# LaTeX Lab Report Template

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**Abstract**

This document outlines a few important aspects of a lab report. It contains some advice on both content and layout. The LaTeX source for this document is also published, and you can use it as a template of sorts for your own report. You can find an up to date version of the source at `https://github.com/ntnu-itk/labreport`. The main file, "labreport.tex", defines the structure of the document. The "preamble.tex" file is the document preamble, and contains a lot of informative comments. The document is based on work done by Tor Aksel Heirung for TTK4135, and is now under continuous improvement by Andreas L. Flåten and Kristoffer Gryte (happily accepting suggestions and contributions from the community).

When you write your own report, this section (the abstract) should contain a *very* short summary of what the lab is about and what you have done.

# Contents

# 1 Introduction

Your introduction should contain an overview of the work you were assigned, as well as a few sentences putting the work into a larger perspective. You should also give a quick description of how the report is organized (as is done below).

You should of course put most of the work into doing good work in the lab and then presenting it in the report. When presenting your work in the report, both content and presentation/layout matters. Since your only way of communicating your good effort in the lab is through writing about it here, the way you write about it is essential. This means that even if you have the very best controller but describe it poorly, you will probably not be rewarded for the good results. A plot showing perfect control is worth very little if it is not accompanied by a clear description of what it represents.

Layout is naturally less important than content, but it still matters. You can think of report writing like selling an apartment; when you present your apartment for potential buyers you will of course clean the apartment and make it good looking. How clean the apartment is does of course not determine its value, but it is still important since it influences the subjective value your buyers will put on the apartment.

## 1.1 Software

You are of course free to use whatever software you want for report writing. You can also submit a handwritten report, although this is probably not a great idea if your handwriting can be hard to read.

You can also use Word or a similar word processor. However, it is next to impossible to achieve decent layout with Word. The support for vector graphics (discussed later) is extremely poor, and text tends to look pretty bad (bad support for kerning and ligatures). Furthermore, math is both time consuming and difficult to input, and tends to look very ugly. In general, a report written in Word looks like a draft.

It is strongly recommended to use Latex. Unless you tweak the layout too much, your report will almost certainly look very good. Although it can take a bit of effort to get started, it is also much quicker to use than Word and similar programs. The support for math and vector graphics is also great.

If you are new to Latex, you can have a look at the source for this document to get started. You can also look at the presentation by [1] (in Norwegian) or consult [3]. Another good reason to learn Latex is that you probably don't want to write your master's thesis in something like Word, doing so would likely be very frustrating. Being reasonably fluent in Latex before you get that far will make your thesis work much smoother.

Some of you are probably fluent in Latex and might plan to write the report using it. Please resist the temptation (if any) to change the fonts, make super fancy headers (they are not necessary for a report like this), change the margins, change the paragraph indentation and/or spacing, and similar things.

A great tool for collaborating on Latex documents is ShareLaTeX at `https://www.sharelatex.com/`; if you use this you won't have to install anything on your computer. Texmaker at `http://www.xm1math.net/texmaker/` is a good cross-platform editor. Some people like Lyx, which is a Latex editor that behaves a little bit like Word. If you prefer to compile your Latex document on the command line, the latexmk `https://www.ctan.org/pkg/latexmk` command is a great tool included in most TeX distributions. There is also a simple Vim plugin that uses latexmk as its backend called LaTeX-BoX `https://github.com/LaTeX-Box-Team/LaTeX-Box`.

## 1.2 Other Comments

Unless you have a very good reason not to, you should write the report in English. If you have problems with Latex, the solution is usually just a few Google searches away.

This report is organized as follows: Section 2 contains some course specific equations, and some tips on how to create illustrations. Several LaTeX tips can be found in **??**, such as how to create a table and matrix equations. Section 4 contains some advice on using plots from MATLAB. The closing remarks are in Section 5, respectively. Appendix A contains a MATLAB file while Appendix B shows an example Simulink diagram. The Bibliography can be found at the end, on page 17.

