Control Engineering Practice 21 (2013) 1250–1258

Contents lists available at SciVerse ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Nonlinear model predictive control of a magnetic levitation system

Thomas Bächle, Sebastian Hentzelt, Knut Graichen *

Institute of Measurement, Control, and Microtechnology, Ulm University, Albert-Einstein-Allee 41, 89081 Ulm, Germany

ARTICLE INFO

Article history:
Received 1 June 2012
Accepted 20 April 2013

Keywords:
Magnetic levitation system
System identification
Nonlinear model predictive control
Real-time optimization
Optimal control

ABSTRACT

The paper presents a fast nonlinear model predictive control (MPC) scheme for a magnetic levitation system. A nonlinear dynamical model of the levitation system is derived that additionally captures the inductor current dynamics of the electromagnet in order to achieve a high MPC performance both for stabilization and fast setpoint changes of the levitating mass. The optimization algorithm underlying the MPC scheme accounts for control constraints and allows for a time and memory efficient computation of the single iteration. The overall control performance of the levitation system as well as the low computational costs of the MPC scheme is shown both in simulations and experiments with a sampling frequency of 700 Hz on a standard dSPACE hardware.

1. Introduction

Magnetic levitation systems are of growing importance in the industry. Typical applications are, for instance, frictionless bearings for high-speed machining (Knospe, 2007), magnetically levitating trains (Hasirci, Balikci, Zabar, & Birenbaum, 2011) like the Transrapid, micro-manipulation of levitating objects (Kummer et al., 2010), or nanoscale positioning systems (Khamesee & Shameli, 2005; Kim, Verma, & Shakir, 2007).

Magnetic levitation systems with a single axis are widely used as benchmark problems for advanced control strategies due to their inherently nonlinear and unstable open loop nature. In recent years, a variety of control methods have been proposed for these systems. For instance, feedforward and feedback linearization for trajectory tracking of the levitating mass was considered by Morales and Sira-Ramírez (2010) and El Hajjaji and Ouladsine (2001). Additional robustness regarding parameter uncertainties for this approach can be provided by means of backstepping (Yang & Minashima, 2001). Further nonlinear control methods applied to magnetic levitation systems are, for instance, adaptive control (Yang, Kunitoshi, Kanae, & Wada, 2008; Yang & Tateishi, 2001), sliding mode controllers (Elahi & Nekoubin, 2011; Shieh, Siao, & Liu, 2010), and neuronal networks (Chen, Lin, & Shyu, 2009; Lin, Chen, & Shyu, 2009).

Another modern control method that became increasingly popular over the last years is model predictive control (MPC). MPC relies on the solution of an optimal control problem on a receding horizon (Camacho & Bordons, 2007; Grüne & Pannek, 2011; Mayne, Rawlings, Rao, & Scokaert, 2000) and is well suited for nonlinear multiple-input systems and to account for state or control constraints. The drawback of MPC is the high computational effort that is usually required to solve the underlying optimal control problem (OCP) in each sampling step. MPC schemes for fast systems therefore often rely on approximations or tailored algorithms to reduce the computational load, see e.g. Ohtsuka (2004), Ferreau, Bock, and Diehl (2008), DeHaan and Guay (2007), and Graichen and Kugi (2010).

For magnetic levitation systems, which typically necessitate sampling times in the (sub)millisecond range, the MPC design was investigated by several authors. An explicit MPC scheme is presented by Ulbig, Olaru, and Dumur (2008, 2010) based on a piecewise affine, linear system approximation. Further MPC approaches for magnetic levitation systems concern linear (discrete-time) MPC in combination with linear matrix inequalities (Matos, Galvão, & Yoneyama, 2010) and feedback linearization (Maia & Galvão, 2007) as well as bit-stream based MPC (Camasca, Swain, & Patel, 2011) and networked MPC (Wang, Liu, & Rees, 2009). All these MPC approaches rely on a linear or linearized model of the levitation system and various specializations with the goal to minimize the computational effort and to achieve real-time feasibility. However, an accurate model capturing the nonlinearities of the unstable system in combination with a real-time nonlinear MPC scheme is essential if a high control performance as well as fast setpoint transitions over a wide operational region of a magnetic levitation system are desired.

