

Physics-Guided Neural Networks for Feedforward Control: An Orthogonal Projection-Based Approach

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1 Background

Feedforward control can significantly improve the performance of dynamic systems [1]. It aims at finding the input to a dynamic system such that this system's output tracks a desired reference. Typically both high performance and flexibility to varying references are desired. An extensive feedforward control framework that addresses these requirements has been developed for linear time-invariant (LTI) systems, based on system identification and inversion [2], or direct identification of the inverse in a learning setting [3]. Extensions to nonlinear dynamics typically require the dynamics to be fully known [4].

2 Problem Formulation

Increasing performance requirements in industrial applications, such as precision mechatronics, lead to a situation in which the LTI assumption is no longer satisfied. These nonlinear dynamics do not fit the LTI feedforward parametrization and subsequently limit the performance.

The goal is to develop a feedforward control framework that integrates physical models containing prior knowledge together with universal function approximators, e.g., neural networks, to compensate the unknown nonlinear dynamics in an explainable manner.

3 Approach

The developed feedforward framework is a class of nonlinear finite impulse response (FIR) parametrizations, i.e.,

$$f(k) = \sum_{i=0}^{\ell} \theta_i q^{-i} r(k) + \mathcal{C}_{\phi} \left(r(k), q^{-1} r(k), \dots, q^{-\ell} r(k) \right),$$

which is a parallel combination of a linear FIR model and a function approximator \mathcal{C}_{ϕ} acting on the reference and its ℓ lags, parametrized as a neural network with coefficients ϕ .

The parameters θ, ϕ are optimized using an orthogonal-projection based cost function, in which the neural network output in the subspace of the model is penalized through orthogonal projection. This results in uniquely identifiable model coefficients θ .

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4 Results

Figure 1 shows the application of this feedforward framework to a system with nonlinear friction. It illustrates that the developed parallel parametrization (middle) is able to capture the unknown nonlinear dynamics, resulting in high performance, whereas the an LTI parametrization (top) is not able to. The non-uniqueness of the developed parallel parametrization results in opposing contributions, and is removed by the orthogonal-projection based cost function (bottom), such that the neural network captures only the unknown dynamics.

Future research focuses on extending the feedforward parametrization to (nonlinear) zero dynamics for flexible modes, and its application to CT scanners and wafer stages.

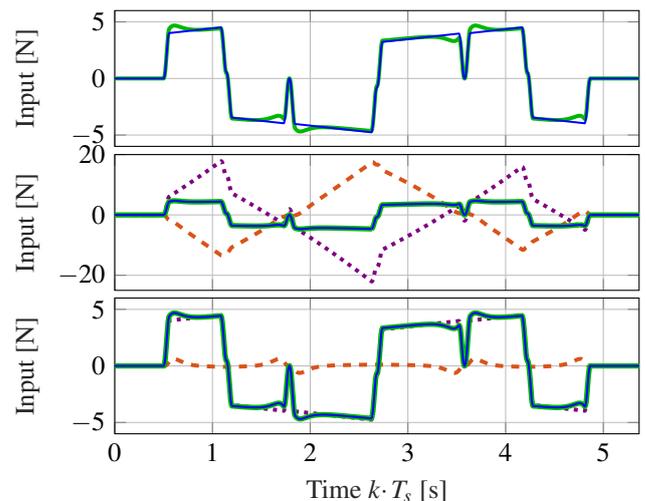


Figure 1: Optimal (—) and generated (—) feedforward with model (···) and neural network (---) for LTI (top) and developed parallel parametrization without (middle) and with (bottom) orthogonal-projection based cost function.

References

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