## 2 Problem Description

You should have a section that describes the lab setup, including a model of the helicopter. If you want, you can copy the source code for the model equations:

$$\ddot{e} + K_3 K_{ed}\dot{e} + K_3 K_{ep} e = K_3 K_{ep} e_c \quad (1)$$
$$\ddot{p} + K_1 K_{pd}\dot{p} + K_1 K_{pp} p = K_1 K_{pp} p_c \quad (2)$$
$$\dot{\lambda} = r \quad (3)$$
$$\dot{r} = -K_2 p \quad (4)$$

Since these equations belong together, it's a good idea to number them like this:

$$\ddot{e} + K_3 K_{ed}\dot{e} + K_3 K_{ep} e = K_3 K_{ep} e_c \quad (5a)$$
$$\ddot{p} + K_1 K_{pd}\dot{p} + K_1 K_{pp} p = K_1 K_{pp} p_c \quad (5b)$$
$$\dot{\lambda} = r \quad (5c)$$
$$\dot{r} = -K_2 p \quad (5d)$$

You can then both reference individual equations ("the elevation equation Equation (5a)") or reference the entire model ("the linear model Equation (5)"). Regardless of your choice of software, never hard-code a reference, always use dynamic references.

You could also align the equations like this:

$$\begin{aligned}
\ddot{e} + K_3 K_{ed}\dot{e} + K_3 K_{ep} e &= K_3 K_{ep} e_c && (6a)\\
\ddot{p} + K_1 K_{pd}\dot{p} + K_1 K_{pp} p &= K_1 K_{pp} p_c && (6b)\\
\dot{\lambda} &= r && (6c)\\
\dot{r} &= -K_2 p && (6d)
\end{aligned}$$

You can consult [2] for more about writing math.

### 2.1 Illustrations

If you decide to include an illustration, that's great. You can in general copy figures and illustrations from the textbook, the assignement text, or other places. However: ALWAYS CITE THE SOURCE. You can also draw your own (cite the source if it is heavily based on someone else's.). Figures 1 and 2 was created quickly with Ipe (`http://ipe.otfried.org/`). Inkscape is a good alternative for more advanced illustrations. Some people prefer the Latex package TikZ (`http://texample.net/tikz/examples/`), but this takes a little effort to learn.

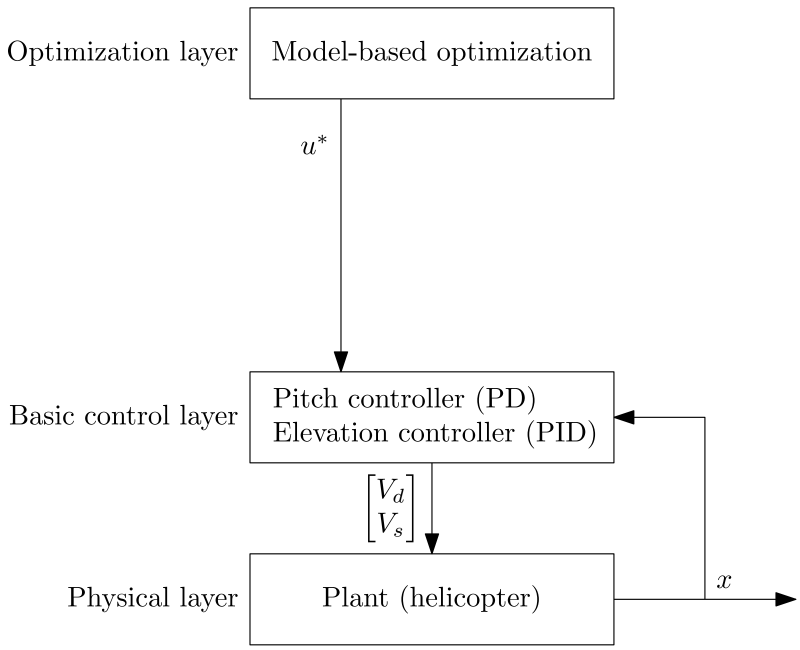


Figure 1: A figure created with Ipe for TTK4135.