This contribution describes a nonlinear MPC scheme for an experimental magnetic levitation system with a maximum levitation height of 70 mm. Special attention is paid to the modeling and identification of a mathematical model with state-dependent parameters, using a similar approach as employed by Truong, Wang, and Huang (2007). The experimental magnetic levitation system provides several challenges for the modeling process as well as for the MPC scheme. On the

* Corresponding author. Tel.: +49 731 50 26304; fax: +49 731 50 26301.
E-mail addresses: thomas.baechle@uni-ulm.de (T. Bächle), sebastian.hentzelt@uni-ulm.de (S. Hentzelt), knut.graichen@uni-ulm.de (K. Graichen).

0967-0661/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conengprac.2013.04.009

one hand, the electromagnet's core is highly conductive, which has to be accounted for in the model. On the other hand and in order to achieve the fastest possible control performance, no cascaded current controllers are used in the MPC design. Instead, the constrained duty cycles of the pulse width modulated (PWM) terminal voltages serve as control inputs in the model. This, however, necessitates an accurate model of the nonlinear inductor current dynamics. A further challenge for the MPC scheme arises from the comparatively high sampling frequency of 700 Hz corresponding to the PWM frequency.

The nonlinear MPC scheme employed in this paper to control the magnetic levitation system is based on a recently presented real-time gradient algorithm that is tailored to nonlinear MPC with control constraints (Graichen & Käpernick, 2012; Graichen & Kugi, 2010) and allows for a memory and time efficient execution of the single iterations. A first version of this real-time MPC scheme was successfully used to control a laboratory crane in the millisecond range on a standard PC (Graichen, Egretzberger, & Kugi, 2010). For the magnetic levitation system considered in this contribution, however, the nonlinear MPC design is significantly more challenging due to the strong nonlinearities, fast current dynamics, and considerable stiffness of the overall system. The runtime efficiency of the nonlinear MPC scheme is demonstrated by a constant computation time of approximately 900 μs on a dSPACE real-time hardware which is well below the sampling time of 1.43 ms (700 Hz). In addition to the mathematical modeling of the magnetic levitation system and the actual MPC design, a robustness analysis is carried out and a comparison with linear MPC shows the superior control performance which underlines the importance of a nonlinear MPC setup.

The paper is organized as follows. The experimental setup and the nonlinear model of the magnetic levitation system are described in Section 2. Section 3 introduces the MPC scheme as well as the real-time optimization algorithm. Section 4 presents the numerical and experimental results for the magnetic levitation system. Finally, conclusions are drawn in Section 5.

2. Experimental setup and mathematical model

This section describes the experimental setup of the levitation system and derives a mathematical model that is used for the MPC design. In order to achieve a high MPC performance, the model of the system dynamics needs to be sufficiently accurate while requiring only moderate computational effort to allow for a high sampling frequency of the overall control system. In a first step, a detailed model is derived based on physical considerations that gives insight into the levitation system. In a second step, a reduced order model is identified that is suitable for real-time purposes and which will be used in the remainder of the paper.

2.1. Magnetic levitation system

A picture and a schematic drawing of the experimental levitation system are shown in Fig. 1. The levitating mass is a hollow object made of constructional steel with the mass $m = 134$ g. The electromagnet consists of a steel cup core and two coils with 2000 windings each. The electromagnetic field applies the electromagnetic force F_{mag} to the levitating mass in opposite direction to the gravitational force mg with the acceleration due to gravity $g = 9.81\ \mathrm{m/s^2}$. The intention behind the two coils setup is to generate the major part of the electromagnetic field by means of the outer coil with the larger inductance, while the inner coil with the smaller inductance is more suitable to rapidly adapt the electromagnetic field for stabilization purposes. The experimental setup is designed for large levitation heights of up to $z = -70$ mm, corresponding to a maximum electrical power consumption of

