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SINGULARITY-FREE DYNAMIC EQUATIONS OF SPACECRAFT-MANIPULATOR SYSTEMS

Abstract

We derive the singularity-free dynamic equations of spacecraft-manipulator systems using a minimal representation. Spacecraft are normally modeled using Euler angles, which leads to singularities, or Euler parameters, which is not a minimal representation and thus not suited for Lagrange's equations. We circumvent these issues by introducing quasi-coordinates which allows us to derive the dynamics using minimal and globally valid non-Euclidean configuration coordinates. This is favorable as the spacecraft's configuration space is non-Euclidean. We thus obtain a computationally efficient and singularity-free formulation of the dynamic equations with the same complexity as the conventional Lagrangian approach. We focus on the dynamic properties of free-floating and free-flying spacecraft-manipulator systems and show how to calculate the inertia and Coriolis matrices so that this can be implemented for simulation and control without extensive knowledge of the mathematical background. The approach then becomes more accessible and should reach a wider audience, including engineers and programmers.

We follow the generalized Lagrangian approach which allows us to combine Euclidean joints and more general joints, i.e., joints that can be described by the Lie group SE(3) or one of its ten subgroups, and we extend these ideas to spacecraft-manipulator systems. There are several advantages in following this approach. The use of quasi-coordinates, i.e., velocity coordinates that are not simply the time derivative of the position coordinates, allows us to include joints (or transformations) with a different topology than that of $\mathbb{R}^n$. For a spacecraft we can represent the transformation from the inertial frame to the spacecraft body frame as a free-floating joint with configuration space SE(3) and we avoid the singularity-prone kinematic relations between the inertial frame and the body frame velocities that normally arise in deriving the spacecraft dynamics. To the authors' best knowledge we present for the first time the dynamic equations of spacecraft-manipulator systems that are valid globally and with a minimal representation.

The dynamics are expressed locally in exponential coordinates ϕ, but the final equations are evaluated at $\phi = 0$. This has two main advantages. Firstly, the dynamics don't depend on the local coordinates as these are eliminated from the equations and the global position and velocity coordinates are the only state variables. This makes the equations valid globally. Secondly, evaluating the equations at $\phi = 0$ greatly simplifies the dynamics and make the equations suited for implementation in simulation software. The explicit equations make the approach well suited for system analysis and model-based control.