ACS6116 Advanced Industrial Control
Model Predictive Control

Assignment

Dr Paul Trodden
p.trodden@shef.ac.uk
Room C10, AJB

Assignment weighting
25% (of the total mark for ACS6116)

Assignment released
Wednesday 27th March 2019 (Week 8)

Assignment due
23:59:59 on Wednesday 15th May 2019 (Week 12)

Penalties for late submission
Late submissions will incur the usual penalties of a 5% reduction in the mark for every working day (or part thereof) that the assignment is late and a mark of zero for submission more than 5 working days late. For more information see `http://www.shef.ac.uk/ssid/exams/policies`.

Feedback
This will include the overall mark, individual component marks and comments on performance on the assignment. The attached assessment criteria (at the back of this document) provides a guide to what areas the feedback will be provided on. Note that marks may be subject to change as a result of unfair means.

Unfair means
The assignment should be completed individually. You should not discuss the assignment with other students and should not work together in completing the assignment. The assignment must be wholly your own work. References must be provided to any other work that is used as part of this assignment. Any suspicions of the use of unfair means will be investigated and may lead to penalties. See `http://www.shef.ac.uk/ssid/exams/plagiarism` for more information.

Exenuating circumstances
If you have extenuating circumstances that cause you to be unable to submit this assignment on time or that may have affected your performance, please complete and submit a special circumstances form along with documentary evidence of the circumstances. See `http://www.sheffield.ac.uk/ssid/forms/circs`, particularly noting point 6 (Medical Circumstances affecting Examinations/Assessment).

Assignment briefing
This laboratory assignment will assess your fundamental understanding of Model Predictive Control and your ability to design MPC controllers and simulate MPC-controlled systems.

The assignment comprises an open-ended design exercise: you are asked to design and evaluate an MPC controller for a given system, subject to a performance specification.

Produce a report (limit: 4 pages) containing your answer.

In order to create a level playing field between candidates' submissions, you are asked to prepare your submission using the document templates supplied on MOLE. This is a 10pt, two-column format, which allows ample space for this assignment even with the 4-page limit. (Please note that no appendices are necessary, and any appendices included will not be read.)

It is up to you how you tackle the problem and stucture your answer. However, you are strongly advised to consult (i) the help below and (ii) the attached assessment criteria (at the back of this document) for guidance on what to include.

Assessment criteria
The assessment criteria for this exercise are derived from the module learning outcomes:

1. Describe and explain the principles of more than one advanced control technique.
2. Analyse practical performance specifications and convert these into functional requirements on controllers.
3. Design, implement and evaluate an advanced control system against these requirements.
4. Compare and contrast different advanced control solutions to a particular control problem or application.
5. Describe the receding-horizon principle, and hence compare and contrast LQ-optimal control and MPC.

6. Construct a constrained finite-horizon optimal control problem — including constraint, model and cost definition — re-formulate it as an optimization problem, and recall and evaluate the analytical expression for the control law in the unconstrained case.
7. Analyse, design, implement and simulate MPC controllers with guaranteed properties, including feasibility, stability and offset-free tracking.

In particular, learning outcomes 2, 3, 6 and 7 are relevant to this assessment, and the attached assessment criteria — the marksheet that will be used to assess the assignment — are derived from these.

The marksheet indicates the criteria that will be used in assessing your answer, and also the expectation for each criterion in order to achieve a mark within the specified ranges. It is strongly recommended that you study this marksheet before completing the assignment.

Please note that a **4-page limit**, using the supplied template, applies to your report, and you should consider carefully how you can effectively meet the assessment criteria within this limit.

