Enhanced Model-Based Approach of Spacecraft Docking System Simulation

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EXTENDED ABSTRACT

1 Introduction

The presented paper aims to write a tool to model a docking system from a multi-body dynamics point of view, to allow its simulation's integration in the docking mission's design in all the algorithms for the optimization, guidance, navigation & control (GNC) and attitude determination & control systems (ADCS) from the beginning of the design. The goal is to allow the engineer to take into account the whole docking process for different subsystems with an integrated approach, from the beginning.

Simulating the docking mechanics embedded in the aforementioned subsystems and design approach allows a more accurate off-nominal situations management and a good way to forecast different global designs, like for a new space station with smaller inertia e.g. for the lunar gateway.

A docking system allows the joining of two spacecrafts (SC) such as a space station and Boeing Starliner. Specifically, Docking refers to an active GNC of the visiting vehicle (VV), until the active Soft Capture System (SCS) engages the passive SCS of the hosting vehicle (HV).

This paper modeling follows the international Docking System Standards (IDSS) the standard providing the characteristics of the system to allow the compatibility between different space agency's systems, e.g. the NASA Docking System Block 1 (NDSB1). IDSS details the physical geometric mating interface and design loads requirements, as well as the initial condition and vehicles' inertia. From NDSB1 this work recovers the system specifics.

Docking requires a prescribed sequence of stages characterized by different states with dedicated control laws. The first stage establishes the initial capture and is performed by SCS, during this stage SCS is extracted, then it touches the passive SCS and starts its lunge state to ensure capture, then it passes through an attenuation state followed by alignment and retraction states. The second stage happens at the end of the retraction state and provides structural latching.

Modeling and simulation of the docking process via finite element method (FEM) are suitable for detailed mechanical analysis, but balancing the computational efficiency and accuracy required in an integrated design requires a different approach.

The presented system shall be modeled by lumping parameters and properties for computational effectiveness, to support embedding its design with different subsystems. To this end, the free general purpose solver MBDyn (`https://www.mbdyn.org/`) [1, 2] has been chosen.

2 Preliminary Description and Method

The system is supposed to be androgynous. The SCS interface consists of a capture ring, guide petals, mechanical latches, mechanical latch strikers, sensors and sensors strikers. The HCS interface consists of a tunnel, 12 active/passive hook pairs on each side, dual concentric pressure seals, fine alignment guide pin and guide pin receptacles, sensors, sensor strikers, separation system.

The study has been implemented in MBDyn, a multibody analysis program developed at the Department of Aerospace Engineering of Politecnico di Milano. The first is the modeling of the VV docking system involving one rigid body for the SCS, one for HCS and one for the SC. SC and HCS are connected by a rigid joint, while HCS and SCS by 6 customized actuators displaced in Stewart's platform geometry. HV docking system modeling is symmetric with its parameters.

This paper presents:

- A preliminary mechanical system model following NASA documentation [3].
- A modeling of the docking phase's sequence described by NASA procedures, implementing in MBDyn a state machine that manages all the states and their activations.
- The non-linear control laws characterizing the system actuation illustrated in NASA documentation.

3 About non-linear control functions

Control laws can be written as linear functions with a limiting threshold (saturation in the response), but this implies some discontinuities.

To overcome this issue, these cases were explored:

1. To utilize some linking polynomials up to a finite continuity of class **n**.
2. To optimize a parametric sigmoid function minimizing the approximation error, constrained over zeros and slopes.
3. To find a good mollifier, exploiting Urysohn's lemma results.

The first approach introduces at least $2N(n+1)$ parameters for **N** discontinuity points (in one dimension, surfaces, for higher dimensions) and **n** continuity class.

The sigmoids manipulated by the second approach did not have enough degrees of freedom to simultaneously recover the slope in the zeros locus and the "time" to reach steady conditions. A promising function is provided by Liying Cao et al., but it suffers from having coupled parameters recovered with constrained global optimization meta-heuristic methods like Differential Evolution.

The third approach should be good, but it shall allow avoiding direct convolution and integration in the software and it does not provide directly tunable flexibility. The use of linear description, following [4] and O. Chua's works provides an n-dimensional infinite continuity class function with tunable error, handled just by one parameter more than the minimum set for piece-wise functions (canonical representation, which is different from standard system notation).

This notation suffers from some overflow problems, dealt with by a multi-objective optimization approach, trying to minimize both the governing parameter and approximation error, exploiting a weighted utopia method, both numerically and analytically.

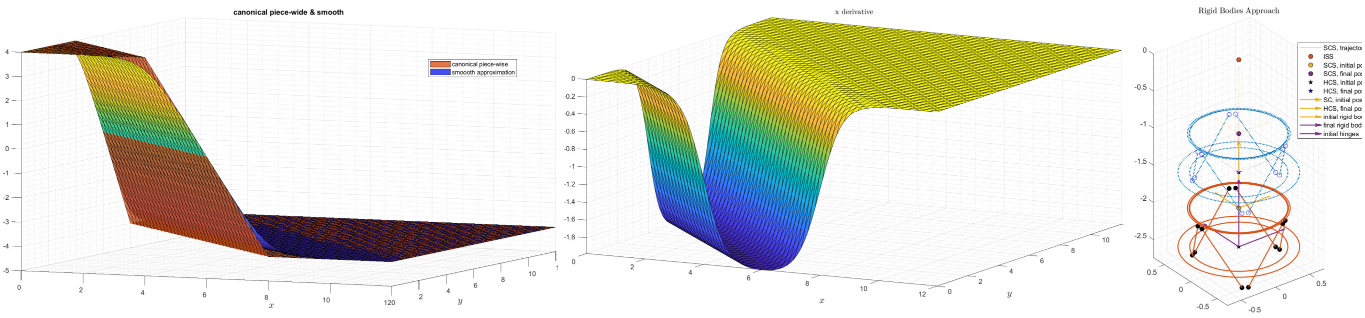
4 Preliminary Results

This modeling required writing a new MBDyn module for the state machine and control laws implementation using the software's easy integration with new modules.

The main achievement of this work is to provide a designing tool for docking missions, taking into account the docking simulation from early stages, to permit an embedded approach and enhance forecast capability.

The paper will add detailed modeling methods and results. The results will contain positions, velocities and accelerations of each node, actuator force history, normal contact forces, and frictional forces in the sliding direction.

Another sub-result was to obtain a sigmoidal function that overcomes the Liying Cao et al. aforementioned problems, providing the minimum set of parameters required to achieve the goal flexibility, with decoupled parameters with a straightforward meaning. This allows easier data fit through the optimization process since the initial guess is more manageable.



(a) Piecewise-linear and smooth approximation (b) Derivative along x variable (c) NDSB1

References

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