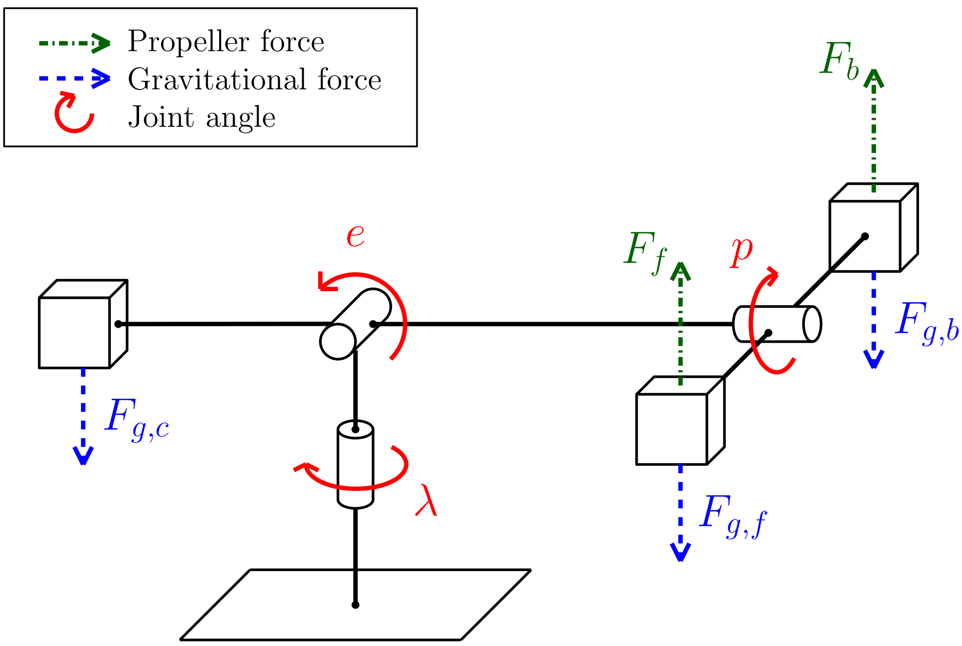


Figure 2: A figure created with Ipe for TTK4115.

# 3 Multivariable control

## 3.1 Introduction

As the helicopter is a complex system with multiple states, it is reasonable to implement a multivariable control system. The system is controlled by an LQR-controller, as it provides an intuitive way to design a control rule based on minimizing a cost function. Analyzing the controllability matrix of the system showed that the system was indeed controllable. Because the LQR controller provides the feedback gain maktrix $K$ which minimizes a cost function based on the states and input, it will naturally try to drive the states towards 0. In order to actually have the states reach their target reference, a feed forward input is also implemented. Lastly because our system, and also thus our control rules, are based on a linearized approximation of the real system there has been added an integral action to remove the steady-state error.

The system matrices (before the integral action) are shown in 7.

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \; B = \begin{bmatrix} 0 & 0 \\ 0 & K_1 \\ K_2 & 0 \end{bmatrix} \tag{7}$$

Using this we can calculate the controllability matrix 8, which has a rank of 3 and the system is thus controllable.

$$\mathcal{C} = \begin{bmatrix} 0 & 0 & K_1 & 0 & 0 \\ 0 & K_1 & 0 & 0 & 0 \\ K_2 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{8}$$

Our control rule is then given by 9, where $K$ is given by LQR and $F$ is derived in 10 from $K$ to drive the system to our target reference $r$.

$$u = -Kx + Fr \tag{9}$$

$$F = \begin{bmatrix} K_{11} & K_{13} \\ K_{21} & K_{23} \end{bmatrix} \tag{10}$$

The system matrices (after the integral action) are shown in 11. The G matrix here is being multiplied the the reference.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \end{bmatrix}, \; B = \begin{bmatrix} 0 & 0 \\ 0 & K_1 \\ K_2 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \; G = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{11}$$

## 3.2 Hypothesis and test plan

All our test were conducted the same way with a test plan structured as this:

- Start up the system.
- Apply a change in the reference from 0 to $\frac{\pi}{4}$ between time 3s and 5s.
- Simulate a disturbance by applying an external pulse in the input voltage at 13s.

