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Robust State-Input Estimation for Differential Algebraic Equations and Application to Multibody Systems

Tommaso Tamarozzi[1], Pavel Jiránek[1] and Daniel De Gregoriis[1*]

[1] Siemens Digital Industries Software, Interleuvenlaan 68, 3001 Leuven, Belgium, tommaso.tamarozzi@siemens.com, pavel.jiranek@siemens.com, daniel.de_gregoriis@siemens.com

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Digital Twins (DT) allow to accelerate the development of new products and enable new insights throughout the different product lifecycle stages. Smart virtual sensors based on DTs are capable of estimating quantities that cannot be easily measured, such as the full system states (and related quantities like strain and stress fields) and unknown inputs. Using a Kalman Filter approach [1], such a Digital Twin can be created by combining data coming from physical sensors with the asset's numerical model.

For complex mechanical systems composed of interconnected bodies and experiencing large motions and small deformations, a multibody formulation is commonly employed. The resulting equations of motion allow to efficiently express the kinematic constraints (i.e. connections) between the different components (i.e. bodies) using algebraic equations in combination with Lagrange multipliers. This yields a system of Differential Algebraic Equations (DAEs). Different approaches have been presented in literature to combine these DAEs (i.e. the multibody model) with a Kalman Filter ([2]-[4] and references therein). These approaches mainly differ in their handling of the algebraic constraint equations. They typically require using a specific multibody formulation and/or allow constraint violation (i.e. soft constraint enforcement). This tends to limit their use to either special cases or requires problem-specific tuning that can be detrimental for the application as a Digital Twin.

This work therefore presents a robust, general Kalman Filter-based state-input approach that allows to directly enforce the kinematic constraints exactly. More specifically, the estimated state is enforced to lie on the manifold described by the constraint equations and therefore meet the equality constraints exactly. This allows to generate a robust and smart virtual sensor using the Digital Twin of complex mechanical systems. The proposed methodology is numerically validated using closed and open kinematic chain multibody models.

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