University of Stuttgart
Institute for Systems Theory and Automatic Control
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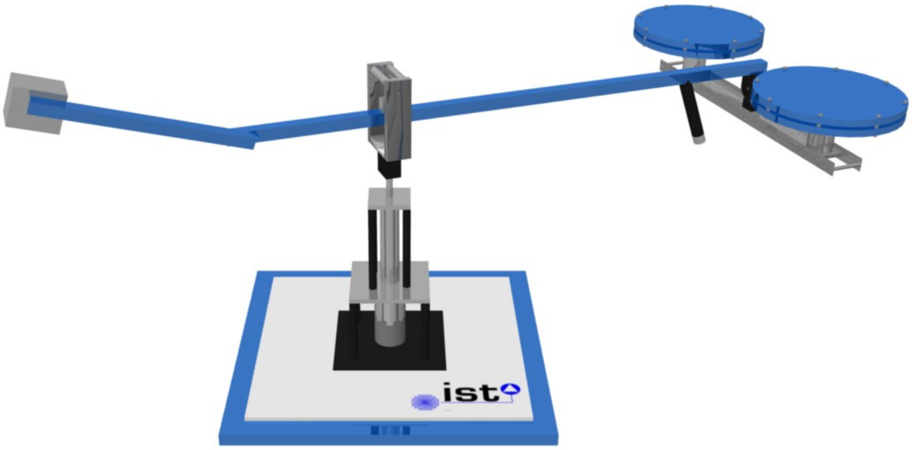
— Laboratory Course “Concepts of Automatic Control” —

Control of a 3-DOF Helicopter



Handbook

Winter term 2021/22

Contents

1 Introduction

The laboratory course "concepts of automatic control" provides you the great chance to solve an interesting control problem by yourself all the way from A to Z. Working on the task, you will get many valuable experiences and insights in addition to lectures you have already attended. Finally, after having solved the task, you will experience the triumph of having your own individual solution for the control problem. On your way to a solution of the task, of course you will be supported by advisors and by comprehensive information like, e.g. this document.

1.1. Goals of the course

The main goals of this course are to ...

- **... completely solve a realistic control task from start to finish.**
- **... apply learnt methods under realistic conditions.**
- **... become acquainted with a systematic way to approach realistic control problems.**
- **... become aware of how knowledge and methods from disjunct courses connect.**
- **... work goal-oriented and cooperatively in a team.**
- **... motivate and defend your approach.**
- **... secure the achieved results and document them in an appropriate way.**
- **... present your approach and your results to others.**
- **... solve an engineering task with no guarantee to access the lab.**

1.2. Purpose of this document

The present paper is the central document of the laboratory course "concepts of automatic control". It contains all relevant instructions and it references further required and recommended documents and sources of information. Starting out from this handbook, you will be guided through this labcourse. Beyond that, the document serves the following purposes:

- This document includes a general guideline for a systematic approach to solve control problems (see particularly Chapter 2). This guideline does not only apply to the lab-course, but it is very valuable in other control design problems, too. Thus, in particular Chapter 2 can be used as general reference work.
- This document provides further hints on carrying out the given steps of the systematic approach. Some of these hints are of quite general nature, others highly focus on the particular tasks in this lab course. Further, many of these hints refer to lecture notes and books or to the applicable documents dealing with the technical details of the experimental setup.
- Finally, this document defines the main task of this course (see Chapter 4). Furthermore, it structures the course into eleven lecture units (cf. Chapter 3).
- Five of these lecture units are to be done in the lab and thus called Labwork 1-5 (or shortened L1-L5). The other six lectures are to be done outside of the lab, e.g. at home, and thus are called Homework 0-5 (short: H0-H5). Starting with a homework, homework and labwork will take turns. A main objective of Homework H0-H4 each is to prepare for the following labwork. Further, H1-H5 in each case serve the purpose of recapitulating the previous labwork and documenting the activity and the results.
- Each course unit is structured in three parts namely “Goals”, “Hints and Remarks” and “Deliverables Checklist”.
- In “Goals”, first the main goal of the course unit is outlined. Then, the main goal is itemized in smaller and more concrete subgoals. So, in general it is kept to your own responsibility what actions you take to achieve these goals. However, sometimes also practical tasks to achieve the main goal are designated. Note that the subgoals and even the tasks are formulated quite general in the sense that they are not referring to the system under consideration.
- The last part of each homework and labwork description is the “Deliverables Checklist”. Here, all the documents and files you have to deliver after completing the lecture unit are named and specified. The documents and files are to be delivered by uploading them into your folder on the ILIAS server. You are supposed to fulfill at least these requirements and, in fact, these lists will be used to check your work for correctness and completeness. So take advantage of the check lists and use it to check each of your submissions for completeness before concluding it. Failures to meet these mandatory requirements may result in a warning and, in case of repeated occurrence, in a disqualification from the course.

2 A systematic approach to solve control problems

In the following, we present, explain and summarize a systematic approach to solve general control problems. This means, given a particular plant and a corresponding control task, the information given in this section should enable you to solve the task systematically.

The approach presented is based on [1] where a more detailed discussion on this issue can be found. The following list which has been taken from [1] directly summarizes the procedure.

1. **Study** the plant and obtain initial information about the control objectives.
2. **Model** the system and simplify the model, if necessary.
3. **Analyze** the resulting **model**; determine its properties.
4. **Decide** which variables are to be controlled (**controlled outputs**).
5. **Decide** on the **measurements and manipulated variables**; what sensors and actuators will be used and where will they be placed.
6. **Select** the **control configuration**.
7. **Decide** on the **type of controller** to be used.
8. **Decide** on **performance specifications**, based on the overall control objectives.
9. **Design** a controller.
10. **Analyze** the resulting controlled system to see if the specifications are satisfied; if not, modify the specifications or the type of controller.
11. **Simulate** the resulting **controlled system** on a computer and, if possible, on a pilot plant.
12. **Repeat** from step 2, if necessary.
13. Choose hardware and software and **implement** the controller.
14. **Test** and validate the control system. Tune the controller (on-line), if necessary.

The whole procedure is illustrated in Figure 2.1. Further, Figure 2.1 shows the different layers of abstraction which are used while solving the task. Starting with the real plant, a detailed mathematical model is derived, analyzed and simplified. The simplified model then is used for controller design. The designed controller is tested in simulations using the simple/design model in a first step and the detailed/simulation model in a second step. Finally, the controller is implemented on the real plant.

