Model Predictive Control For Active Magnetic Bearings

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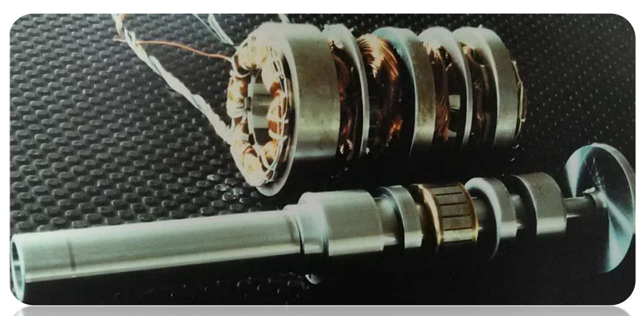
Research context and motivation

Active Magnetic Bearings (AMB) are mechatronic systems where there is no contact between bearing and rotor, and this permits operation with no lubrication and no mechanical wear. Turbomolecular vacuum pumps, flywheel energy storage systems and other high speed rotating machinery are the most significant industrial applications. The number of industrial AMB applications is growing steadily.

Why Model Predictive Control (MPC) on AMB systems?

- Input and output constraints
- Stringent control requirements.
- Multivariable system.



Implementation Challenges:

- Inherent nonlinear and unstable open loop nature.
- Very fast dynamics.

The main idea of Model predictive control:
Obtain the control actions by solving, at each sampling time, a **finite-horizon optimal control problem.**

Addressed research problem

- **Linear MPC requieres solving a Quadratic Programming (QP) problem.**

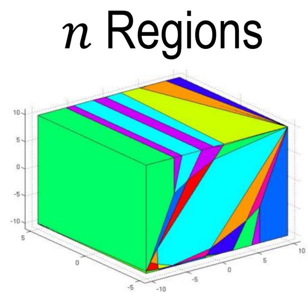
$$\min_{z} \ \frac{1}{2}z'Hz + x'(t)F'z + \frac{1}{2}x(t)'Yx(t) \qquad z = \begin{bmatrix} u_0 \\ u_1 \\ \vdots \\ u_{N-1} \end{bmatrix}$$
$$s.t. \ \ Gz \leq W + Sx(t)$$

The main limitation of MPC in fast dynamic systems is the computational effort required to solve an optimization problem online. Still a lot of research is going on to address real-time requirements…

- **Explicit MPC.** Solve parametrically the QP problem **offline**, resulting in an explicit solution that is function of the measured state and control parameter. The control action is then implemented online in the form of a lookup table.

$$u(x) = \begin{cases} F_1x + g_1 & if \ \ H_1x \leq K_1 \\ F_2x + g_2 & if \ \ H_2x \leq K_2 \\ \vdots \\ F_nx + g_n & if \ \ H_nx \leq K_n \end{cases}$$

n Regions



n depends (exponentially) on the number of constraints. When n grows: too much **memory** required, too much **time** to locate state $x(t)$

- **Implicit MPC.** Fast **online** QP solvers.

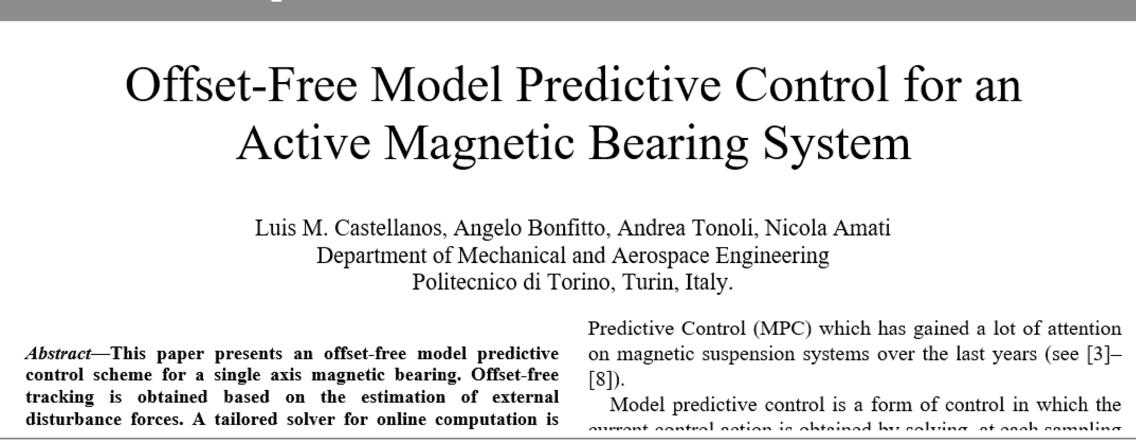
$x(t)$ → Embedded QP Problem → u_0

Some code generation tools:

- FORCES pro
- FiOrdOs
- CVXGEN
- µAO-MPC

Research objective: Verify the feasibility of embedded, online MPC on AMB systems.