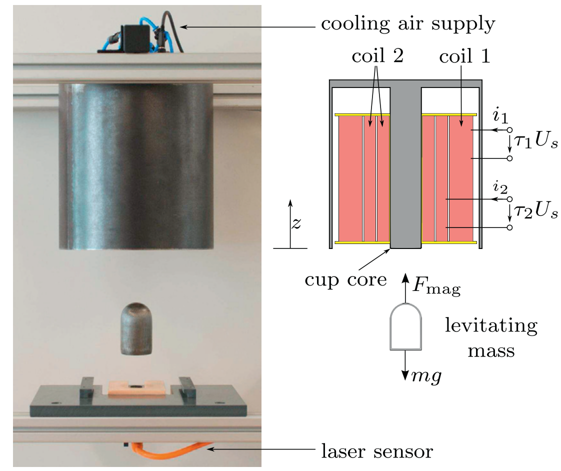

Fig. 1. Experimental setup of the magnetic levitation system.

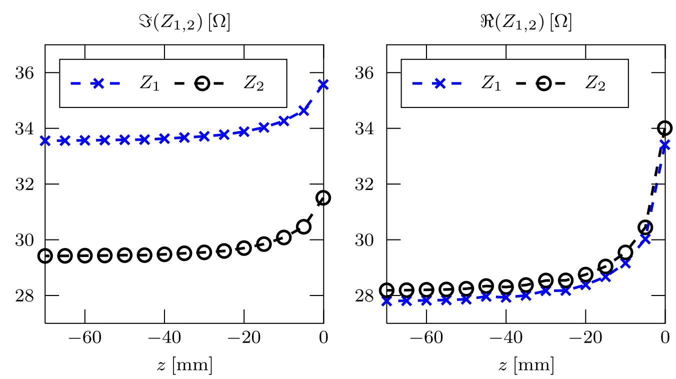

Fig. 2. FE simulated impedances (imaginary and real parts) for levitation heights of $z \in [-70, -1]$ mm, computed for coil currents of 1 A at a frequency of 5 Hz.

800 W. Overheating of the coils is avoided by pressurized air that flows through cooling channels inside the electromagnet.

The control inputs of the electromagnet are the duty cycles $\tau_1, \tau_2 \in [0, 1]$ of two PWM controlled buck converters that adjust the voltage applied to the coil terminals. Both buck converters are supplied by a shared direct voltage source U_s and allow the terminal voltages to be controlled individually within the interval $[0, U_s]$, while both coil currents i_1, i_2 are restricted to positive values. The levitation height z and the currents i_1, i_2 are measured with a laser sensor (see Fig. 1) and resistive current sensors. The levitation system is controlled by a dSPACE MicroAutoBox I real-time hardware equipped with an 800 MHz PowerPC processor.

The dynamics of the levitation system comprise the electrical and the mechanical subsystems. In general, the distance of the levitating mass affects the inductance of the coils. This property can, for instance, be taken advantage of for sensor-free position estimation (Glück, Kemmetmüller, Tump, & Kugi, 2011). For the experimental setup in this contribution, however, FE simulations[1] have shown that the air gap between the levitating mass and the electromagnet has only limited effect on its inductances for the considered operational region of $z \in [-70\ \mathrm{mm}, -40\ \mathrm{mm}]$. To illustrate this point, Fig. 2 shows the impedances Z_1 and Z_2 of both coils as computed in FE simulations for the currents $(i_1, i_2) = (1\ \mathrm{A}, 0\ \mathrm{A})$ and $(i_1, i_2) = (0\ \mathrm{A}, 1\ \mathrm{A})$ at a frequency of 5 Hz.

[1] The software FEMM (Meeker, 2010) was used to develop a 2D axisymmetric finite element (FE) simulation of the experimental setup.