Nonlinear Modeling with Learned Parameter Refinements for NMPC on a Real-World Aerodynamic System

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Summary

- Comparison of classical and machine-learning modeling methods
- Design of a nonlinear model predictive controller
- Hard real-time implementation in C++
- Evaluation on a real-world AWE prototype

Modeling

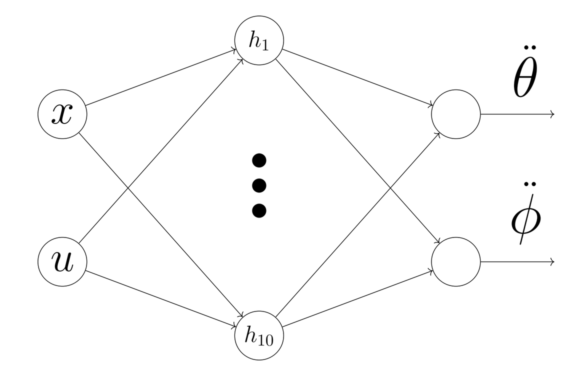
- Classic Approach: Quadratic Model & LLS Fitting

$$\dot{x}_i = x^\top A_i^{\text{quad}} x + A_i^{\text{lin}} x + B_i u + C_i$$

linear: $A_i^{\text{quad}} = 0, C_i = 0$
affine: $A_i^{\text{quad}} = 0$

lasso, **elastic** and **huber** use respective regularizer with learned weighing parameters

- Novel approach:
  - approximate system dynamics via neural network (NN)
  - nonlinear state augmentation (quadratic and trigonometric)



Real-world setup

- Reduced-DOF plane for rotational start experiments
- Custom hardware designed in-house for sensor/actuator IO
- Fully equipped for lift-mode energy production

