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Dissipatively actuated manipulation

W.J. Wolfslag*, M.C. Plooij, W. Caarls, S. van Weperen, G.A.D. Lopes

Delft University of Technology, Robotics Institute, The Netherlands

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ABSTRACT

This paper addresses the design of control systems whose actuation can only dissipate energy. Such systems provide intrinsic safety, and can be used in scenarios where energy is supplied by external entities and point-stabilization is possible with only energy dissipation. Three control synthesis methods are proposed that range from model-based to a learning approach and their validity is demonstrated on a passively controlled manipulator performing a positioning task. These three methods are the Zero Control Velocity Field, Monte-Carlo Tree Search and Reinforcement Learning. The simulation results are corroborated by experiments on a physical two link manipulator.

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1. Introduction

On many robotic arms, actuators actively provide the power needed to achieve motion. Designers often aim for the cheapest or lightest actuator that suffices the power requirements, in order to reduce the cost and the weight of the arm. This paper takes this aim to an extremum and proposes control systems for a manipulator that does not use active actuators to power the motion. In such a manipulator, motions can only be influenced by clutches and dissipative components such as brakes. As a case study for this idea, the system shown in Fig. 1a is examined: a two DOF manipulator in the vertical plane which picks up objects and places them at a lower height. While doing so, the controller can dissipate energy but cannot add energy to the manipulator. Such a system shows resemblance with a skier (see Fig. 1b), who can steer and brake by dissipating energy while going down to end up at a desired location.

Systems with solely dissipative components have several advantages. First, they exhibit intrinsic safety: such systems cannot make unexpected motions caused by unexpected inputs. Therefore, the motions are very transparent for the user, causing the system to be safer. The advantage of intrinsic safety is that it does not rely on active control, as in De Luca, Albu-Schaffer, Haddadin, and Hirzinger (2006), or clever trajectories enforcing safety during control failures, as in Holzinger, DiMatteo, Schwartz, and Milam (2008), both of which can potentially fail in operation. Obtaining intrinsic safety was the prime motivation for previous research on dissipatively actuated systems in the field of haptic devices (Matsuoka & Townsend, 2001; Reed, 2003; Swanson & Book, 2000), particularly for rehabilitation purposes (Asadi, Hoyle, & Arzanpour, 2011; Dellon & Matsuoka, 2009). Second, manipulators without motors are cheaper in both purchase (actuators are expensive) and usage (lower energy costs). The energy considerations prompted research in walking robots to consider purely unactuated robots (McGeer, 1990), and derived robots which use very limited actuation combined with the dynamic properties of walking (Goswami, Espiau, & Keramane, 1996; Hobbelen & Wisse, 2007; Hürmüzlü & Moskowitz, 1986). Finally, dissipatively actuated manipulators could lead to lightweight designs.

The goal of this paper is to introduce the concept of *dissipatively actuated manipulation*. This concept turns out to be challenging from a controls perspective, as the resulting systems do not fulfill the required assumptions of the traditional control approaches for nonlinear input-affine models. Therefore we compare three controllers that do not make these assumptions: a Zero Control Velocity Field (ZCVF) controller, a Monte-Carlo Tree Search (MCTS) controller and a Reinforcement Learning (RL) controller. These three controllers are chosen as they form a scale from a mostly model-based towards a purely numerical approach. As such, they represent three main paradigms in control: model-based, receding horizon and learning.

Past research into the control of dissipatively actuated systems has largely been guided by the requirements of haptic devices. Two prime topics of interest are the regulation of admittance using dissipative actuators (Goswami & Peshkin, 1999; Goswami, Peshkin, & Colgate, 1990), and the creation of position dependent steering forces at an end-effector (Asadi et al., 2011; Gao & Book, 2010). In both these cases the desired behavior is expressed locally, which is not possible in our tasks: position control.

More global behavior was obtained in research on walking-guidance by means of wheeled robots (Ko, Young, Huang, & Agrawal, 2013). However, as the desired behavior of that robot was guidance, the control system was based on a user supplying

* Correspondence to: Delft University of Technology,Robotics Institute, Mekelweg 2,2628 CD Delft, The Netherlands. Tel.: +31 15 27 88620.
E-mail address: w.j.wolfslag@tudelft.nl (W.J. Wolfslag).

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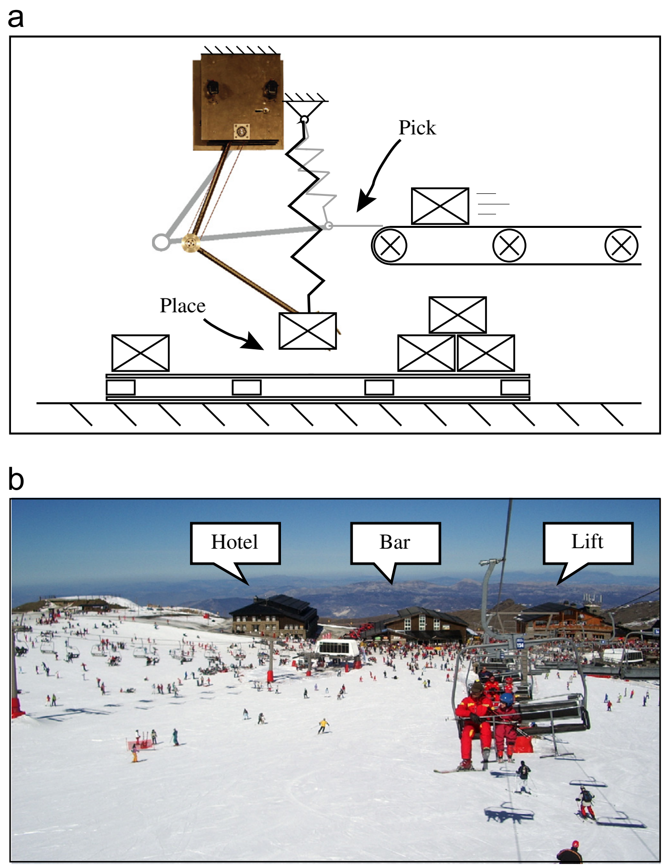