The main things we wanted to test was how different choices of Q and R affected the sytem as well as how the integral action affected the system. We came up with 5 cases to test the relation between Q and R, and tested these 5 cases both with and without integral action:

- $R = 5\mathbf{I},\ Q = \mathbf{I}$
- $R = 100\mathbf{I},\ Q = \mathbf{I}$
- $R = \mathbf{I},\ Q = 5\mathbf{I}$
- $R = \mathbf{I},\ Q = 100\mathbf{I}$
- $R = \mathbf{I},\ Q = \mathbf{I}$

Our Hypothesis were that an R larger than Q would give a slow system response as the cost of the input was weighted higher than the cost of the state, meanwhile the opposite would give a fast response. When both Q and R were equal to an identity matrix we hypothesized that we would get some form of balanced response. As for with or without integral gain our hypothesis was that the integral gain would remove the steady state error of the system.

## 3.3 Results

Here are the test results for all the cases

### 3.3.1 $R = 5\mathbf{I},\ Q = \mathbf{I}$

The pitch response fails to even respond to the reference at all without the integral action. The integral helps some but the response is still very sluggish.

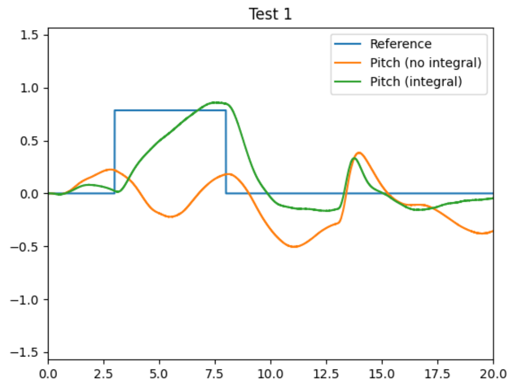


Figure 3: Test result for test 1

### 3.3.2 $R = 100\mathbf{I},\ Q = \mathbf{I}$

As with the previous test, the response without integral fails to respond at all. THe integral helps some, but is way too slow to even reach the reference point.

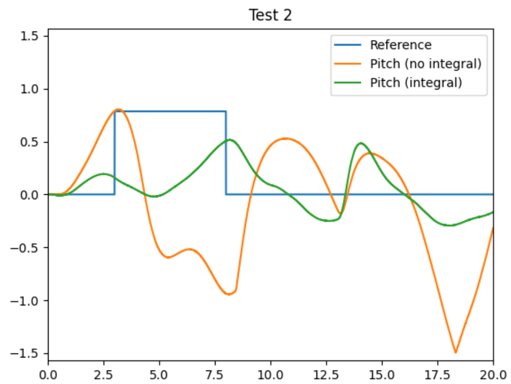


Figure 4: Test result for test 2

### 3.3.3 $R = \mathbf{I},\ 5Q = \mathbf{I}$

Here the pitch is able to track the reference better, but does converge to a stationary error without the integral. The integral does overshoot a bit, but converges after to the reference. This can also be seen towards the end of the series.

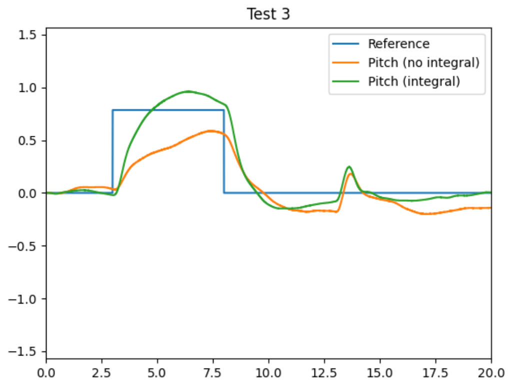


Figure 5: Test result for test 3

#### 3.3.4 $R = \mathbf{I},\ 100Q = \mathbf{I}$

The reference is being followed by both the controllers. The integral action eliminates the stationary error.

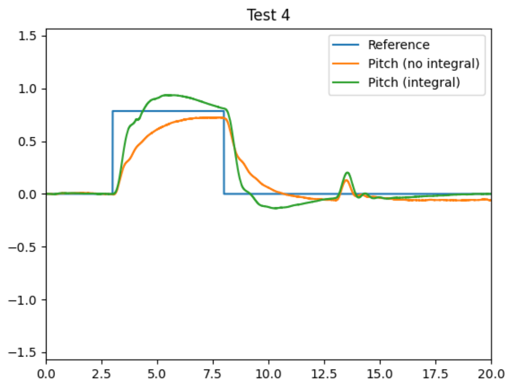


Figure 6: Test result for test 4

#### 3.3.5 $R = \mathbf{I},\ Q = \mathbf{I}$

Both signals track the reference, but both controllers are a bit slower to reach it. Also the controller with no integral action has a stationary error.

