

Modular and Hybrid Numerical-Analytical Approach - A Case Study on Improving Computational Efficiency for Series-Parallel Hybrid Robots

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Abstract—Modeling closed loop mechanisms is a necessity for the control and simulation of various systems and poses a great challenge to rigid body dynamics algorithms. Solving the forward and inverse dynamics for such systems require resolution of loop closure constraints which are often solved via numerical procedures. This brings an additional burden to these algorithms as they have to stabilize and control the loop closure errors. In order to avoid this issue, analytical solutions are preferred for commonly studied parallel mechanisms. This paper has two contributions. Firstly, it reports a case study on a modular and hybrid numerical-analytical approach to model and control series-parallel hybrid robots which are subjected to large number of holonomic constraints. The approach exploits the modularity in the robot design to combine analytical loop closure for the known submechanisms and numerical loop closure for submechanisms where analytical solutions are not available. This offers an edge over purely numerical approach in terms of computational efficiency. Secondly, an adaption of the constraint embedding approach in Articulated Body Algorithm (ABA) is presented which yields a recursive algorithm in minimal coordinates for computing the forward dynamics of series-parallel hybrid systems. The proposed modification exploits the Lie group formulations and allows easy implementation of recursive forward dynamics of constrained systems in state of the art multi-body solvers.

I. INTRODUCTION

The recent developments in robotics demand tackling high complexity in modeling rigid body systems. Series-parallel hybrid robots can be defined as a combination of series or tree-type chains and parallel mechanisms. The serial and parallel robots are often combined to exploit advantages of both the topologies. For instance, serial robots provide larger workspace and are easier to control, and parallel robots provide high stiffness, high precision, and high payload capacities. An extensive survey on series-parallel hybrid robots is available in literature [1]. While there are many advantages of having such hybrid robots, the kinematic complexities are inherited from the serial and parallel robots. The number of holonomic constraints that the system is subjected to increases with number and complexity of parallel kinematic chains (PKNs). Hence, it becomes very important to resolve the loop closures in such hybrid robots in a computationally efficient and error free manner.

This work was supported by the VeryHuman (FKZ 01IW20004) and M-Rock (FKZ 01IW21002) projects funded by the German Aerospace Center (DLR) with federal funds from the Federal Ministry of Education and Research (BMBF).

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There are many commercial software (e.g. ADAMS, RecurDyn, Simmechanics, V-Rep, etc.) and some open source rigid body dynamics libraries (e.g. RBDL [2], OpenSim [3], [4]) which provides support for modeling closed loop robots. Solving equations of motion for rigid body system with closed loops require resolution of loop closure constraints which are often solved via numerical procedures. This brings an additional burden to these algorithms as they have to stabilize and control the loop closure errors. Also, the numerical solvers may lead to inaccuracies, and the errors increase as the number of loop closures increase in the system. To circumvent this issue, a modular and analytical approach was implemented in Hybrid Robot Dynamics (HyRoDyn) software framework [5], [6]. HyRoDyn allows solving the loop closures in the PKNs analytically. A hybrid robot is modeled as a serial composition of submechanisms module (serial or parallel). Analytical solutions to the most common PKNs used in hybrid robots are already available in HyRoDyn. However, a disadvantage of HyRoDyn is the lack of its ability in dealing with any general mechanism. For any unknown mechanism type, symbolic expressions are required for the analyses which requires expert knowledge and their derivation may be a time-consuming process.

The most naïve solution of the forward dynamics involves the computation and inversion of mass-inertia matrix for computing accelerations. If the robot has several degrees of freedom, a numerical inversion of such a large mass-inertia matrix is not efficient. Other approaches have been discussed in the literature that performs forward dynamics recursively leading to $O(n)$ algorithm, where n is the number of bodies in the system. Featherstone's Articulated Body Algorithm (ABA), introduced in [7], is a recursive forward dynamics algorithm for tree type systems and is deemed to be the most efficient. But, for complex closed loop systems, generally mass-inertia matrix inversion is performed. To circumvent this, Jain introduced the idea of embedding the loop closure constraints within the ABA algorithm [8] leading to a recursive forward dynamics for constrained systems in minimal coordinates. In the recent years, the algorithms from Featherstone [9] has become increasingly popular among the robotics community. Their implementation can be found in many open source libraries such as RBDL [2], Pinocchio [10], MuJoCo [11], Drake [12], Bullet [13], DART [14] etc. The main difference between the formulations from Featherstone and Jain is the numbering scheme. Featherstone's algorithms use a numbering scheme where the numbers increase from base to tip of the kinematic tree while Jain's algorithms use an opposite numbering

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