TECHNISCHE UNIVERSITÄT CHEMNITZ

Fakultät für Elektrotechnik und Informationstechnik

Praktikumsbericht

Entwicklung und Implementierung einer automatisierten szenariobasierten Unit-Test Strategie für einen modellprädiktiven Pfadfolgeregler in einer GitLab Pipeline

vorgelegt von

Georg Ehrler

Matrikel-Nr.: 521446

Studiengang: Energie- und Automatisierungssysteme

Betreuer: Francisco Moreno, M.Sc.
Robert Ritschel, M.Sc. (IAV)

Prüfer: Prof. Dr.-Ing. habil. Stefan Streif

Datum: 31. März 2024

IAV GmbH

Regelungstechnik und Systemdynamik
Prof. Dr.-Ing. habil. Stefan Streif

Kurzfassung

Diese Arbeit ist ein Beispiel für die Verwendung der ACSD-**internen** Vorlage für Abschlussarbeiten und Forschungsberichte aller Art. Es werden sowohl einige Hinweise zur korrekten Verwendung gegeben, als auch Beispiele für die verschiedenen Umgebungen und Bestandteile einer wissenschaftlichen Arbeit.

Der Inhalt dieser Arbeit wurde aus verschiedenen anderen Arbeiten zusammengetragen und hat daher nicht den Anspruch, einen sinnvollen zusammenhängenden Text zu bilden. Machen Sie das nicht in Ihrer Arbeit!

Beachten sie zudem, dass die Kurzfassung nicht als eine Seite umfassen sollte!

Abstract

This work is an example for the usage of the ACSD-**internal** template for final theses and research reports of all kinds. It contains hints for the correct usage as well as examples for the different environments and parts of a scientific thesis.

The content of this example thesis is taken from different other theses and does therefore not have the aspiration to form a meaningful coherent text. Do not do that in your thesis!

Also note that the Abstract should not be longer than one page!

Inhaltsverzeichnis

Notation

k	time instant for the high level prediction model
κ	time instant for the low level prediction model
$\boldsymbol{x}$	state vector
$\boldsymbol{u}$	input vector
$\boldsymbol{y}$	output vector
$\bar{\boldsymbol{x}}$	predicted state vector
$\bar{\boldsymbol{u}}$	predicted input vector
$\bar{\boldsymbol{y}}$	predicted output vector
$\boldsymbol{x}_i$	state vector of the i^{th} subsystems
$\boldsymbol{u}_i$	input vector of the i^{th} subsystems
$\boldsymbol{x}_{\max}$	upper bound for the state
$\boldsymbol{x}_{\min}$	lower bound for the state
$\boldsymbol{u}_{\max}$	upper bound for the input
$\boldsymbol{u}_{\min}$	lower bound for the input
$\boldsymbol{N}$	length of the prediction horizon
$\boldsymbol{I}$	identity matrix of appropriate dimension
$\mathcal{X}$	state sequence of the prediction
$\mathcal{U}$	input sequence of the prediction
$\mathbb{R}$	set of real numbers
$\mathbb{R}^n$	set of n-dimensional vectors of real numbers
$\mathbb{R}^{n \times m}$	set of $n \times m$ matrices of real numbers
$\mathbb{U}$	set of feasible inputs
$\mathbb{X}$	set of feasible states

List of Abbreviations

MPC	Model Predictive Control
HMPC	Hierarchical Model Predictive Control
mpP	Multi-Parametric Programming
PWA	Piecewise Affine
KKT	Karush-Kuhn-Tucker optimality condititon
SCS	Strict complementary slackness
LICQ	Linear indipendent constraint qualification
SOSC	Second-order sufficiency condition

Abbildungsverzeichnis

1 Introduction

This chapter is an introduction to the topic of the thesis. It gives the reader an idea of the problem at hand and why it is relevant. Simplified pictures and illustrations help to understand the problem on a general level.