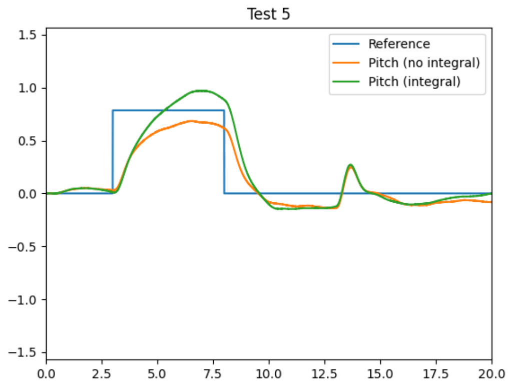


Figure 7: Test result for test 5

### 3.4 Conclusion

All our hypotheses matched with our findings. The tests with high R and low Q had weak, in fact too weak, responses. The tests with high Q values and low R had very fast responses, while the test with equal Q and R values had converging but somewhat slow responses. In addition it was shown that the integral action helped remove the staionary error.

# 4 Results and Figures

Answer all the parts of the exercise in an organized and clear manner. You should of course try to get good results in all the exercises, but if you have made a good effort without achieving great performance, a good discussion of possible reasons is just as good. Present your thinking and efforts and discuss possible reasons for good or bad results.

Include plots and/or tables of all relevant results, but make sure you don't overwhelm the reader with too many plots. Have a clear plan about what you want to communicate with a specific plot/figure, and use appropriate labels and comments. Keep in mind that the plots should be as "readable" as possible; that is, they should not be too hard to interpret and be reasonably self contained.

There are some important things to consider when exporting figures from MATLAB, most importantly which format you use. Never ever use JPEG for anything that is not a photography or similar. Any figure, like a plot or block diagram, must never be stored as a JPEG. If you zoom in on Figure 8 you can see a lot of noise close to any of the dark curves and lines, this is due to the compression in JPEG. Figure 8 will look horrible both on a screen and on paper.

The PNG format is slightly better for plots, but since it is a raster format (a grid of pixels), it looks ugly if you zoom in. It also looks ugly if you scale it, both on a screen and on paper. Try to avoid PNG if you can. Figures 9 and 10 are both PNG figures; the latter being a larger figure scaled more than the former. Note both how choppy and ugly the blue curve is, and how the different sizes create inconsistent font sizes.

The simplest way to get a reasonably good looking plot is to save it as EPS in MATLAB. Do this by clicking "File" in the figure window, and the "Save As…"; choose "EPS file (*.eps)" in the "Save as type:" menu.[1] Figure 11 shows a plot in EPS format. Since EPS is a vector format, the Figure can be scaled and still look good (but mind the font size!). If you zoom in you can see that the curve and the letters/numbers are smooth. A figure in vector format will usually look good both on a screen and on paper.

Note that the size of the actual figure window in MATLAB determines how large the exported figure is. Hence, if you enlarge the figure window before exporting, you will need to scale the figure by a larger factor in the report. This will lead to a tiny font in the figure. There are many better ways of exporting graphics from MATLAB, but they quickly become fairly involved. The above method of exporting to EPS will in most cases give nice figures.

You can write Latex in your MATLAB figures. The script used to create

[1] pdfLatex does not support EPS directly, but since we have loaded the *epstodf* package, this is not a problem.

Figures 8 and 11 is included in Appendix A.1. Do not use a screen shot of a scope of figure in MATLAB in your report.