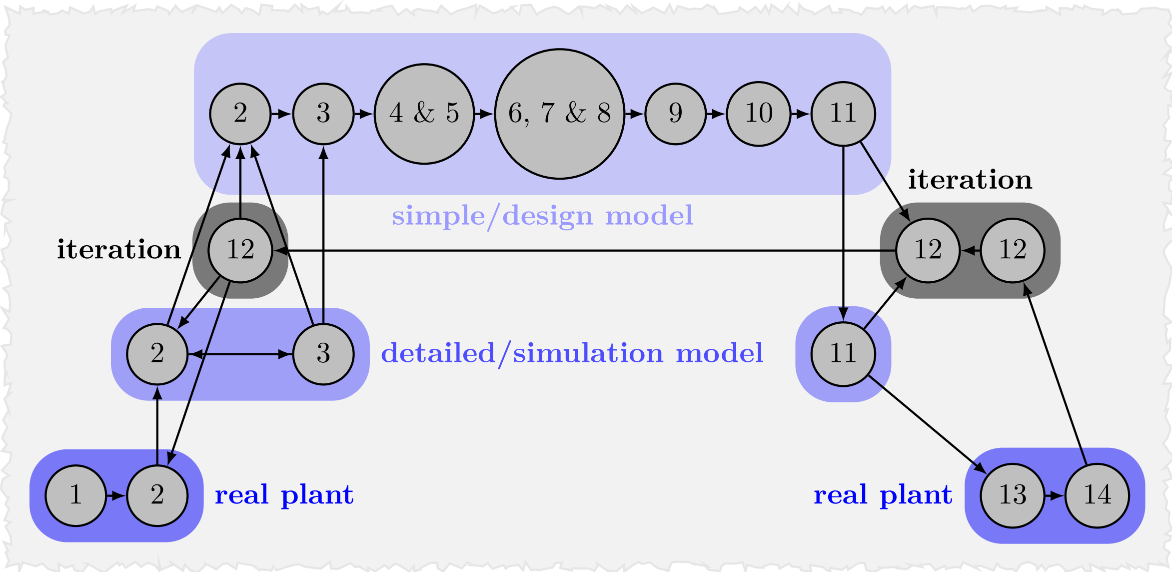


Figure 2.1.: A systematic approach to solve control problems.

1. **Study the plant and obtain initial information about the control objectives:** In this very first step, the goal is to obtain as much (preliminary) information as possible about the system and how it works. Gathering information can be done e.g. by reading technical manuals, performing a literature review, consulting colleagues and experts or by just playing with the system and its components. The latter is particularly helpful to get a good intuition which - besides hard facts, of course - often helps you to solve the problem. Finally, before starting the design procedure, you should think about how the main task can be approached, what the overall control objectives are and what kind of constraints and requirements this might imply on the controller. Usually, this kind of questions cannot be answered at this very early stage. However, keeping them in the back of your mind throughout the whole design procedure prevents you from following the wrong track and avoids blind spots.

2. **Model the system and simplify the model, if necessary:** The goal of the modelling step is to derive a mathematical model of the system - usually in terms of ordinary differential equations. In order to do so, you can use first principles and model the system according to the laws of physics. When doing so, the parameters of the system model directly represent physical properties. This often allows to directly measure these parameters. If it is not possible to measure all of the parameters directly, parameter identification can be a useful tool. A different way to model a dynamical system is to postulate a particular structure for the system behavior (e.g. PT2) and determine numerical values of the parameters within this structure via some identification procedure. No matter how it is done, modelling is a very important step in the procedure of a systematic control design as all the steps following are based on the model derived in this step.

Obviously, the most advanced control design is worthless if the design model does not represent the real system in an appropriate way. Thus, this fact immediately leads to the first requirement of a useful model which is high accuracy. However, deriving a model with high accuracy may demand too much effort. Consequently, the modelling process always includes a trade-off between accuracy and modelling effort. Further, in many cases a very accurate model is also a model with high complexity - which cannot always be dealt with. Thus, the second requirement of a useful model is to keep the complexity of the model in an acceptable range. What an acceptable range of complexity is depends very much on the purpose which the model is used for. For controller design for example, fast dynamics, delays, nonlinearities, constraints and discontinuities are typical effects which can or have to be neglected in the design model. However, as these effects might influence the behavior of the system considerably, the use of a more accurate system model for simulation purposes can be very beneficial in the control design procedure. Thus, it often makes sense to derive a quite accurate simulation model and to simplify it to a design model by neglecting or approximating effects which cannot be coped with in the controller design.

3. **Analyze the resulting model; determine its properties:** In this step, you analyze system properties of interest. This can be done by simply running simulations representing scenarios of interest. However, calculating system theoretical properties based on the mathematical model is in general more helpful and important for the following steps in the design procedure. Typically, properties of interest are steady states, the dynamic behavior (in particular stability) as well as controllability and observability (after defining inputs and outputs, cf. following steps). Further, e.g. system structure, robustness properties and the influence of disturbances might give useful insight. Finally, for any obtained property you should check whether the derived results are in agreement with the observable physical properties of the system and your intuition. If this is not the case, your model might be erroneous, oversimplified or involves nonexisting phenomena.

4. **Decide which variables are to be controlled (controlled outputs):** Decide which variables you want to control. The controlled variables should be chosen such that it is (easily) possible to formulate the overall control objectives in terms of these variables. Further, you should consider that the choice of the outputs (in combination with the inputs) defines not only the input-output behavior but also the internal dynamics. For the internal dynamics you desire them to be stable or sometimes even nonexistent.

5. **Decide on the measurements (measured outputs) and manipulated variables (control inputs); what sensors and actuators will be used and where will they be placed:** In this step you decide how the system is connected to the outside world. For each variable you want to measure you need to place a sensor at the system. For each variable you want to manipulate you need to place an actuator at the system. Sometimes you will have very little freedom in this decision as you are to work with an already completely designed system setup and have to deal with the system as it is. However, in other cases you can influence how many and which kind of sensors and actuators are to be implemented. In this case, this is a very important step in the design procedure as it strongly influences the achievable performance. Fortunately, a sound system theoretic analysis of the plant, in particular of observability and controllability, can give precious advises on a good decision. Of course, this decision is not only influenced

by the system theoretic analysis, but to the same extent by physical and economical considerations. Finally, note that in general measured and controlled outputs are not required to coincide - although this is a very popular case at least for illustrative issues (cf. e.g. standard control loop).