1.1 Packages

This template already comes with a large variety of packages. BEFORE YOU ADD CUSTOM PACKAGES PLEASE CHECK IF THEY ARE NOT ALREADY INCLUDED IN `ACSDthesis_config.tex`, SINCE DOUBLE INCLUSIONS CAN INTERFERE WITH OPTIONS AND DESTROY THE LAYOUT! Table 1.1 lists all included packages with their according options. If you need to add custom options for a specific package, use the `\PassOptionsToPackage{<options>}{<package>}` command, BEFORE the package is included.

Tabelle 1.1: Packages included in this template. The entry *cf. config* refers to the file `ACSDthesis_config.tex`, where extended setups are included.

Package	Options	Package	Options	Package	Options
accents		acronym	smaller	algorithm2e	*cf. config*
amsmath		amsthm		amssymb	
amsfonts		babel	ngerman /english	calc	
caption	*cf. config*	csquotes	*cf. config*	epsfig	
epstopdf		enumerate		fontenc	T1
fixltx2e		graphicx	pdftex	here	
listings	*cf. config*	mparhack		multicol	
pdfpages		pstricks		scrhack	
subcaption		textcomp		tikz	
units		xcolor	dvipsnames	xspace	

1.2 Citation

At some point in your thesis you will have to cite another author's work. If not you either did something extremely wrong or extremely right.[1] This template uses the `csquotes` package for citation, which is set up in the file `ACSDthesis_config.tex`. In order to cite

1 But probably the first of the two.

use the `\cite{<bibtexkey>}` command. Natbib citation commands like `\citet{}` are also supported. Table 1.2 shows the different available commands and their results.

If you cite more than one paper at a time, PUT THEM ALL IN A COMMA-SEPARATED LIST WITHIN THE SAME CITE COMMAND! For example, `\cite{Betti2013, Picasso2016}` produces [1, 3] and `\cite{Limon2008, Betti2013, Picasso2016}` produces [1–3].

Tabelle 1.2: Citation styles supported in this thesis using the bibtexkey *Limon2008* as an example. If not otherwise specified by your supervisor, use the `\cite{<bibtexkey>}` command.

Command	Result
`\cite{Limon2008}`	[2]
`\cite[see][chap. 2]{Limon2008}`	[see 2, chap. 2]
`\citet{Limon2008}`	Limon u. a. [2]
`\citet*{Limon2008}`	Limon, Alvarado, Alamo und Camacho [2]
`\citeauthor{Limon2008}`	Limon u. a.
`\citeyear{Limon2008}`	2008

1.3 Block Diagrams and Code Snippets

A small example of a simple block diagram in tikz is shown in Figure 1.1. The according code is the following:

```
\begin{tikzpicture}
\tikzstyle{arrow} = [thick, color = black, -latex] % define standard arrow
\tikzstyle{block} = [draw, rectangle, minimum height = 2em, minimum width = 2em,
    align = center] % define standard block
\tikzstyle{dot} = [draw, shape = circle, inner sep = 0em, minimum size=0.15em,
    fill = black] % small dot on line junctions
\node(system)[block] at (0,0){$\Sigma$}; % draw system block at (0,0) ->
    reference for other stuff
\draw[arrow](system.east)--++(4.5em,0)node[near end, above]{$y$}; % draw output
    arrow of length 4em from sys block
\node(controller)[block, below of = system, node distance = 3em]{$K$}; % draw
    controller gain block
\draw[arrow](system.east)++(2em,0)node[dot]{}|-(controller.east); % draw arrow
    from output signal to controller gain
\node(sum)[draw, shape = circle, radius = 0.25em, left of = system, node distance
     = 4em]{}; % draw summation point
% draw arrows that connect with the summation point
\draw[arrow](controller.west)-|(sum.south)node[below right]{\small -}; % feedback
\draw[arrow](sum.west)++(-3em,0)--(sum.west)node[very near start, above]{$w$}node
    [below left]{\small +}; % reference
\draw[arrow](sum.east)--(system.west)node[midway, above]{$u$}; % input
\end{tikzpicture}
```

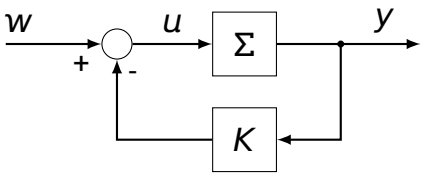


Abbildung 1.1: This is an example for a simple block diagram using tikz.