Paper for submission


Offset-Free Model Predictive Control for an Active Magnetic Bearing System

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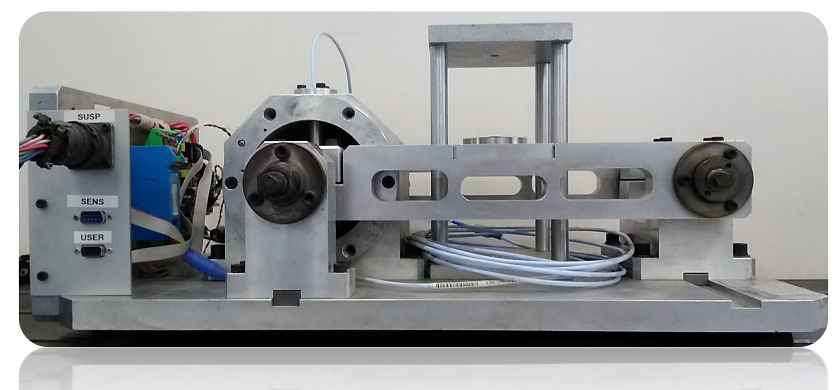
Abstract—This paper presents an offset-free model predictive control scheme for a single axis magnetic bearing. Offset-free tracking is obtained based on the estimation of external disturbance forces. A tailored solver for online computation is

Predictive Control (MPC) which has gained a lot of attention on magnetic suspension systems over the last years (see [3]–[8]).
Model predictive control is a form of control in which the

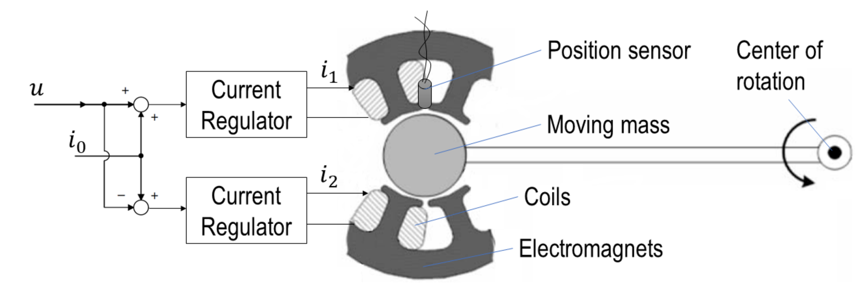
Ongoing Work

MPC implementation in dSPACE MicroLabBox rapid prototyping unit

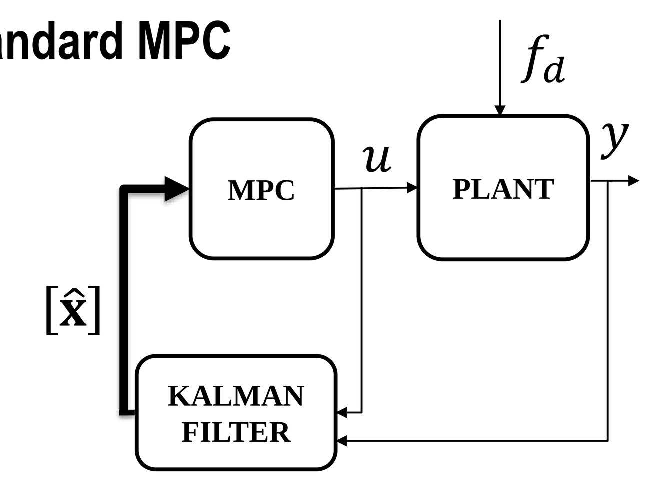
Single Axis Magnetic Bearing



Scheme



Standard MPC

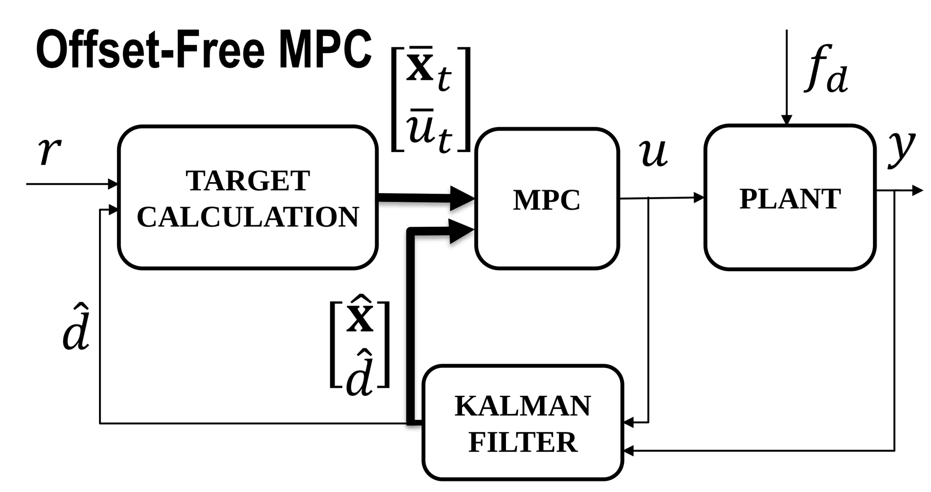


$$\min_{\mathbf{x},u} \sum_{k=0}^{N-1} l(\mathbf{x}_k, u_k) + V_f(\mathbf{x}_N)$$

subj. to:

$$\mathbf{x}_0 = \hat{\mathbf{x}}(t)$$
$$\mathbf{x}_{k+1} = F(\mathbf{x}_k, u_k)$$
$$H(\mathbf{x}_k) \in \mathbb{Y}, \ u_k \in \mathbb{U}$$
$$\mathbf{x}_N \in \mathbb{X}_f$$