6. **Select the control configuration:** Select a control configuration, e.g. the standard control loop. In general, the control configuration defines which blocks (besides obvious ones like plant and controller e.g. measuring filter, decoupling, disturbance compensation, feedforward or a prefilter) are used in the control loop and how they are connected among each other and with the plant. The connections between the blocks are realized by signals like e.g. reference, control input, measured and controlled outputs. The control configuration is typically described by a block diagram. In the following design steps it is desirable to keep to the structure of the control configuration e.g. by mimicking it in your Simulink model.

7. **Decide on the type of controller to be used:** Decide which type of controller you use. First, you decide whether you do the controller design in frequency or in time domain. Then, you specify the type of the controller and a corresponding design method like e.g. P-/PI-/PID-controller or state-feedback in combination with an observer done e.g. by pole placement or LQR design. Depending on how strict "type of controller" is interpreted this is either a whole family of controllers or only one particular structure with an already fixed number of parameters (in the first interpretation P- and PI-controllers are in the same family, in the second they are already different types of controllers).

8. **Decide on performance specifications, based on the overall control objectives:** Reformulate the verbally defined overall control objectives mathematically as definite requirements on the closed loop. Note that the requirements on the closed loop implicitly impose requirements on the controller. Hence, you have to take care of formulating the requirements such that there exists a realizable controller. Further, the performance specifications have to be considered when the parameters of the controller are determined and tuned in the next step. Thus, the mathematical performance specification should be formulated such that they fit to the type of controller and design method chosen in the previous step. For example, if you have chosen a frequency domain method you should define the performance specifications in frequency domain e.g. as requirements on the bandwidth of the closed loop.

9. **Design a controller:** In this step you determine the parameters of the controller such that the performance specifications can be met. This step is strongly connected to the analysis in the next step. Thus, the two steps are typically performed synchronously by an immediate calculation and visualization of the system properties of interest.

10. **Analyze the resulting controlled system to see if the specifications are satisfied; if not, modify the specifications or the type of controller:** In this step you utilize different methods to analyze the open as well as the closed loop, e.g. Bode and Nyquist plots or the step response of the system. This step is typically considered as the central step of controller design. However, which performance you are able to achieve strongly depends on your decisions in the previous steps. Thus, iterating the design procedure and revising some of your decisions might become necessary to achieve the overall control

objectives.

11. **Simulate the resulting controlled system on a computer and if possible on a pilot plant:** Before implementing your controller on the physical system, you should test it in simulations. For these simulations, it makes sense to use models simultaneously increasing complexity and accuracy. Thus, you start with the design model to verify your design by just checking whether the controlled system behaves like expected. If this is the case, you use a more accurate simulation model to check whether your controller can cope with the effects neglected in the design model and whether the performance degradations caused by these effects are still within an acceptable range. Finally, as a good simulation model mimics the connection between plant and controller, this helps you to avoid a wrong wiring and often momentous sign errors.

12. **Repeat from Step 2, if necessary:** Sometimes even a systematic and profound design does not meet the overall control objectives at first try. So you have to start again at the beginning. However, after the first try you have studied the system quite intensively and often have a perception of what went wrong and how you can improve the design process. Thus, the "initial information" for the second try is much better which will guide you to e.g. a modelling including previously unmodelled but relevant effects or to a better choice of actuators/sensors.

13. **Choose hardware and software and implement the controller:** In this step you have to decide how you realize your controller and connect it with the plant. Sometimes, the hardware and software might be predetermined and cannot be changed. In this case, possible limitations like available memory and computational power as well as the achievable sampling time have to be considered earlier in the design process in particular in the choice of the controller and its specifications. If there is still the possibility to choose the hardware and the software, besides the system theoretic requirements and wishes you have to consider physical and economical aspects (similar as in Step 5). As these aspects often imply considerable limitations it might be beneficial to already have them in mind in earlier design steps. Finally we note that, when using digital devices, your controller has to run in discrete-time. As the design process is often done in continuous-time and the conversion from continuous to discrete is nontrivial and error-prone you should take care of it.

14. **Test and validate the control system. Tune the controller (on-line), if necessary:** In the final step you test your controller at the real system. In general, you should start with easy and slow tasks and maneuvers in combination with mildly tuned controllers to avoid putting yourself or the system setup at risk. Then, you can increase the complexity of the tasks and the velocity of maneuvers as well as the aggressiveness of the control. However, in any case, only implement controllers with parameters you have checked before by simulation.

3 Organization

The course is structured into eleven lecture units. Five of these lecture units are to be done in the lab and thus are called Labwork 1-5 (or shortened L1-L5). The other six lectures are to be done outside of the lab, e.g. at home, and thus are called Homework 0-5 (short: H0-H5). Starting with a homework, homework and labwork take turns. A main objective of Homework H0 to H4 is in each case to prepare for the following labwork. Further, H1-H5 in each case serve the purpose to recapitulate the previous labwork and to document the activity and the results.

