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Passive Compensation of Nonlinear Robot Dynamics

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1 Introduction

Many robot applications demand a robot to interact with an environment that is not exactly known beforehand. In these situations, the controller should be careful not to make the robot unstable, i.e. keep its kinetic energy bounded.

One way to accomplish this is to use a form of impedance control (introduced by Hogan [1]): the control torques are taken equal to the gradient of an (artificial) potential field with the minimum at the desired position. Thus, the controller mimics a spring connected between the robot and the desired position. The kinetic energy of the robot is determined by the potential field, and if this field has a global minimum, the kinetic energy is bounded.

However, if we 'release' the robot in the potential field, coriolis and centrifugal forces cause it to oscillate around the minimum in a seemingly chaotic way. We want to improve this behavior, such that the robot oscillates along a predefined curve instead of on the whole potential field. We *do* want to keep the nice passivity properties of the impedance controller, though, so we look for power-continuous (i.e. energy-conserving) extensions of the potential field.

2 Mathematical Framework

In order to have all results be coordinate-independent (and, as a pleasant side-effect, keep the equations short and readable), we use the mathematical framework of differential geometry [2] to describe the dynamics of the robot as well as the controller.

We use coordinates q and velocities $\dot{q}$ to describe the current state (configuration and velocity) of the robot. We can then describe the dynamics of a robot as

$$\nabla_{\dot{q}}\dot{q} = g^{-1}\tau \qquad (1)$$

where $\nabla_{\dot{q}}\dot{q}$ is the covariant directional derivative that describes the 'acceleration', g is the metric (inertia tensor), and τ are the control torques (one motor per joint). In this way, we can relate the necessary control torques in a one-to-one way to the desired accelerations.

We describe the desired curves using a vector field w in joint space. The vector $w(q)$ describes the direction of the desired curve at point q.

3 Control Law

We want to obtain a controller that makes the robot move along the curves defined by w (first constraint), while the change in kinetic energy is determined by the potential field (second constraint).

The first constraint results in a desired acceleration (A) in a direction perpendicular to the current velocity, i.e.

$$\left\langle \left(\nabla_{\dot{q}}\dot{q}\right)_A, \dot{q}\right\rangle_g = 0 \qquad (2)$$

with the inner product $\langle\cdot,\cdot\rangle_g$ defined by the metric. The second constraint results in a desired acceleration (B) in the same direction as the current velocity, i.e.

$$\left(\nabla_{\dot{q}}\dot{q}\right)_B = \alpha\dot{q} \qquad (3)$$

with α a real number depending on the current state. The total controller is just the sum of these two parts. Additional terms can be added to be able to recover from disturbances or to add collinear damping.

The resulting controller can be easily explained by the control of a simple system like a point mass moving in the plane: we can change its direction by applying a force perpendicular to the current velocity (similar to Equation 2), and we can independently change its speed by applying a force in the same direction as the current velocity (similar to Equation 3).

In the presentation, we derive the actual control law and show some simulation results.

References

[1] N. Hogan, "Impedance control: An approach to manipulation" *Journal of Dynamical Systems, Measurement and Control 107(1)*, pp. 1–24, 1985.

[2] M. Spivak, *A Comprehensive Introduction to Differential Geometry*, Berkeley: Publish or Perish, second edition, 1979.