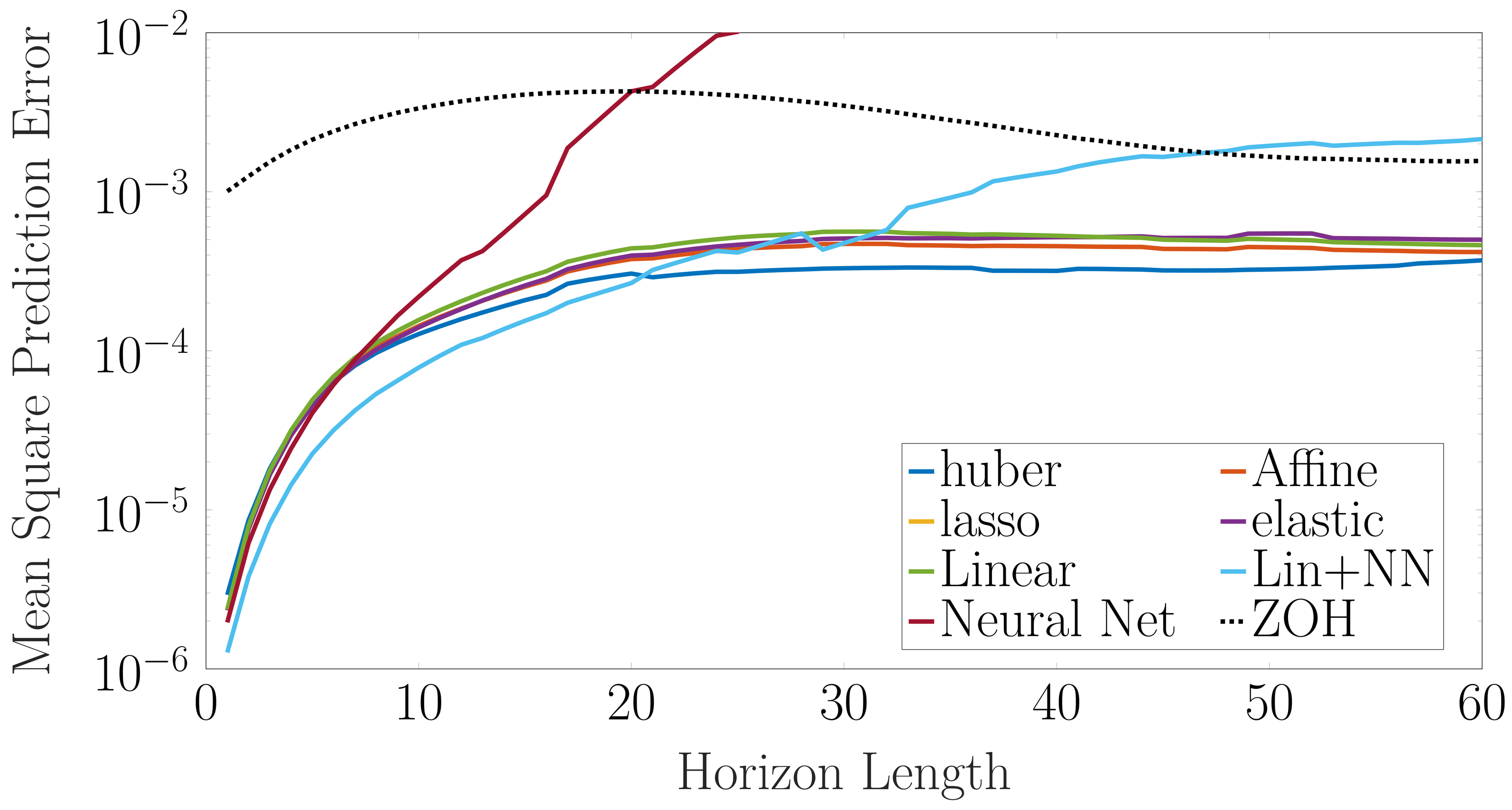
Control

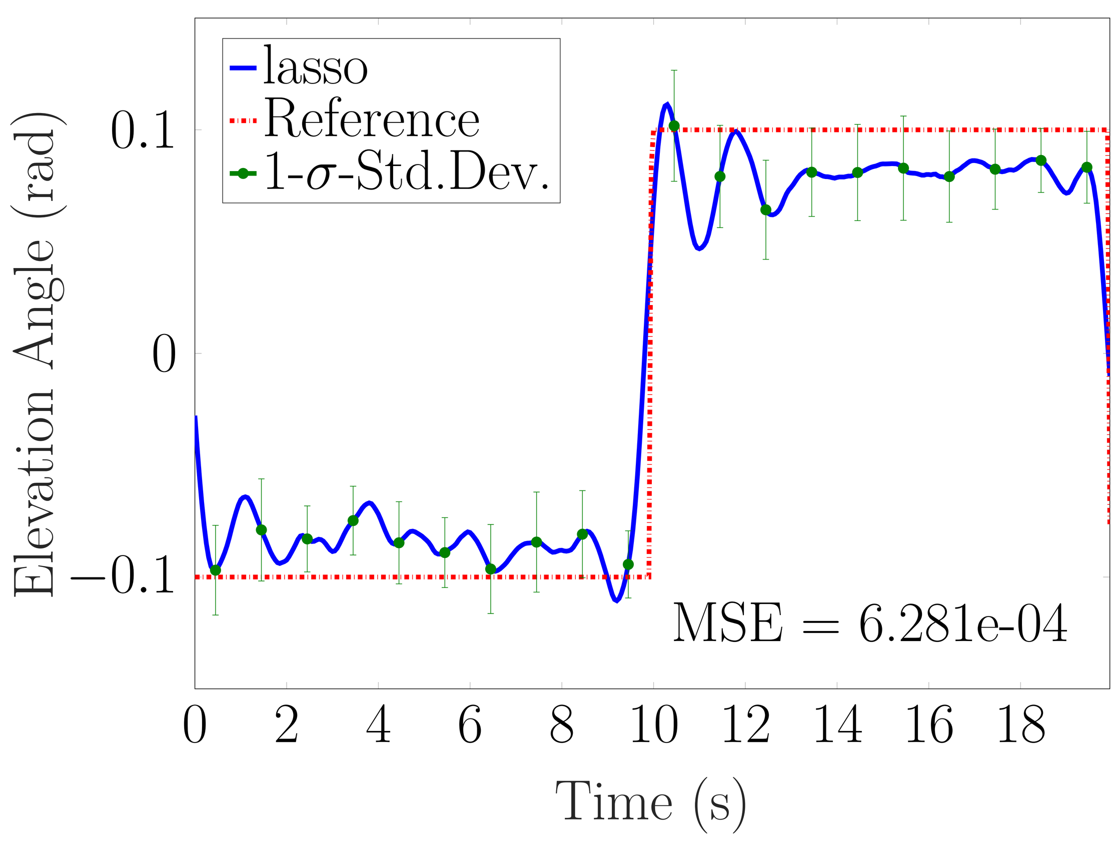
- Nonlinear Model Predictive Control (NMPC)
- Direct Multiple Shooting using explicit RK4
- Gauss-Newton Hessian approximation + condensing
- Constrained control surface position and speed
- C++ Code Generation from MATLAB via ACADO / QPOASES
- 4 states, 1 control, 100 steps, @20Hz, 5 sec Horizon

Conclusion

- Robust results with linear regression fit
- Quadratic elements can reduce error, but are easy to overfit
- ML refinements achieve further improvement reduce overfitting
- Neural networks achieve good short time prediction and are suitable for integration in NMPC
- Evaluation on real-world setup shows adequate performance of machine learning approaches in a real-time control setup
- Future research aims to apply the presented approaches to tethered flight operation

Experimental Results





Model	MSE
lasso	**6.281e-04**
linear	6.826e-04
elastic	6.949e-04
quad	9.100e-04
huber	9.161e-04
ridge	1.826e-03
Δu-lin	3.164e-03
Lin+NN	1.269e-02