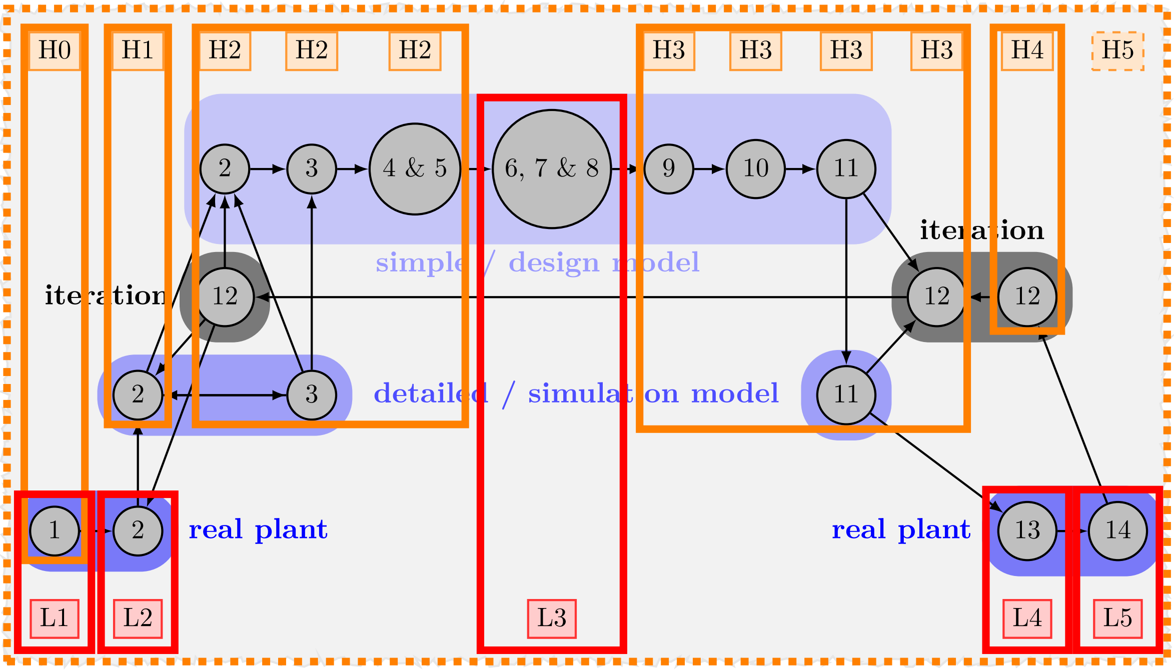


Figure 3.1.: Structure of the lecture and assignment to the items of the systematic approach.

In each of the lecture units you work on at least one of the items of the systematic approach. The assignment of items to the lecture units is done in the detailed description of the lecture units following. An illustrative overview is given in Figure 3.1. The illustration clearly shows that major parts of the work have to be done or to be prepared at home. When doing the homework, you should keep in mind that lab time is precious. Thus, you should not only be well prepared for the labworks but also come with a plan what to do during the labwork.

Note that the illustration in Figure 3.1 also shows that L3 is a special labwork. There, you are not working with the plant or a virtual representation of it (actually, there is really no possibility to work with the experimental setup!). However, L3 gives you the opportunity to discuss your work in detail with the supervisor. Further, you can ask questions how to proceed with your work.

For Labwork L1 to L4, each group has to deliver a protocol summarizing the results of the corresponding labwork and answering the subsequent homework questions. A separate protocol for Labwork L5 does not have to be written. However, in the last course unit H5 you will document the whole lab course in a summary of seven to eight pages. This final document is meant to combine and condense the five protocols into one thus giving an overview and a summary. You will get a detailed feedback for each of the protocols and, if applicable, necessary corrections will be pointed out. At the latest, your final document has to comply with all of the corrections of the previous protocols.

3.1. Important dates

The course units L1-L5 take place in the IST lab room. There, we have four helicopters such that up to four groups can work in parallel. Due to Covid-19 it might be that certain labworks take place online via WebEx. In Table 3.1, the dates for the groups in the first block are given. In each week you have to come at one weekday, either Monday, Tuesday, Wednesday, or Thursday, depending on in which group you are. In Table 3.2, the dates for the groups in the second block are given. Note that the dates may change due to current Covid-19 situation.

The following applies to all of the Labworks L1-L5:

- **Place:** V9 Room 0.255
- **Time:** 14:00 - 18:15
- **Recurrence:** Every two weeks, always at the same weekday.
- **Deadline for deliverables:**
  - H1 - H4: 4 days before the next labwork, 11:59pm
  - H5: 14 days after the last labwork
  - See Table 3.1 and Table 3.2.

Table 3.1.: Dates and deadline for deliverables of block A

	Monday	**Tuesday**	**Wednesday**	**Thursday**
L1	Nov 08	Nov 09	Nov 10	Nov 11
H1	Nov 18	Nov 19	Nov 20	Nov 21
L2	Nov 22	Nov 23	Nov 24	Nov 25
H2	Dec 02	Dec 03	Dec 04	Dec 05
L3	Dec 06	Dec 07	Dec 08	Dec 09
H3	Jan 13	Jan 14	Jan 15	Jan 16
L4	Jan 17	Jan 18	Jan 19	Jan 20
H4	Jan 27	Jan 28	Jan 29	Jan 30
L5	Jan 31	Feb 01	Feb 02	Feb 03
H5	Feb 17	Feb 18	Feb 19	Feb 20

Table 3.2.: Dates and deadline for deliverables of block B

	Monday	**Tuesday**	**Wednesday**	**Thursday**
L1	Nov 15	Nov 16	Nov 17	Nov 18
H1	Nov 25	Nov 26	Nov 27	Nov 28
L2	Nov 29	Nov 30	Dec 01	Dec 02
H2	Jan 06	Jan 07	Jan 08	Jan 09
L3	Jan 10	Jan 11	Jan 12	Jan 13
H3	Jan 20	Jan 21	Jan 22	Jan 23
L4	Jan 24	Jan 25	Jan 26	Jan 27
H4	Feb 03	Feb 04	Feb 05	Feb 06
L5	Feb 07	Feb 08	Feb 09	Feb 10
H5	Feb 24	Feb 25	Feb 26	Feb 27

4 The Main Task

4.1. Cargo transportation with a helicopter

The main idea of the challenge is inspired by a cargo transport of a real helicopter like it is shown in Figure 4.1.

Figure 4.1.: A helicopter transporting cargo.

The cargo transport is thus the Main Task of the lab course. This is illustrated in Figure 4.2. The requested flight route is as follows. The helicopter has to

- start at point 1,
- fly to point 2 and pick up the cargo,
- fly to point 3 and deposit the cargo,
- and finally fly back to starting point 1 where it has to land safely.

For a safe flight, the helicopter[1] has to travel above a minimal altitude. Further, the helicopter is not allowed to fly through the gray shaded regions. The **whole task should be performed automatically**, i.e. you are only allowed to push a start button and not allowed to intervene during the flight.

[1] For this purpose, we neglected the geometry of the helicopter and only consider its center.