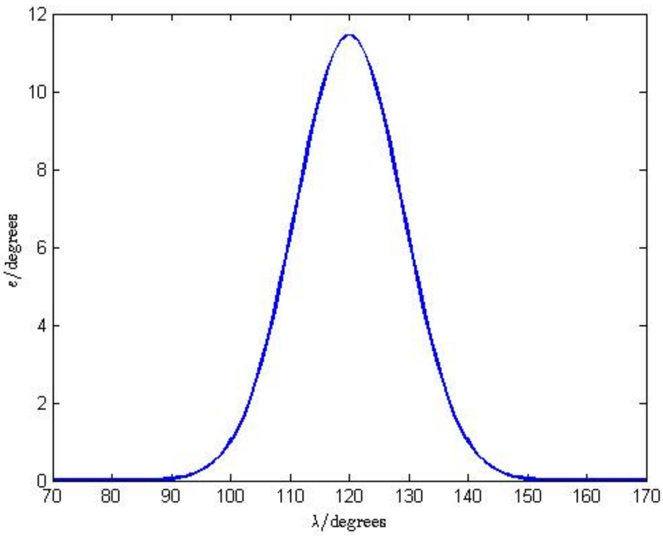


Figure 8: A plot in JPEG format — a very bad idea.

Remember to reference all figures in the text. Figures have a number and should be referenced by that number (again, always use dynamic references). They also tend to float around, meaning they generally don't appear where you ask them to in the text. This is fine, do not try to force a figure (or a table) to appear in a particular place. As long a you refer to it, it's easy to find. No figure should be included without being referenced in the text.

If you look at the source code for including figures, you can see that the optional option `[htb]` has been used. This tells Latex where you wish the figure to appear, in prioritized order. `h` means "Here", t means "Top of this page", b means "Bottom of this page", and p (not used here) means "on a Page with only floats (such as figures and tables)". Note that your wish might not be granted, and this is because Latex actually optimizes the placement of figures. If you start forcing figures to be in specific places, it often leads to really strange layout somewhere else in the document.

Generally, let Latex handle the documentation layout. This is one of the main reasons to choose Latex over software such as Microsoft Word.

### 4.1 Results and Discussion

All problems should have their own discussion of results.

Remember: all plots and results need a description, explanation, and discussion.

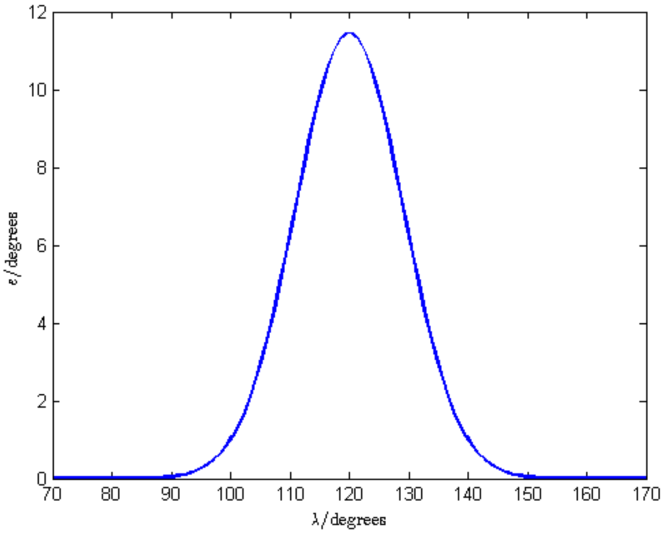


Figure 9: A plot in PNG format — a bad idea.

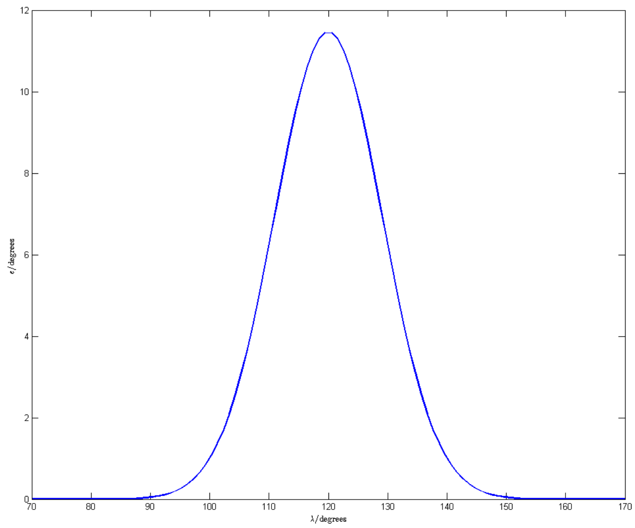

Figure 10: A plot in PNG format — a bad idea. This figure is originally larger than the other PNG figure, but both are scaled to the same size.

