AE4320: System Identification of Aerospace Vehicles

Assignment

Pilot Model Identification

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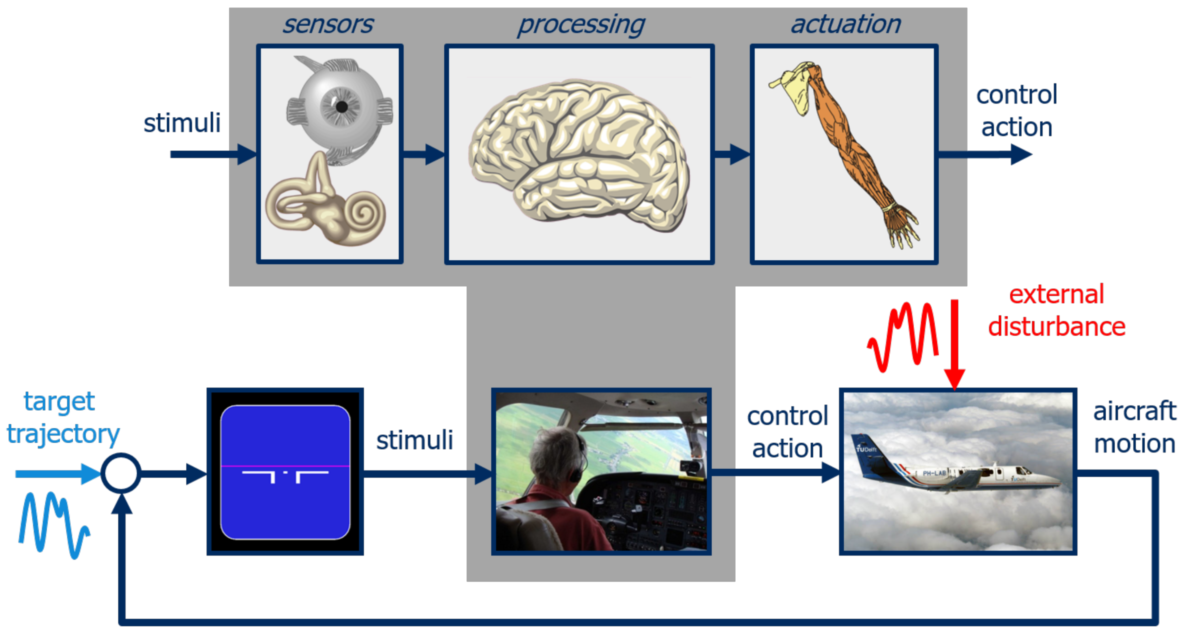
This document describes one of the assignments of the course on advanced system identification. In this assignment, you will consider system identification, parameter estimation, and model validation applied to *measured pilot control dynamics* in a closed-loop tracking task. This take-home assignment consists of 6 parts. The deliverable of the assignment is a report of **maximum 20 pages** containing the background, theory and results of the 6 parts, and the Matlab or Python source files used to obtain all reported results.

For your pilot model identification assignment you only need to analyse **one of the ten** available datasets. You select your dataset based on the **FINAL** digit in your study number. So, for example, if your study number is **5423310** the final digit is **0**, so you have to use the data file in the **dataset0** folder.



Description of the Dataset

In a tracking task as shown in Figure 1, a pilot is manually controlling the "controlled element", whose dynamics are given by the transfer function $H_c(s)$. For the tracking task you will be considering, the pilot was to make the controlled element follow the reference trajectory defined by the target forcing function f_t, while also countering the perturbation of the controlled element by the disturbance forcing function f_d. These two forcing function signals are both multisine signals, to allow for application of black-box frequency-domain system identification for this closed-loop system. As indicated in Figure 1, the input and output of the pilot's control dynamics are the tracking error signal (e) and the control signal (u), respectively. In this assignment, you will apply system identification techniques to find a good model for describing the pilot dynamics $H_p(s)$ based on real measurements of these in- and outputs of the pilot.