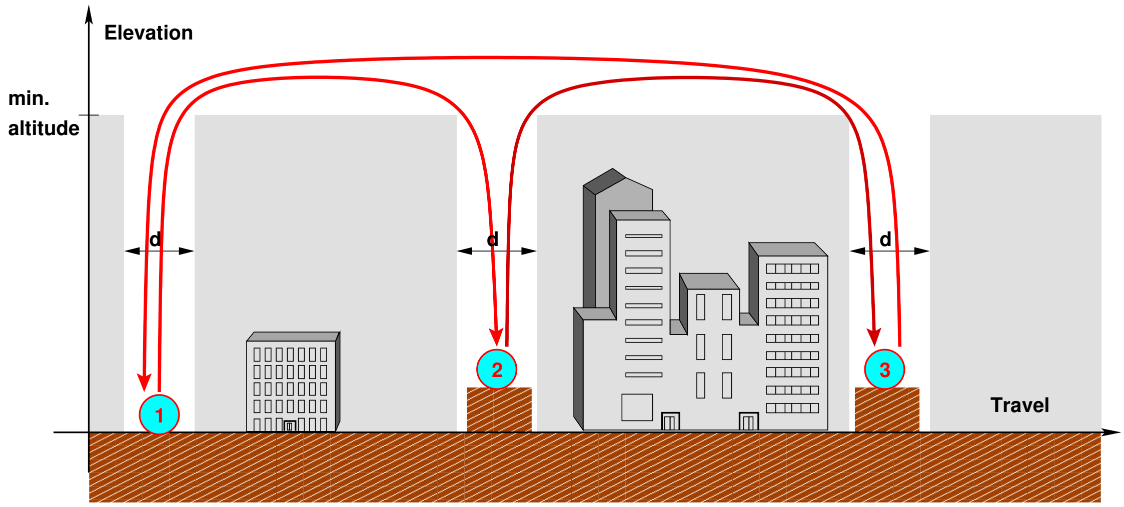


Figure 4.2.: Main Task of the labcourse: cargo transportation.

To formally define the Main Task, we introduce the coordinate system given in Figure 4.3. Therein, the coordinates “travel angle”, “elevation angle” and “pitch angle” are polar coordinates. The origin of this coordinate system is given by the starting point (travel angle), horizontal orientation of the main arm (elevation angle) and the point where both motors are on the same level (pitch angle). Within this coordinate system, the desired minimal altitude of the helicopter for travel is at elevation $-7.5°$. Further, the width d of the corridor for starting and landing is $d = 15°$. Finally, the exact position of the points 1, 2 and 3 are given in Table 4.1.

Table 4.1.: Coordinates of the Main Task.

Subtask	Point	Travel α	Elevation β
Start	1	$0°$	approx. $-27°$
Cargo pick-up	2	$90°$	approx. $-22°$
Cargo deposition	3	$450°$	approx. $-22°$
Finish (landing)	1	$0°$	approx. $-27°$

You should only use the given coordinate system in your work. Further, in your protocols as well as in Simulink and Matlab files you should use the following terms and symbols. When documenting in German use *Schwenkwinkel*, *Steigwinkel* and *Nickwinkel* for travel, elevation and pitch. In your model and your working files use the symbols α, β and γ for travel, elevation and pitch. Use for the corresponding axis the symbols x, y and z, respectively. Symbols referring to the motors should use the indices F and B for front and back motor, respectively, e.g. the voltage at the front motor and back motor is U_F and U_B, respectively. An overview of the described terms and symbols is given in Table 4.2 and Table 4.3. **Do not use terms and symbols which are inconsistent with those given in Table 4.2 and Table 4.3.**

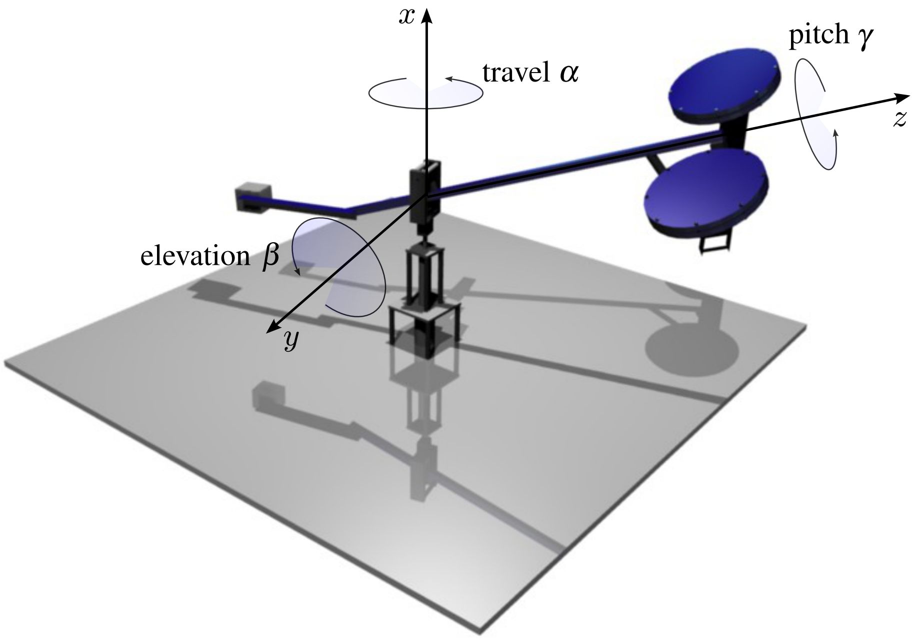


Figure 4.3.: Coordinate system.

Table 4.2.: Overview on coordinates.

Coordinate	German term	Symbol	origin of coordinate	corresponding axis
travel angle	Schwenkwinkel	α	starting position	x
elevation angle	Steigwinkel	β	horizontal position of the arm	y
pitch angle	Nickwinkel	γ	horizontal position of the helicopter	z

Table 4.3.: Overview on actuators.

Actuator	German term	Symbol for applied voltage
front motor	Frontmotor	U_F
back motor	Heckmotor	U_B

5 Homework 0 (H0): Preparation

This homework is intended to cover parts of item 1 of the procedure for a systematic approach to solve control problems given in Section 2. The following points help you to concretize your tasks.

5.1. Goals

You are well prepared for the tasks and challenges in the lab course.

Subgoals and Tasks

- You know the relevant methods of
  - modelling and identification,
  - systems theory and control,
  - simulation technology and digital signal processing.