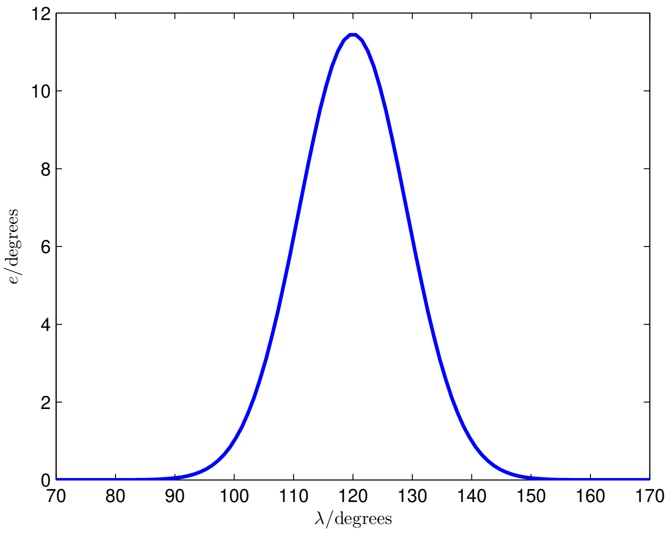


Figure 11: A plot in EPS format — a much better idea.

# 5 Conclusion

This does not have to be long, but try to write a few reasonable closing remarks.

# A MATLAB Code

This section should contain your MATLAB code. DO NOT attach files posted online (that you didn't write). Note that the method used to input code below does not look as pretty when the lines are too long.

## A.1 plot_constraint.m

```
% Plot a figure with some Latex in the labels
l = linspace(70,170)*pi/180;
a = 0.2;
b = 20;
l_b = 2*pi/3;

e = a*exp(-b*(l-l_b).^2);

l_deg = l*180/pi;
e_deg = e*180/pi;

figure(1)
plot(l_deg,e_deg, 'LineWidth', 2)

handles(1) = xlabel('$\lambda$/degrees');
handles(2) = ylabel('$e$/degrees');
set(handles, 'Interpreter', 'Latex');
```

# B Simulink Diagrams

This section should contain your Simulink diagrams. Just like the plots, these should be in vector format, like in Figure 12. Make them tidy enough to understand.

## B.1 A Simulink Diagram

Figure 12 shows a Simulink diagram. You can use the `print_simulink.m` function, included in the source code repository for this document, to export a Simulink model to EPS.

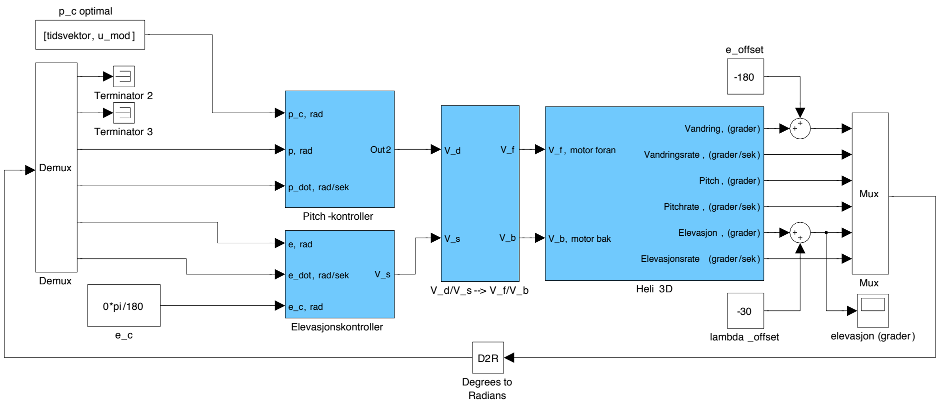


Figure 12: A Simulink diagram.

## References


[1] H Berland. *En introduksjon til Latex*. `http://www.pvv.ntnu.no/~berland/latex/latexintro4up.pdf`. 2010.

[2] M. Downes. *Short Math Guide for LATEX*. `ftp://ftp.ams.org/pub/tex/doc/amsmath/short-math-guide.pdf`. 2002.

[3] T. Oetiker et al. *The Not So Short Introduction to LATEX 2e*. `http://tobi.oetiker.ch/lshort/lshort.pdf`. 2011.