This was also an example of how to add code blocks to your text using the listings environment. The according setup is included in the file `ACSDthesis_config.tex`.

Note that it is often times a good idea to not write your tikz code directly in the source code, but to store it in a separate file and use the `\input{}` command instead. This was for example done with Figure 2.1.

1.4 Definitions, Theorems, and so forth

If you want to include definitions or theorems just use the respective environment, which are created with the usual `\begin{}` and `\end{}` commands. Available environments are `definition`, `assumption`, `lemma`, `theorem`, `proof`, and `remark`. It is of course also possible to reference them in the usual way.

Definition 1 (Convexity)**.** *A function $f : \mathcal{X} \to \mathcal{R}$ is called **convex**, if $\forall x, y \in \mathcal{X}, \forall t \in [0, 1] : f(tx + (1-t)y) \leq tf(x) + (1-t)f(y)$.*

Lemma 1 (Sum of convex functions)**.** *Let $f : \mathcal{X} \to \mathcal{R}$ and $g : \mathcal{X} \to \mathcal{R}$ be two convex functions. Then the sum $h(x) = f(x) + g(x)$ is also convex.*

Proof of Lemma 1. The proof is trivial and follows directly from Definition 1. □

Anmerkung 1. *Don't do proofs like that!*

Problem Setup

2

This chapter generally defines the actual problem to be addressed in this thesis. Illustrations help to explain the task to the reader.

2.1 Simple Formulas and Complex Tikz

Regarding this dummy thesis, a general hierarchical problem setup is depicted in Figure 2.1.[2] The system $\bar{\mathcal{S}}$ used in the presented figure is defined as

$$\bar{\mathcal{S}} : \begin{cases} \dot{\bar{x}} = \bar{A}\bar{x} + \bar{B}\bar{u}, \\ \bar{y} = \bar{C}\bar{x}, \end{cases}$$

where $\bar{B} = \sum_{i=1}^{N} \hat{B}_i \alpha_i$. Is this was an actual thesis you should properly define all other variables that are used in a figure as well! But since this is a dummy, let's just pretend this was the case here. An important thing to note is that LaTeX does not like footnotes and figures on the same page, since both take up space at the bottom.

The following section provides some dummy equations that utilize some nice alignments and combined equation numbering.

2.2 Formula Heaven

The value function considered in the high-level MPC is defined as (cf. [1])

$$\begin{aligned} V_H = &\|r - \bar{r}_t\|_S^2 + \|\Delta\bar{x}(t+N_H)\|_P^2 + \|\bar{y}(t+N_H) - \bar{r}_t\|_P^2 \\ &+ \sum_{k=t}^{t+N_H-1} \left\{ \|\Delta\bar{x}(k)\|_Q^2 + \|\bar{y}(k) - \bar{r}_t\|_Q^2 + \|\Delta\bar{u}(k)\|_R^2 \right\}. \end{aligned} \tag{2.1}$$

The resulting optimization problem is then given by

$$\begin{aligned} \bar{u}^\star = \arg\min_{\bar{u}, r_t} &\left\{ V_H(\delta\bar{x}_t, \bar{y}_t, r_t, \delta\bar{u}_{[t:t+N_H-1]}; x_t, y_t, r) \right\} \\ \text{s.t. } &\bar{\mathcal{S}}^T, \\ &\delta\bar{u}(k) = \bar{u}(k) - \bar{u}(k-1) \\ &\bar{u}(k) \in \bar{\mathcal{U}} \\ &\bar{x}(k) \oplus \mathcal{W} \in \bar{\mathcal{X}}. \end{aligned} \tag{2.2}$$

Always make sure to format your formulas in a pleasing way.