  You refresh your knowledge about the details of the methods such that you can apply them to the questions arising in the lab course.
- You are familiar with the technical details of the experiment.
- You have a working knowledge of the necessary software tools which are
  - LaTeX for documentation,
  - MATLAB for computation,
  - Simulink for simulation,
  - QuaRC for real-time control.
- You are aware of the required work load for the whole lab course. You plan your schedule accordingly and synchronize it with your team mates.

5.2. Hints and Remarks

Methods

A physical system with electrical and mechanical subsystems is considered. You will have to model the overall system up to a reasonable level of detail. For the electrical part you require some basic knowledge about electric circuits and motors (see e.g. lecture notes "Einführung in die Elektrotechnik" or "Grundlagen der Elektrotechnik"). For the mechanical part you should know at least one method to model rigid body dynamics, e.g. the Newton-Euler equations or Lagrange's equations. These methods are treated, e.g., in the lecture notes "Technische Mechanik I-III", "Maschinendynamik" or [2, 3].

In order to analyze and control the system, you need a sound knowledge in the fields of systems theory and control theory. In particular, all aspects of the lectures "Systemdynamik" / "Systemdynamische Grundlagen der Regelungstechnik" and "Einführung in die Regelungstechnik" are relevant. Methods already covered in the lecture "Konzepte der Regelungstechnik" might be helpful and, hence, may be used. Also, aspects treated in the lecture "Mehrgrößenregelung" might be applicable. See the corresponding lecture notes for details.

In order to simulate the control system and to apply your controller to the real system, you need some knowledge in the fields of simulation technology and digital signal processing. For some basics in these fields, see the lecture notes of the lectures "Numerische Methoden der Dynamik", "Simulationstechnik" and "Echtzeitdatenverabeitung". The numerical solution of differential equations is of particular importance.

Technical Details

To familiarize yourself with the technical details of the overall experimental setup you should read carefully Section 1 and Section 2[1] of [4] and browse Section 3. [5] gives further information on controlling the magnet used during the labcourse to pick up the load (a metal ball). Further, the background material [6] and [7] - although not essential - might become helpful at some point. Finally, [8] contains technical drawings of the experimental setup and information on geometry and mass of the components.

Software

For help concerning Matlab and Simulink you can use the embedded product help and the demo files.

In preparation of using the QuaRC software you should read [5]. Further, you should read in [9]

- in section "QuaRC User's Guide > QuaRC Basics":
  - "Basic Procedures" (`quarc_procedures.html`),

[1] Our helicopters are not equipped with the Active Disturbance System (ADS). Thus, you can just skip the part dealing with the ADS.

  - “Data Collection” (`quarc_data_collection.html`),
- the description of the blocks mentioned in [5],
- the description of the block “Game Controller” (`game_controller_block.html`).

Documentation

For Homework 1 to Homework 5 and again for the whole laboratory course, you will have to deliver a protocol each. The protocols have to be written using the typesetting system LaTeX and they have to comply with a certain format. This format is given in [10] and you will also find a template for this format on ILIAS. For further details on requirements and expectations concerning the protocols as well as for writing tips and for hints on how to use LaTeX, also see [10] and the references therein.

Workload

During this labcourse, you will solve a control problem all the way from scratch. Besides that you will justify and document your steps in detail. These are two substantial and demanding tasks. So you should be aware that attending the lab course, preparing the homework tasks and writing the protocols will be fairly time-consuming.

5.3. Deliverables Checklist

Documents

None.

Files

None.

Miscellaneous

This homework should already be done before the entrance test and is an important step to prepare for the course and the entrance test. In the test and throughout the entire lab course, you need to be able to answer questions from the following fields:
☐ Control theory and modelling,
☐ technical details of the experimental setup,
☐ a systematic approach to solve control problems.

6 Labwork 1 (L1): Actuation

This labwork is intended to cover the remainder of item 1 of the procedure given in Section 2. Hence, the following tasks are important.

6.1. Goals

You become familiar with the experimental setup and become able to activate it.

Subgoals and Tasks

- You are able to interact with the experimental setup, i.e., to readout the sensor data, to actuate the helicopter and to control the magnet.
- You study the experimental setup to obtain initial information about the system.
- You think about a strategy to solve the main task of the lab course.

6.2. Hints and Remarks

The applicable documents concerning experiment setup and QuaRC might be helpful.

After you have activated the system you have time to play with the system, e.g., by manually controlling the helicopter.

6.3. Deliverables Checklist

Documents

None.

Files

☐ You are required to upload files containing today's results immediately at the end of this lab course on ILIAS into your group's folder. The files will be used only to make the results available to all members of your group and, if necessary, to track back your results by the advisors. An elaborate version of the files is to be submitted with the next protocol.
☐ Make sure to create subfolders within your group's folder and use a consistent naming for your files in order to keep a clear and neat structure of all of your submissions.

Your files should contain the following Simulink subsystems:
☐ "Input generation": Allows to control the motors via joystick.
☐ "Data acquisition": Allows to save and visualize the measurements in a meaningful way.
☐ "Plant": Resembles the plant and can be replaced by a model of the plant later on.

Your Simulink subsystems should provide well defined interfaces. This means, you should label input and output ports and choose useful signals and meaningful units for them.

Miscellaneous

☐ Prepare yourself to verbally motivate and explain your work to the advisor.

7 Homework 1 (H1): Modelling

Within this homework, parts of item 2 of the procedure given in Section 2 are covered. The following tasks are what you should work on in detail.

7.1. Goals

You derive a qualified model of the dynamics of the experimental setup.

Subgoals and Tasks

- Model the system with an adequate precision while keeping the complexity of the model within an acceptable range.
- Detect the parameters in your model and look up their numerical values in the applicable documents.
- Name the parameters for which no numerical values are supplied and think about whether it is possible to compute them from given data. If possible, do so.
- Name the parameters for which you can neither look up nor compute their numerical values. Think about experiments to measure or identify those parameters. Plan the execution of these experiments.
- Implement a first version of your model in Simulink and justify its plausibility.

7.2. Hints and Remarks

Lab time is limited. Do not waste your precious lab time in L2 on tasks that you could have completed in H1! That is, any theoretical work concerning the modelling of the plant should be completed during Homework 1. Plan carefully what experiments you want to do and how much time they will consume.

Use “Matlab functions” rather than elementary blocks to build your simulation model.

Technical drawings and masses of the parts of the experimental setup are available.