Fig. 1. This paper considers the control of systems with dissipative components instead of actuators. A two DOF arm in the vertical plane is studied, which picks up objects and places them at a lower height (a). While moving downwards, the arm can only brake. This case study shows resemblance with a skier that can only brake while going downslope (b), in order do steer itself to a certain goal at the bottom of the hill (e.g. a hotel, a bar or the entrance of the lift).

a force in approximately the right direction. Furthermore, the main external force, gravity, was compensated for using active actuators. For these two reasons their approach is not directly applicable to the problem here. The zero-control-velocity-field controller (discussed in Section 4) is the most similar to their approach, as it tries to steer towards a preplanned trajectory.

Outside of haptic guidance, dissipative actuators are less commonly used. In underactuated robot manipulators, brakes have been used as a locking mechanism, allowing the robot to reach a desired configuration by sequentially manipulating and locking the unactuated degrees of freedom (Arai & Tachi, 1991; Chen, Yu, Zhao, Zhao, & Sun, 2011; Oriolo & Nakamura, 1991). Although such a decoupling mode could be used in a fully dissipatively actuated robot arm, the decoupling structure severely limits the possibility of control.

The rest of the paper is structured as follows. Section 2 formulates the dissipatively actuated manipulation problem mathematically. Section 3 describes the test case chosen to test the controllers: a two DOF manipulator in the vertical plane. Sections 4–6 discuss the three controllers compared in this paper: ZCVF control, MCTS control and RL control. The paper ends with a discussion in Section 7 including a comparison between the three controllers and a conclusion in Section 8.

2. Dissipatively actuated systems

Consider a class of mechanical systems in which the controller cannot add energy to the system. For mechanical systems, the energy is expressed as (Bullo & Lewis, 2004)

$$H(q,p) = \tfrac{1}{2} p^T M(q)^{-1} p + V(q) \tag{1}$$

where $q \in \mathbb{R}^n$ are the generalized coordinates, $p = M(q)\dot{q}$ are the generalized momenta, $M(q)$ is the positive definite mass matrix, and $V(q)$ is the potential energy.

The equations of motion can now be expressed in port-Hamiltonian form (van der Schaft, 2006)

$$\begin{pmatrix} \dot{q} \\ \dot{p} \end{pmatrix} = \begin{pmatrix} 0 & I \\ -I & -R \end{pmatrix} \begin{pmatrix} \nabla_q H \\ \nabla_p H \end{pmatrix} + \begin{pmatrix} 0 \\ I \end{pmatrix} u$$
$$\xi = \begin{pmatrix} 0 & I \end{pmatrix} \begin{pmatrix} \nabla_q H \\ \nabla_p H \end{pmatrix} \tag{2}$$

where $u \in \mathbb{R}^n$ are the input torques, R is a positive definite matrix representing mechanical damping (e.g. friction), and $\xi = \nabla_p H = \dot{q}$ is the output of the system.

From this formulation, one can show that the system is *passive* with the total energy H as a storage function, as can be seen by expressing the time derivative of H

$$\dot{H} = -\dot{q}^T R \dot{q} + \xi^T u \leq \xi^T u \tag{3}$$

The input does not add energy to the system as long as $\xi^T u \leq 0$, or equivalently

$$\dot{H} \leq -\dot{q}^T R \dot{q} \tag{4}$$

In this case, the controlled system is passive with respect to the original Hamiltonian, even if there is no damping ($R=0$). Denote systems (respectively controllers) that satisfy Eq. (4) as *dissipatively actuated systems* (respectively dissipatively actuated controllers). Such systems should be distinguished from dissipative control systems, described in for instance (Khalil, 2002; Ortega, 1998), in which both the controller and the uncontrolled system meet a demand similar to Eq. (3). Do note that a dissipatively actuated system is always a dissipative control system, the converse is not true.

A more strict demand is

$$\xi_i^T u_i \leq 0 \quad \forall i = 1, \ldots, n \tag{5}$$

which gives rise to *elementwise dissipatively actuated systems*. This distinction is important in implementation, because elementwise dissipatively actuated systems can be constructed using only brakes, whereas dissipatively actuated systems in general require clutches. The implementations discussed later in this paper are all elementwise dissipatively actuated controllers.

The control goal is dissipatively actuated manipulation: steering a dissipatively actuated system to a desired state. The first challenging aspect of dissipatively actuated manipulation can be understood from Eq. (4). Since the energy in the system must always be decreasing, the problem of point stabilization becomes challenging: if the energy of the desired final state is higher then the total energy of the initial condition, then there exists no solution.

Even neglecting such reachability issues, the design of dissipatively actuated controllers is not solved by standard methods. To see this, consider the following structure of an elementwise dissipatively actuated controller

$$u = -D(q, \dot{q})\dot{q} \tag{6}$$

where D is the positive diagonal. If instead of this diagonal constraint, $D + D^T$ is constrained to be positive definite, a normal dissipatively actuated system is obtained, as Eq. (4) is then satisfied. In either case, if D is allowed to be discontinuous, all (elementwise) dissipatively actuated state feedback controllers can be written in this form.

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