{subject to } &: \; L_f h_i(x) + L_g h_i(x) u \geq -k_1 \alpha(h_i(x)), \end{aligned} \tag{3}$$

where $i \in \{1,2\}$ is chosen by the switching condition (4) that appropriately selects either $h_1(x)$ or $h_2(x)$ at a given time.

$$S_w = \{x \in \mathcal{D} | h_1(x) < (c+\gamma), |\theta| < \delta_\theta \; \& \; |r_y| < \delta_y\} \tag{4}$$

The switching condition (4) effectively identifies a neighborhood of a deadlock point of CBF $h_2(x)$, where $h_2(x) < \gamma$, the attitude of Slider is close to the attitude desired for smooth docking (parameterized by δ_θ) and the Slider has close alignment with the docking port along the r_y-axis (parameterized by δ_y). The conditions in the set definition (4) are satisfied when Slider is favorably positioned to initiate docking. The funnel-shaped region (shown in yellow in Figure 2, which was unsafe when $h_2(x)$ was active, becomes part of the safe region when $h_1(x)$ is activated, thus initiating the docking contact maneuver.

D. Experimental results and conclusions

In Figure 4, we present the experimental results obtained using the docking control strategy proposed in this work. We present results from three initial conditions, picked from the two quadrants of the planar space from which the Slider can be initialized within the limitations of the experimental setup. In Figure 5, four snapshots from Trial 1, illustrating the different phases in a successful docking maneuver, are shown. A video of experimental demonstrations can be found at: https://youtu.be/eBiWvnKtG7U?si=QFPD-vm11wydyZSd. The switching strategy resulted in robust docking, even when the Slider entered unfavourable docking configurations due to tethering-induced disturbances and drifts induced by the non-flat floating surface. Experimental results were presented to validate the effectiveness of the proposed approach.

References

[1] A. Banerjee, S. G. Satpute, C. Kanellakis, I. Tevetzidis, J. Haluska, P. Bodin, and G. Nikolakopoulos, "On the design, modeling and experimental verification of a floating satellite platform," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 1364–1371, 2022.

[2] T. Rybus and K. Seweryn, "Planar air-bearing microgravity simulators: Review of applications, existing solutions and design parameters," *Acta Astronautica*, vol. 120, pp. 239–259, 2016.

[3] A. D. Ames, S. Coogan, M. Egerstedt, G. Notomista, K. Sreenath, and P. Tabuada, "Control barrier functions: Theory and applications," in *2019 18th European Control Conference (ECC)*, pp. 3420–3431, 2019.