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Energy-regenerative model predictive control

Olugbenga Moses Anubi*, Layne Clemen

UC Davis – Department of Mechanical and Aeronautical Engineering, Davis, CA 95618, United States

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Abstract

This paper presents some solution approaches to the problem of optimal energy-regenerative model predictive control for linear systems subject to stability and/or dissipativity constraints, as well as hard constraints on the state and control vectors. The problem is generally non-convex in the objective and some of the constraints, thereby resulting in a non-convex optimization problem to be solved at each time step. Multiple extended convex *relaxation* approaches are considered. As a result, a more conservative semi-definite programming problem is proposed to be solved at each time step. The feasibility and stability of the resulting closed-loop system are also examined. The approaches are validated using a numerical example of maximizing energy regeneration from a single degree of freedom vibrating system subject to a level-set constraint on some performance metric characterizing the quality of vibration isolation achieved by the system. The constraint is described in terms of an upper bound on the $\mathcal{L}_2-$gain of the system from the input to a vector of appropriately selected system outputs.
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1. Introduction

The development of energy-regenerative engineering systems is on the rise due to the ever-increasing awareness of limited resources and the need to recuperate energy that would otherwise be wasted system operation. Many human activities involve converting energy from one domain to another. For example, the conversion of mechanical energy to electrical energy, which can then power computers, light, motors, etc. The input energy propels the work and is mostly converted to heat or follows the product in the process as output energy. Energy recovery systems harvest the output power and provide it as input power to the same or another process [1]. Examples of such

*Corresponding author.
E-mail addresses: anubimoses@gmail.com (O.M. Anubi), laclemen@ucdavis.edu (L. Clemen).

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systems include using heated water from sources like steel mills as heating for homes, regenerative braking, energy harvesting from vibrating systems, heat regenerative engines, etc.

The approaches used in the control systems of energy-regenerative systems can be seen from two perspectives: direct and indirect methods. Indirect methods utilize control systems for some primary objective and as a result extracts energy from the system. An example is a vibrating system. Any controller results in the closed-loop system being dissipative which makes the energy available for regeneration [2–4]. On the other hand, direct methods seek to directly extract energy from the system while satisfying some performance constraint. Examples of direct methods include a sliding mode control with an appropriate choice of the sliding surface [5] and model predictive control [6].

Model predictive control (MPC) refers to a class of control systems in which the current control action is obtained at each sampling instant by solving a finite (or infinite) horizon open-loop optimal control problem. While the result of the optimization is a sequence of control actions over the prediction horizon, only the first control action is applied at the current time.[1] The process is repeated at each sampling time to obtain the desired control input. Using this framework, it is easy to cope with hard constraints on controls and states. As a result, MPC has received a lot of attention in the literature for both discrete and continuous time systems [8–17].

Consequently, MPC-based solutions for energy regeneration problems are receiving a lot of research attention. Interested readers are directed to the reference [18] and the references therein for a survey of prior works in this area. Moreover, it was reported in [19] that it is troublesome to ensure stability if the problem is nonconvex, and in addition, the explicit methods are not suitable for larger problems due to extremely large state-space models. In this paper, the stability issue is tackled by explicitly imposing stability/dissipativity constraints which are then *convexified* by introducing some extended convex relaxation approaches. More concretely, this paper considers the problem of optimal energy-regenerative MPC for linear systems subject to stability/dissipativity constraints, as well as hard constraints on the state and control vectors. The problem is generally non-convex in the objective and some of the constraints, thereby resulting in a non-convex optimization problem to be solved at each time step. Some convex relaxation approaches are considered. As a result, a more conservative semi-definite programming problem is proposed to be solved at each time step. The feasibility and stability of the resulting closed-loop system are also examined. The approaches are validated using a numerical example of maximizing the power regenerated from a single degree of freedom vibrating system subject to a level-set constraint on some weighted performance metric. The constraint is described in terms of an upper bound on the $\mathcal{L}_2$-gain of the system from the input to a vector of appropriately selected system outputs.

The rest of the paper is organized as follows: notations used throughout the paper are introduced in Section 2. The problem formulation is given in Section 3. The convex relaxation procedures are described in Section 4 with the feasibility and stability of the resulting relaxed MPC problem. In Section 5, the relaxed MPC problem is extended to the output feedback case. A numerical simulation example is given in Section 6. Conclusions follow in Section 7.

2. Notations

Throughout the paper, the following notations are used: $\mathbb{R}$ and $\mathbb{R}_+$ denote the set of real numbers and positive real numbers respectively. The set of all symmetric positive definite and positive semi-definite matrices are denoted by $\mathbb{S}_{++}$ and $\mathbb{S}_+$ respectively. The Euclidean norm of

[1]Except otherwise required in some special circumstances (for example, see reference [7] and references therein).

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