2 Just by chance it also gives you an example for a more complex block diagram using tikz.

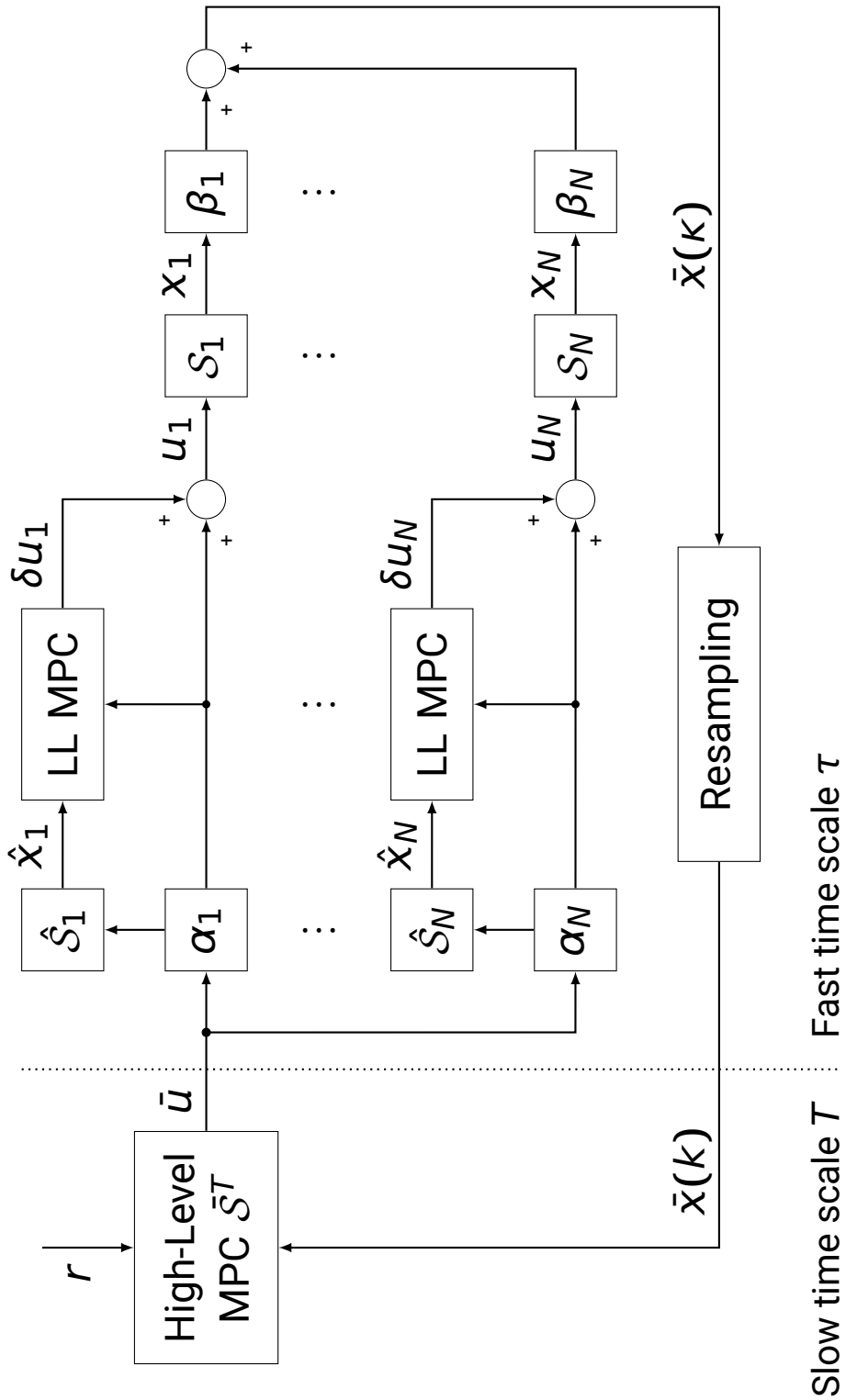


Abbildung 2.1: General problem setup. This is also an example for a more complex block diagram using tikz. The code for this picture is located in the separate file `./figures/tikz_problem.tex`; it also demonstrates how to scale entire tikz-images. The last thing this figure shows is how to rotate things that are not images using the `\rotatebox{<angle>}{<stuff to rotate>}` command. Since no positioning of the figure has been enforced, it got moved to the next page to avoid clashes with footnote 1.