Lab equipment for experiments and measurements like a scale as well as strings and tape to fix certain degrees of freedom will be available during L2.

Note that the document [4] provided by Quanser contains some inconsistencies concerning the masses of the helicopter. Hence, for the masses needed for your model parameters, refer to the CAD files [8] provided on ILIAS.

Always ask yourself in which dimensions you are calculating, whether they fit together, and whether you got the signs (Vorzeichen) right. This hint applies for the whole lab course (and the rest of an engineer's life).

7.3. Deliverables Checklist

Documents

Protocol for L1 and H1 wherein you address items 1 and 2 of the list for a systematic approach to solve control problems given in Section 2 of this document. Include

- [ ] the derived model equations and
- [ ] a working plan for L2.

Files

A neat version of the Simulink subsystems

- [ ] "Input generation",
- [ ] "Data acquisition",
- [ ] "Plant" which you created during L1, and
- [ ] "Simulation Model" with the same interfaces as your plant.

Miscellaneous

- [ ] Prepare yourself to verbally explain the content of the protocol and discuss it with the advisor.

8 Labwork 2 (L2): Identification

This labwork is meant to cover parts of the second item of the procedure given in Section 2. The following tasks resemble this.

8.1. Goals

You identify the missing parameters for your model and verify the usefulness of the model.

Subgoals and Tasks

- Set up and carry out your planned experiments to identify the missing parameters.

8.2. Hints and Remarks

Lab equipment for experiments/measurements like a scale as well as strings and tape to fix certain degrees of freedom are available.

Keep in mind how you want to incorporate the measured quantities into your overall system model. Be absolutely precise about the meaning of the measured quantities.

In general, the next step after having obtained a system model would be to validate it. The main goal of this validation procedure is to determine whether the obtained model is suitable for its particular purpose, in our case for controller design and controller tests. Due to the special system properties of the helicopter, simulation and heuristic interpretation of the obtained model in order to validate it is difficult. Yet, once you have obtained a linearized version of your model, analyzing it and checking the equations is considerably easier. This will be subject of H2. Whether your system model is ultimately suitable to design a controller for the helicopter will become obvious only when applying your controller to the real plant. Hence, iteration in modeling the system might become necessary at this point.

8.3. Deliverables Checklist

Documents

None.

Files

☐ Upload all the Matlab scripts and Simulink models you used to execute the experiments and to identify the parameter values on ILIAS right after today's lab course. Again, this is to make your results available to all members of the group and to the advisors.

Miscellaneous

☐ Prepare yourself to verbally motivate and explain your work to the advisor.

9 Homework 2 (H2): System Analysis

This homework is concerned with items 3, 4 and 5 of the systematic procedure given in Section 2. Your tasks are given in more detail below.

9.1. Goals

You have a controller design model of your plant. You are prepared to design controllers during L3.

Subgoals and Tasks

- Compose a final model of your system using the results of the previous labwork. This model should cover all relevant properties of the real system, especially constraints and quantization of signals.
- Implement this *simulation model* as a Simulink subsystem in order to be able to test your controllers with it later on.
- For the purpose of controller design, simplify your model, i.e. neglect certain effects and linearize the system.
- Validate your linearized system.
- Implement this *controller design model* as a Simulink subsystem.
- Analyze your controller design model, e.g. in terms of inputs, outputs, controlled quantities, controllability, observability,...
- Recall several controller design methods and be prepared to apply at least one of them during L3.

9.2. Hints and Remarks

The controller design model will be your nominal model to design a controller for. Hence, it should only cover effects which you can deal with while designing a controller. For these reasons your controller should always work applying it to the corresponding Simulink model.

The simulation model will be used to test your controller in a setting as similar to the actual plant as possible. Therefore, the more realistic your simulation model resembles the actual plant, the better. The benefit you get from this approach is that once your controller works with the simulation model, you have a fair chance to have it working with the actual plant, too. Yet, this is true only if your model does not contain any substantial errors. In other words, if your controller works with your simulation model but fails to control the actual plant, this indicates errors or neglected relevant effects in your simulation model.

As mentioned before, the easiest way to verify your model is to consider the linearized system. In order to validate the linearized system, check the entries of your state space matrices for plausibility. This means, gain an insight into their physical meaning, check their sign, their order of magnitude and so on (e.g. "entry a determines how quantity b affects the derivative of quantity c, the sign is positive and the order of magnitude is similar to the one of d").

For controller design, applying methods introduced in the courses "Einführung in die Regelungstechnik" and "Systemdynamische Grundlagen der Regelungstechnik" is sufficient. Beyond that, you may apply methods which have already been introduced in the lecture "Konzepte der Regelungstechnik".

9.3. Deliverables Checklist

Documents

Protocol for L2 and H2 including consideration of items 3, 4 and 5 of the list for a systematic approach to solve control problems in Section 2. Include

☐ the equations of your simulation model of the helicopter,
☐ the equations of your controller design model,
☐ numerical values of your controller design model,
☐ the derivation of both of your models,
☐ a detailed analysis of the controller design model, and
☐ a working plan for L3.

You should address all above tasks in detail and do not forget to reference your Simulink models in your protocol.

Files

☐ A Simulink subsystem called "Controller Design Model" containing your controller design model.
☐ A subsystem called "Simulation Model" containing your simulation model of the plant.
☐ The interfaces of your models should be identical to those of the real system, i.e., those of your subsystem "Plant" delivered in H1.

Miscellaneous

☐ Prepare yourself to verbally explain the content of the protocol and the Simulink model and discuss it with the advisor.
☐ During L3 you will have the chance to retrospect on your model. So if applicable, be prepared to clarify any issues you might have with your model.

10 Labwork 3 (L3): Controller Design

This labwork covers items 6, 7, 8, 9, and partly 10 of the approach given in Section 2. In detail, solve the following tasks.

10.1. Goals

You have the basics of a controller for the model of the plant.

Subgoals and Tasks

- Decide on a control configuration.
- Decide on a type of controller.
- Draw a detailed diagram of your whole closed loop system.
- Define requirements and suitable reference signals for a controller for your system keeping in mind both the overall control goal and the restrictions of your plant.
- Determine a controller and choose suitable parameters.
- In doing so, keep your requirements in mind and
- Start to think about a strategy to fulfill the overall control task while keeping to all constraints of the system.