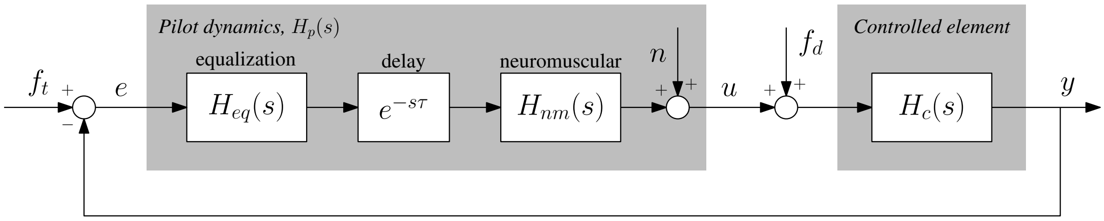


Figure 1: Block diagram of a tracking task.

For this assignment you will receive **two datasets**, one for performing system identification and parameter estimation, and another for performing model validation. Both datasets include a single measurement (time trace) of e and u. In addition, the time traces of the forcing function signals f_t and f_d are also included in your dataset.

Part 1: Report introduction (10 points)

You are asked to write a brief introduction (max. 1.5 pages) for your report which should contain the following items:

1. A brief introduction on the characteristics of pilot control behavior in tracking tasks, as depicted in the block diagram of Figure 1. (**3 points**)

2. A brief explanation of the working principles of system identification techniques and parameter estimation methods. (**2 points**)

3. A discussion of the relevance of System Identification for investigating the characteristics of pilot control behavior. (**5 points**)

Part 2: Identifying the pilot control dynamics FRF (15 points)

You are asked to apply a black-box system identification technique for estimating the frequency response function (FRF) of the pilot control dynamics $H_p(s)$ from supplied measurements of the tracking error signal (e) and the control signal (u):

1. Determine the excitation frequencies at which this FRF of the pilot can be estimated from the measurements of the forcing function signals, f_t and f_d. (**5 points**)
   Hint: These excitation signals are multisine signals (both sums of 10 sinusoids). The frequencies of the individual sinusoids in the signals can be obtained from the Fourier transforms of these signals.
   Note: The Fourier transform should only be applied to data covering exactly the measurement window for your dataset, which is 81.92 seconds in length!

2. Estimate the FRF of the pilot control dynamics using the identification dataset. (**5 points**)
   Hint: Use the Fourier transforms of the error and control signals to estimate the FRF using:

   $$\hat{H}_p(j\omega) = \frac{U(j\omega)}{E(j\omega)} \tag{1}$$

   Take care that you only estimate $\hat{H}_p(j\omega)$ at the excitation frequencies (so where there are peaks in the Fourier transforms of e and u)!

3. Present your estimate of the pilot control dynamics in a Bode plot, with a `loglog` plot for the magnitude response of the system and a `semilogx` plot for the phase response. (**5 points**)

4. Hand in the code used in this part in a separate, well documented file.

Part 3: Parameter estimation & model selection (30 points)

You are asked to fit three different models for the pilot dynamics from literature to your measured data (i.e., estimate their parameters) and compare the fits. The general form of a transfer function model that can be used to describe the measured pilot control dynamics is given by:

$$H_p(s) = H_{eq}(s)e^{-s\tau}H_{nm}(s) \tag{2}$$

with the neuromuscular dynamics $H_{nm}(s)$ modelled as a second-order system:

$$H_{nm}(s) = \frac{\omega_{nm}^2}{s^2 + 2\zeta_{nm}\omega_{nm}s + \omega_{nm}^2} \tag{3}$$

It is already known that the model for the pilot control dynamics needs to include these neuromuscular dynamics and a delay term, as these terms account for inherent limitations of the pilot. That leaves as an unknown the "real" manual control dynamics, here referred to as the pilot equalization dynamics $H_{eq}(s)$. In literature, the transfer function models for $H_{eq}(s)$ listed in Table 1 have been proposed. Note from Table 1 that these different equalization models result in a different number of parameters for the total model for $H_p(s)$, as indicated with the number between brackets in the final column.