Guidance

- This assignment briefing, lecture slides, and the laboratory exercise document provide all the information that is required to complete this assignment.
- Basic MATLAB programming is required, including the use of functions and loops; however, in tackling the assignment you may use the MPC-specific MATLAB functions (used in the laboratory exercises) available on the MOLE page for ACS6116, plus any code you developed during the laboratory exercises.
- You may ask questions in the staffed laboratory sessions about Model Predictive Control and MATLAB functionality that may be of use within this assignment. However, you are **not** allowed to ask specific questions as to how to solve the exercises in the assignment.
- The non-assessed exercises which you completed in the laboratory are necessary preparation for this assignment. However, the laboratory exercises were well structured, whereas this assignment is open-ended: you need to decide what is the most appropriate approach to solve this assignment, and also how to present your results.
- Regarding the report, you are reminded again that you are strongly recommended to consult the attached assessment criteria for guidance on what to include and to what level of detail. In particular, the assessment criteria suggest that your report should include
  - Details of the optimal control problem / MPC formulation you used, including the correct identification and implementation of constraints and any modifications necessary for tracking.
  - A description and explanation of how the controller was designed and tuned in order to meet the specification, including the selection of all parameters, with correct explanations and justifications.
  - Clear reporting and discussion of results (including clear, *labelled* plots), and critical evaluation of the controller. (Think about more than just “Did my controller meet the spec.?” — what are the strengths and weaknesses of your controller? What could be improved?)
  - Some analysis, evaluation and/or qualification of stability and feasibility — does your design come with stability and feasibility guarantees? If so, what are these, and how are they achieved? What else can you say or show?

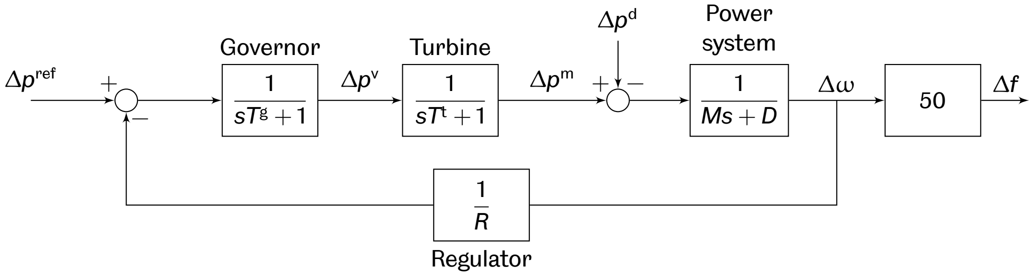
  This is not an exhaustive list. You do not need to include the code that you write, but you may do so (*e.g.* snippets of code) if you think it adds value to your report.

  Please note that, in order to achieve the highest marks, you will need to go beyond simply implementing the methods that you have learned in the lectures and, to some extent, practised in the lab. As a guide, a student who designs and implements a controller that meets spec., and reports this in a clear manner, addressing all of the assessment criteria, might gain a mark of around 70.

- Should you need clarification on any part of the assignment then please ask a GTA, email me (`p.trodden@shef.ac.uk`) or come to my office, C10, Amy Johnson Building.

Submit your report via MOLE/Turnitin by 23:59:59 on Monday 6th May 2019

The operation of an isolated power system under primary frequency control is modelled by the following block diagram.



In this system, a steam turbine produces mechanical power, which is subsequently converted to electrical power via a synchronous generator connected to the grid. A change in power demand, Δp^{d}, causes the system frequency f (Hz) to change. The control objective is to drive frequency deviations, Δf, to zero following a demand change, Δp^{d}. To aid this, a governor controls the steam flow input to the turbine in response to the error between the reference power Δp^{ref} and the regulated frequency $\Delta\omega/R$, where $R > 0$ is the regulation factor.

The primary frequency control loop present in the system is, unfortunately, unable to regulate the frequency error to zero following demand changes (why?). Therefore, the aim is to design a *secondary* frequency control loop that will adjust the reference power Δp^{ref} in response to frequency deviations $\Delta\omega$, in order to eliminate error and improve transient performance. To this end, a continuous-time state-space model of the system is given as:

$$\begin{bmatrix} \Delta\dot{\omega} \\ \Delta\dot{p}^{\mathrm{m}} \\ \Delta\dot{p}^{\mathrm{v}} \end{bmatrix} = \begin{bmatrix} -D/M & 1/M & 0 \\ 0 & -1/T^{\mathrm{t}} & 1/T^{\mathrm{t}} \\ -1/(RT^{\mathrm{g}}) & 0 & -1/T^{\mathrm{g}} \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta p^{\mathrm{m}} \\ \Delta p^{\mathrm{v}} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1/T^{\mathrm{g}} \end{bmatrix} \Delta p^{\mathrm{ref}} + \begin{bmatrix} -1/M \\ 0 \\ 0 \end{bmatrix} \Delta p^{\mathrm{d}}$$

$$\Delta f = \begin{bmatrix} 50 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta p^{\mathrm{m}} \\ \Delta p^{\mathrm{v}} \end{bmatrix}$$

