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Dynamic Gravity Cancellation in Robots with Flexible Transmissions: Constant, Nonlinear, and Variable Stiffness

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Short Summary

Robots in physical interaction with humans are conveniently controlled so as to achieve zero-gravity operation. This avoids biasing the robot reaction to unintended collisions along the gradient of the gravitational potential, with a uniform and more predictable (thus safer) robot behavior in its whole workspace. Perfect cancellation of gravity is trivial for fully rigid manipulators. However, robots for safe pHRI have lightweight (and rigid) links but are typically characterized by the presence of compliant transmissions, either with finite constant or nonlinear stiffness or with variable (and independently actuated) stiffness. For robots with (constant) elastic joints, gravity compensation laws have been already proposed for regulation tasks. However, using these control laws gravity is removed only in static or quasi-static conditions. For highly dynamic tasks, only a partial compensation of gravity effects on the robot link motion is obtained. Based on the general principle of feedback equivalence, we present new control results that allow perfect dynamic gravity cancellation in a variety of robotic systems with flexible transmissions. In particular, for multi-dof robots with constant elastic joints moving under gravity, we show how to accurately match the same dynamic behavior of the links obtained in the absence of gravity. One relevant consequence of this result is that regulation to a desired set-point can be achieved with a simple motor PD feedback closed around the previous nonlinear law, without the need of any strictly positive lower bound on the proportional control gain. Next, considering for simplicity only single dof devices, we extend our method to the following cases: nonlinear (quadratic) joint stiffness; antagonistic actuation with constant but different stiffness at the two motor sides; antagonistic actuation with variable nonlinear stiffness (e.g., the VSA-II device of the University of Pisa). For VSA-based robots, we can also impose a dynamic behavior to the nonlinear stiffness of the device that is identical to when gravity is not present. Furthermore, one can use this result for designing a pure torque-based reaction strategy to collisions. We note that all the above systems are exactly linearizable by static state feedback. While dynamic gravity cancellation involves in general the on-line computation of inertial terms, it should be emphasized that the presented control laws are much simpler in the multi-dof situation than those for feedback linearization. Moreover, the expression of the control law can be found in closed algebraic form in many relevant cases. When this is not possible, simple numerical techniques can be used.