# Model-based control design for inferential and over-actuated control of lightweight motion systems

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### Introduction

Next-generation high-precision positioning systems are designed to be lightweight, in order to enable an increase of the speed of movement. As lightweight systems tend to have complex dynamical system behavior, model-based control design is essential to achieve high-performance. Model-based control typically requires weighting to specify the design objectives, e.g., disturbance attenuation and reference tracking. Hence, for successful control design, the design of weighting functions is of vital importance.

### Weighting function design for lightweight systems

The main control challenge for lightweight systems is the presence of flexible dynamical behavior at frequencies relevant for control. In fact, to achieve high-performance, a controller should be designed that not only delivers accurate positioning at the sensor locations, but also prevents deformation of the structure. This is known as inferential control.

Conventional weighting function design for motion systems [1] poses magnitude bounds on the closed-loop transfer function matrices in order to specify design objectives, see weightings $W_1$ and $W_2$ in Fig.1. However, for lightweight motion systems with flexible phenomena close to the crossover region, i.e., $\sigma_i(L) \approx 1$, the lack of weighting in the mid-frequency range allows lightly damped closed-loop poles, hampering inferential performance. Therefore, weighting should be specified for the dominant gains of the system in all frequency ranges. Fig. 1 shows the proposed design $W_{MF}$ in the mid-frequency range.

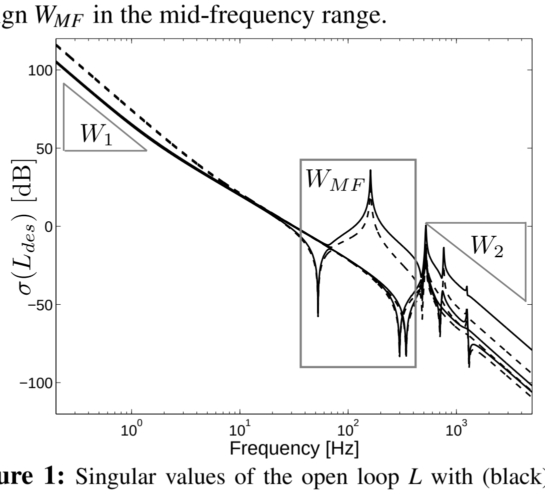


**Figure 1:** Singular values of the open loop $L$ with (black) and without (black dashed) mid-frequency weighting

In this research, conventional design specifications expressed in the weightings $W_1$ and $W_2$ are extended by shaping the dominant gains of the system in the mid-frequency range. The dominant gains in a multivariable system can be shaped if the weighting functions explicitly address the input and output directionality of the system in control-relevant frequency ranges. This is critical, since the directionality associated with deformations of the system is different from the directionality of rigid-body dynamics. The resulting frequency-dependent decoupling enables explicit shaping of the dominant gains. After decoupling the system with respect to the dominant gains, a lead filter is used to create phase lead around the lightly damped flexible mode (Fig. 1).

### Experimental results

The response of a multivariable lightweight motion system to a step excitation in a single motion degree-of-freedom as depicted in Fig 2 shows that the extended weighting function results in additional damping of the closed-loop poles.

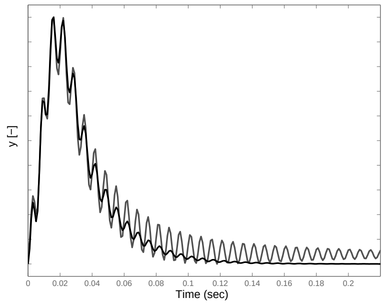


**Figure 2:** Response at the output $y$ for a step in the input disturbance: conventional (gray) and extended (black)

This result shows that exploiting directionality of a multivariable plant is the key to high-performance inferential control for lightweight motion systems.

### Outlook

Although the proposed weighting function design enhances high-performance model-based control, it can not effectively deal with transmission zeros. This typically results in degrading inferential performance. First promising results show that extending the number of actuators and sensors in conjunction with the proposed weighting function design enhances inferential performance.

### References

[1] M. van de Wal, G. van Baars, F. Sperling, and O. H. Bosgra, Multivariable $H_\infty/\mu$ feedback control design for high-precision wafer stage motion. *Contr. Eng. Pract.*, 10(7):735755, 2002.