Implementation

3

The actual implementation of McNaughton's wrap around rule in MATLAB is done according to Algorithm 1. This is also an example of how to incorporate algorithms in a beautiful way using the `algorithm` environment. If you want to customize the appearance of your algorithm, set it up in `ACSDthesis_config.tex`.

Algorithmus 1: McNaughton's wrap around algorithm.

Input : $\left\{ w_{ij}^{q}[\mu] \in [0,1] \mid j \in J, q \in Q \right\}$

for $j = 1, \ldots, j_{\max}$ **do**
  for $q = 1, \ldots, q_{\max}$ **do**
    if $j = 1$ *and* $q = 1$ **then**
      $\eta_{11}^{q}[\mu] \leftarrow w_{11}^{q}[\mu]$
    else
      if $q = 1$ **then**
        $q_{-} \leftarrow q_{\max}$
        $j_{-} \leftarrow j - 1$
      else
        $q_{-} \leftarrow q - 1$
        $j_{-} \leftarrow j$
      end
      $\sigma_{ij}^{q}[\mu] \leftarrow \eta_{ij_{-}}^{q_{-}}[\mu]$
      if $\eta_{ij_{\text{last}}}^{q_{-}}[\mu] + w_{ij}^{q} \leq 1$ **then**
        $\eta_{ij}^{q}[\mu] \leftarrow \eta_{ij_{-}}^{q_{-}}[\mu] + w_{ij}^{q}[\mu]$
      else
        $\eta_{ij}^{q}[\mu] \leftarrow 1$
      end
    end
  end
end

Output: $\left\{ (\sigma_{ij}^{q}[\mu], \eta_{ij}^{q}[\mu]) \right\} \in [0,1] \times [0,1] \mid j \in J, q \in Q \right\}$

4 Simulations

This chapter is concerned with the results of the simulations and in particular with the inclusion of figures. Supported file formats are `.pdf`, `.eps`, `.jpg`, and `.png`. However, in order to achieve best results, try only to use vector graphics (`.pdf`/`.eps`) or high-resolution raster graphics (`.jpg`/`.png`).

4.1 Single Figures and Cropping

If you just want to include a single figure, use the `figure` environment together with the `\includegraphics[<options>]{<graphicpath>}` command, where possible options are `width`, `height`, `scale`, and `angle`. Figure 4.1, for example, shows a nice picture of something technical. If you want to print out a draft version of your thesis without all the plots in order to save toner, you can also use `\includegraphics[draft]{<graphicpath>}`, which replaces the figure by some empty space (cf. Fig. 4.2d).

4.2 Multi-Figures

If you want to include several plots in one figure, use the `subfigure` environment within a `figure` environment. The subcaption package providing this environment is similar to subfig and subfigure, but comes with more flexibility and is a bit more intuitive. An example is given in Figure 4.2, which also demonstrates the different options of the `\includegraphics` command, like scaling, trimming, or rotating images. When you create a subfigure, make sure to use the `[b]` option which aligns the image on the bottom of its subfigure container: `\begin{subfigure}[b]{<widht>}`. The necessary argument `<width>` specifies how big the “containter” for the image should be.