Table 1: Proposed pilot equalization models

Symbol	Equalization model	Parameters (#)
A	K_p	$K_p,\ \tau,\ \zeta_{nm},\ \omega_{nm}$ (4)
B	$K_p(T_L s + 1)$	$K_p,\ T_L,\ \tau,\ \zeta_{nm},\ \omega_{nm}$ (5)
C	$K_p \dfrac{T_L s + 1}{T_I s + 1}$	$K_p,\ T_L,\ T_I,\ \tau,\ \zeta_{nm},\ \omega_{nm}$ (6)

The following items should be included in your report/code:

1. A description of what the different equalization models listed in Table 1 actually mean. (**5 points**)
   Hint: For example, model A implies that pilots' control inputs u are directly proportional to the error e.
2. Formulate a complex least-squares cost function $J(\theta)$ for fitting the pilot models to the estimated FRF from Part 2 and implement it in a Matlab/Python script. (**5 points**)
   Hint: The only output of the cost function script should be the cost function value J. This cost function value is a function of the parameter vector of the model, θ, and should return the sum of the squared complex errors between the FRF and the frequency response of the model for all forcing function frequencies that is obtained for certain θ. In addition, none of the pilot model parameters should become negative. So, add a large penalty term (say 10^6) to your cost function value if any of the model parameters fed to the cost function are negative.
3. Use a nonlinear function optimizer (e.g., `fminsearch` in Matlab or `fmin` in Python) to find the parameter vector that minimizes the cost function for all three models A-C. (**10 points**)
   Hint: Note that `fminsearch`/`fmin` requires you to supply an initial estimate of your parameter vector. You will notice that your final parameter estimate may depend on what you select as the initial parameter estimate. As you may not find the best estimate of your parameters when you only consider one initial parameter set, **consider <u>a minimum of 5</u> different initial conditions** for `fminsearch`/`fmin`, **report on the variation in outcome**, and only use the best fit to your data (lowest J) as your final model.
4. Present the frequency responses of your fitted models for equalizations A-C in a Bode plot together with the estimated FRF from Part 2, with a `loglog` plot for the magnitude response of the system and a `semilogx` plot for the phase response. Also include a Table in your report with the estimated parameter values for all three models. (**5 points**)
5. Compare the model fits for equalizations A-C based on their final cost function values, as well as how well they correspond to the FRF estimated in Part 2, and select the best model for your data. (**5 points**)
6. Hand in the code used in this part in a separate, well documented file.

Part 4: Proposing and fitting an extended model (20 points)

You are asked to verify from your fitted models from Part 3, whether perhaps an extended model is needed for accurately describing your estimated FRF:

1. Argue what extension to the model that provides the best fit to your FRF may provide an even better fit, by comparing its frequency response to the FRF. (**5 points**)
   Hint: Have a very critical look at how well your best fitted model matches the FRF. Is there a range of frequencies for which it could perform better? Decide where you think adding/removing **at most one lead or lag term** to/from the equalization model perhaps provide an even better fit.

2. Consider your extended model as "**model D**" and estimate its parameters using your cost function and `fminsearch`/`fmin`. Make a new Bode plot, showing the FRF from Part 2, the best model from Part 3, and your extended model. (**10 points**)

3. Critically evaluate your proposed pilot model extension by comparing the frequency responses, the estimated values for the model parameters, and the final cost function values. (**5 points**)
   Hint: Did your proposed model really provide a better fit to your data, as expected?

4. Hand in the code used in this part in a separate, well documented file.

Part 5: Validating all fitted models (15 points)

You are asked to validate all of your fitted models (A-D) using the <u>validation dataset</u>. So far, you should have only made use of the <u>identification dataset</u>!

1. Estimate the FRF of the pilot control dynamics based on the error e and control signal u measurements included in the *<u>validation dataset</u>*. (**5 points**)
2. Calculate the cost function values for your estimated parameter for models A-D from Parts 3 and 4 based on the validation dataset FRF. Include a table in your report that lists the cost function values for the identification and validation datasets side-by-side for all four models. (**5 points**)
   Hint: Note that this does **<u>not</u>** require you to estimate your model parameters again!
3. Critically evaluate your model validation results and compare them to your results of the model identification phase. (**5 points**)
   Hint: Do the results from the validation dataset change your conclusions on what is the best model?
4. Hand in the code used in this part in a separate, well documented file.

Part 6: Report conclusions (10 points)

You are asked to write a brief conclusions section (max. 0.5 page) for your report which should at the least contain the following items:

1. A summary of the identification problem and the identification and validation methods that were applied. (**2 points**)
2. A description of your proposed extended model (model D) and its performance compared to the models taken from literature. (**3 points**)
3. Final conclusions on which of the considered models provides the best fit to your (identification and/or validation) datasets. (**5 points**)