In this model, the input, u, is the change in reference power to the turbine governor, i.e., Δp^{ref} (in *per unit* (p.u.) – that is, normalized with respect to a base value), and the output, y, is the frequency of the power system, i.e., Δf (Hz). The states are the (deviations from operating points in) angular frequency, $\Delta\omega$, mechanical output power of the steam turbine, Δp^{m}, and output power reference from the turbine governor, Δp^{v}. The demand change Δp^{d} is a disturbance, d. For the particular power system under consideration, the model parameters are

$$M = 10, D = 0.8, R = 0.1, T^{\mathrm{t}} = 0.5, T^{\mathrm{g}} = 0.2$$

Your task is to design, implement and tune an MPC controller for this system in order to meet the specification on the following page. Your design should specify, as a minimum,

- Constraints
- Cost weighting matrices Q and R
- Horizon length N
- Any terminal conditions employed — the cost matrix P and any constraints on $x(k+N|k)$
- Any modifications to the formulation for tracking and disturbance rejection

Designs with smaller N are typically (but not necessarily) preferable. A strong design will achieve *guarantees* of stability and recursive feasibility. You may assume that the state x and disturbance d are fully measurable. To obtain the discrete-time prediction model for controller, use a sampling time of 0.1 seconds and zero-order hold sampling (*i.e.* `sysd = c2d(sysc,0.1)` in MATLAB).

Specification
In response to a large step-change in demand—up to 0.3 p.u. in magnitude—the closed-loop system

- maintains stability
- frequency settles to $|\Delta f| \leqslant 0.01$ Hz within 2 seconds of the disturbance initiation
- satisfies the constraints

$$\begin{aligned} |\Delta p^{\mathrm{ref}}| &\leqslant 0.5 \\ |\Delta f| &\leqslant 0.5 \end{aligned}$$

- exhibits zero steady-state error in the output

(40 marks)

Criterion	Level				
	0–50%	50–60%	60–70%	70–80%	80–100%
Formulation (10 marks): starting from a problem description, formulate and implement a finite-horizon optimal control problem (OCP), including definition of model, cost, constraints (and any modifications for tracking, etc)	Little or no evidence of a correct formulation and implementation	A formulation is presented and implemented, and is essentially correct but with minor errors; or, the formulation and implementation is correct, but details are unclear or not explained	A formulation is presented and correctly implemented, with basic explanations	A formulation is presented and correctly implemented, with comprehensive explanations and analysis where needed	Formulation and implementation is to a standard that exceeds expectations; for example, using advanced techniques, further analyses, and/or insightful explanations
Design and tuning (10 marks): design and tune an MPC controller in order to meet a specification, including selection of controller parameters	Little or no evidence of tuning	Evidence of tuning, with some explanations of the effects of different parameters	Clear evidence of tuning, with explanations, justification, and links to the specification	Comprehensive evidence of systematic tuning, with concise and correct explanations and justification of the tuning decisions made to meet the specification	Evidence of design and tuning that exceeds expectations, including concise and insightful explanations and discussions, and further analyses
Simulation and evaluation (10 marks): demonstrate that an MPC controller meets a specification, and critically evaluate its design and performance	Little or no evidence of simulations and results	Evidence of simulation results that show the spec. as been met, but with minimal evaluation and critical analysis	Simulation results correct, presented clearly (including labelled plots), and discussed; basic critique of controller	Clear presentation of correct simulation results, with insightful and comprehensive discussion, including critique of controller	Presentation and discussion of results, and evaluation of controller, that exceeds expectations
Stability, feasibility, and advanced considerations (10 marks): construct MPC controllers with guaranteed properties	Little or no consideration of feasibility and stability	Evidence (e.g. plots) of a system with properties (emphi.e. stability is evident)	Evidence of a guaranteed stability, supported by explanations and/or some basic analyses	Evidence of guaranteed stability, supported by comprehensive analysis and explanations	Evidence of stability analysis that exceeds expectations, including use of advanced techniques