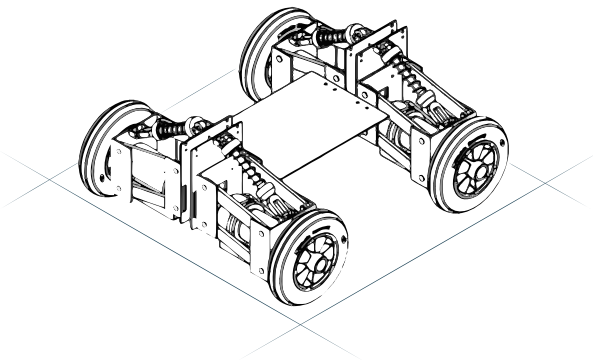
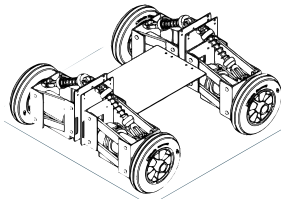
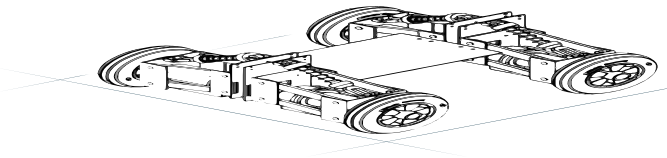


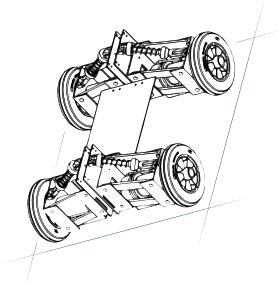
Abbildung 4.1: A nice picture of something technical.



(a) Options: scale=0.2, trim={3cm 2cm 4cm 0}, clip.



(b) Options: width=\textwidth, height=2cm.



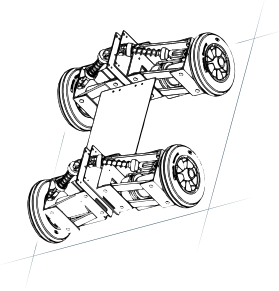
(c) Options: width=5cm, angle=45.

figures/trak_skeleton.pdf

(d) Options: draft, scale=0.25. And this is some dummy text.

Abbildung 4.2: Different options for the `\includegraphics` command.

Note that if the subcaptions of adjacent images span different numbers of lines they will not be aligned vertically (cf. Figs. 4.2a and 4.2b or Figs. 4.2c and 4.2d). In order to circumvent this issue you can use the alternative subcaption command `\subcaptionbox[<list entry>]{<heading>}[<width>][<inner-pos>]{<contents>}` instead, which aligns captions at the top. An example is shown in Figure 4.3 – compare the caption alignment of Figures 4.2c and 4.2d with Figures 4.3a and 4.3b.



(a) Options: width=5cm, angle=45.

figures/trak_skeleton.pdf

(b) Options: draft, scale=0.25. And this is some dummy text.

Abbildung 4.3: Effect of using `\subcaptionbox`: All adjacent captions are aligned at the top, even if they span multiple lines.

5 Conclusion and Outlook

This template might still have some bugs or issues. If you encounter any, here is a checklist of what you should do:

1. Download the latest version from our server! I cannot stress this enough! You will find it either in `P:\students\common` or you can ask your supervisor.
2. Ask your fellow students if anyone has encountered the issue before and if they know what's the problem.
3. Tell me (Felix Petzke) about the issue. I will then either provide you with a fix or a workaround.

Oh look, this was also an example for a numerated list using the `enumerate` environment. A list of bullet-points can be created with the `itemize` environment, as shown in the next section.

5.1 Options of the ACSDthesis Package

You might ask why this section is almost at the end. As it turns out, most of the available options of the ACSDthesis package are not relevant during the writing process. Here is a list of available options and their respective effect:

- `onepage / twopage` – toggle printing on one side or two sides (duplex). For optimal results with respect to the A5 book version (cf. Sec. 5.2) only use the twopage option if you have more than 100 written pages of text in your PDF!
- `english / german` – toggle language setting. This will change all automatically generated marks and labels to the respective language.
- `colorpdf` – adding this will make all references colored. Delete this option before creating your PDF for printing! (cf. Section 5.2)
- `parts` – activate the `\parts{}` command that is one layer above chapters. This option should only be used for very long theses and has to be passed to ACSDthesis in the file `ACSDthesis_config.tex`.