Offset-Free MPC

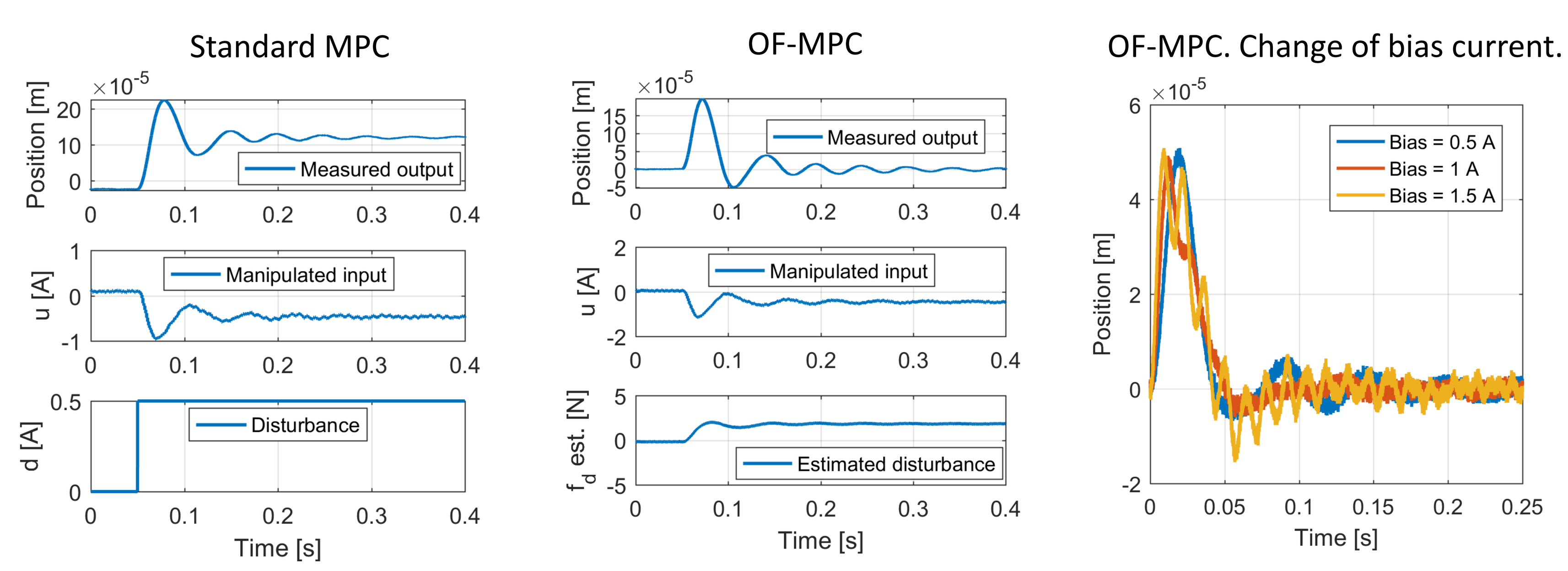


$$\min_{\mathbf{x},u} \sum_{k=0}^{N-1} l(\mathbf{x}_k, \bar{\mathbf{x}}_t, u_k, \bar{u}_t) + V_f(\mathbf{x}_N, \bar{x}_t)$$

subj. to:

$$\mathbf{x}_0 = \hat{\mathbf{x}}(t)$$
$$\mathbf{x}_{k+1} = F(\mathbf{x}_k, \hat{d}(t), u_k)$$
$$H\left(\mathbf{x}_k, \hat{d}(t)\right) \in \mathbb{Y}, \ u_k \in \mathbb{U}$$
$$\mathbf{x}_N \in \mathbb{X}_f$$

Experimental results



- Controller sampling frequency: 1 kHz. Prediction horizon N = 12.
- Standard MPC formulation can not guarantee output zero tracking.
- With OF-MPC, Offset-free tracking is achieved based on disturbance estimation.
- Inacurate models lead to more deteriorated responses and poor performance.
- Many degrees of freedom for tuning.

Future work

- Compare different linear MPC approaches for multi axis AMB systems.
- Implement an explicit MPC controller based on more accurate nonlinear models.
- Test different solvers and c code generation tools on smaller and cheaper boards (i.e., speed, robustness, code simplicity).
- Develop auto-tuning techniques for fast commissioning.

List of attended classes

- 01QSXRU– The measurement of electrical impedance (29/03/2017, 2 CFU)
- 01QTHIU – Techniques of Robust Control (04/07/2017, 6 CFU)
- 01LXBRW - Life Cycle Assessment (03/07/2017, 5 CFU)
- 01QRVIU – Model predictive control: theory and practice (not finished, 4 CFU)