5.2 Printing your Thesis

It is done! You finished your thesis! Now you just have to print it in our beautiful A5 book format so it can join its papery comrades in our ACSD library, to be read again

by generations of suceeding students. The printing process is actually a piece of cake, thanks to our also available book cover template. The following steps will guide you to success:

1. Make sure that you typeset your thesis WITHOUT the colorpdf option (cf. Sec. 5.1)! It will save you a LOT of money!
2. Tell your supervisor that you are ready to print. He will have access to the cover template and help you with it.
3. If necessary, make sure you filled in all the information in the Statement of Authorship (Selbstständigkeitserklärung) at that it has been properly attached to your thesis. You'll find it in the folder `99_Authorship`.
4. Convert your thesis created with this template to an A5-version using the tex-file `MakeA5Version.tex`, which is contained in the folder of the cover-template.
5. Choose a cover image for your thesis and copy it to the cover template folder. This could be an illustration of the main method you used or just a nice picture that fits the topic of your thesis. However, make sure that there are no copyright issues!
6. Open up `MakeCover.tex` and fill in all the necessary data. Especially focus on
   - the volume number of your thesis, which you will get from your supervisor;
   - the short title, which will be printed on the spine of the book and therefore has a limited length of about 70 letters (including whitespaces) – this means that if your title has less than 70 letters you can use it as short title as well;
   - the number of *printed* pages (i. e.number of sheets of paper the printed thesis will have) at the very beginning of the code. Note that if you use two-sided printing the number of pages shown in the PDF editor is twice the number of printed pages! For optimal results this number should not be less than 50, so only use two-sided printing if you have more than 100 written pages!
7. Typeset the file and CHECK EVERYTHING AGAIN ON THE PRODUCED PDF! You can then tell Mr. Trompke that you are ready to print – he will help you from here on.

Literatur

[1] G. Betti, M. Farina und R. Scattolini. „A Robust MPC Algorithm for Offset-Free Tracking of Constant Reference Signals“. In: *IEEE Transactions on Automatic Control* 58.9 (Sep. 2013), S. 2394–2400. ISSN: 0018-9286. DOI: 10.1109/TAC.2013.2254011.

[2] D. Limon, I. Alvarado, T. Alamo und E.F. Camacho. „MPC for tracking piecewise constant references for constrained linear systems“. In: *Automatica* 44.9 (2008), S. 2382–2387. ISSN: 0005-1098. DOI: https://doi.org/10.1016/j.automatica.2008.01.023.

[3] Bruno Picasso, Xinglong Zhang und Riccardo Scattolini. „Hierarchical Model Predictive Control of independent systems with joint constraints“. In: *Automatica* 74.Supplement C (2016), S. 99–106. ISSN: 0005-1098. DOI: https://doi.org/10.1016/j.automatica.2016.07.030.

TECHNISCHE UNIVERSITÄT CHEMNITZ

Studentenservice – Zentrales Prüfungsamt

Selbstständigkeitserklärung

Name: Vorname: geb. am: Matr.-Nr.:	<u>Bitte beachten:</u> 1. Bitte binden Sie dieses Blatt am Ende Ihrer Arbeit ein.

Selbstständigkeitserklärung*

Ich erkläre gegenüber der Technischen Universität Chemnitz, dass ich die vorliegende selbstständig und ohne Benutzung anderer als der angegebenen Quellen und Hilfsmittel angefertigt habe.

Die vorliegende Arbeit ist frei von Plagiaten. Alle Ausführungen, die wörtlich oder inhaltlich aus anderen Schriften entnommen sind, habe ich als solche kenntlich gemacht.

Diese Arbeit wurde in gleicher oder ähnlicher Form noch nicht als Prüfungsleistung eingereicht und ist auch noch nicht veröffentlicht.

Datum: ……. Unterschrift: ……

* Statement of Authorship

I hereby certify to the Technische Universität Chemnitz that this thesis is all my own work and uses no external material other than that acknowledged in the text.

This work contains no plagiarism and all sentences or passages directly quoted from other people's work or including content derived from such work have been specifically credited to the authors and sources.

This paper has neither been submitted in the same or a similar form to any other examiner nor for the award of any other degree, nor has it previously been published.