10.2. Hints and Remarks

Keeping the overall control objective in mind, your controlled system should possess an input for a reference signal. A structure as given in Figure 10.1 for your closed loop system is desirable.

Your detailed diagram of the closed loop system should make obvious how the linear controller is applied to the nonlinear plant. Signals should be named and have a unit. Make sure to pay enough attention to the crucial step of designing this whole closed loop setup.

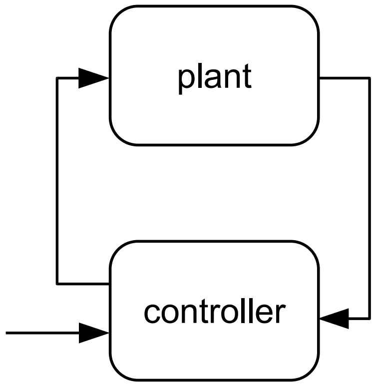


Figure 10.1.: Block diagram of the closed loop system as it is to be implemented in Simulink.

By defining requirements for your controller, you should set up your own framework to evaluate your controllers. Think about what you should pay attention to when finding controller parameters. The requirements can first be set up in terms of qualitative specifications. In general, these qualitative requirements should then be extended towards quantitative ones which can be checked more precisely. Write down your results of this task.

10.3. Deliverables Checklist

Documents

None.

Files

☐ Upload the Matlab and Simulink files you generated today on ILIAS. A draft version of your results is completely sufficient.

Miscellaneous

☐ Prepare yourself to verbally motivate and explain your work to the advisor.

11 Homework 3 (H3): Test Implementation

This homework is concerned with items 9, 10, 11 and 12 of of the systematic procedure to solve control problems given in Section 2. Therefore, focus on the following tasks.

11.1. Goals

You determine a controller which works well with your models of the plant.

Subgoals and Tasks

- Finish designing your controller.
- Test your controller using your simulation model.
- Check if your controller meets the requirements defined in L3.
- If necessary, iterate the controller design process.

11.2. Hints and Remarks

At this point it is important to keep your Simulink files well structured, simple and clear. Make sure the whole structure resembles the diagram you developed during L3.

For the choice of your controller parameters, focus on robustness instead of performance. This means, make sure your controller can cope with some disturbances and parameter uncertainties but do not bother too much about the time your controlled system will need in the end to fulfill the overall control task.

11.3. Deliverables Checklist

Documents

Protocol for L3 and H3 wherein you show how you addressed items 6 – 12 of the list for a systematic approach to solve control problems given in Section 2.

☐ Give your controller structure diagram found in L3,
☐ requirements for your controller defined in L3,
☐ numerical values of your controller,
☐ justification of the chosen design approach and the parameters of your controller,
☐ evidence that your controller meets the requirements defined in L3 and
☐ a working plan for L4.

Keep in mind referencing the Simulink and Matlab files of your controller in your protocol.

Files

☐ A Simulink subsystem block "Controller" containing your controller and
☐ all Matlab files necessary to determine your controller parameters.

Your subsystem should have well defined interfaces that allow using the controller with your system models.

☐ Your controller with the plant should fit into the scheme given in Figure 10.1.

Miscellaneous

☐ Prepare yourself to verbally explain the content of the protocol and the Matlab/Simulink files and discuss them with the advisor.

12 Labwork 4 (L4): Implementation

This labwork should cover item 13 and partly 14 of the approach given in Section 2. To this end, focus on the following goals.

12.1. Goals

You have a controller that basically works with the real system.

Subgoals and Tasks

- Take a Simulink model you used to test your controllers and replace the subsystem resembling the model by the subsystem “Plant” in order to apply your controller to the helicopter.
- Test your controller with the helicopter.
- Look out for potential problems that might appear with the controlled system when pursuing the final control task. For example, try to make your controlled system follow a predefined step in the controlled quantities.
- Based on the results of your tests, improve and adapt your controller. If necessary, you might even want to go back as far as to improve your system model.

12.2. Hints and Remarks

Before applying any of your controllers to the helicopter, test it with your simulation model first. Make sure to choose the Simulink simulation parameters suitably when using your controllers with the real system.

12.3. Deliverables Checklist

Documents

None.

Files

☐ Immediately after the course upload the files you created today on ILIAS. A preliminary version of your results is completely sufficient.

Miscellaneous

☐ Prepare yourself to verbally motivate and explain your work to the advisor.

13 Homework 4 (H4): Iteration

This homework gives you the chance to again work on item 12 of the proceeding given in Section 2. Focus on the following tasks.

13.1. Goals

You finalize your controller design in order to fulfill the overall control task.

Subgoals and Tasks

- Analyze and solve problems that possibly appeared during L4.
- Based on your experiences during L4, improve your controller.
- Think about strategies that allow you to fulfill the overall control problem.
- Prepare an overall solution to the final control problem.
- Prepare yourself to present your results and your solution to the advisors.

13.2. Hints and Remarks

Make sure to choose suitable reference signals to fulfill the overall control problem.

13.3. Deliverables Checklist

Documents

Protocol for L4 and H4 including
☐ working plan for L5
☐ problems experienced during L4 and corresponding solutions.

Keep in mind referencing the Simulink and Matlab files of your controller in your protocol.

Files

☐ A Matlab m-file generating the reference signal you are going to use for your system to fulfill the overall control task.

Miscellaneous

☐ Prepare yourself to verbally explain the content of the protocol and discuss it with the advisor.

14 Labwork 5 (L5): Final Implementation

This labwork again focuses on item 14 of the systematic approach to solve control problems given in Section 2.

14.1. Goals

You successfully perform the overall control task with the helicopter and present your solution.

Subgoals and Tasks

- Plug in your final controller into a Simulink modell and apply it to the system.
- Find, implement and apply a strategy to solve the overall control problem.
- If necessary, iterate over this strategy.
- Make sure your controlled system fulfills the overall control task.
- Present your results and your solution to the final control task to the advisors and the other student groups.

14.2. Hints and Remarks

None.

14.3. Deliverables Checklist

Documents

None.

Files

☐ Upload your Simulink and Matlab files you created and used today right at the end of the labcourse on ILIAS.

Miscellaneous

☐ Prepare yourself to verbally motivate and explain your work to the advisor.
☐ Presentation of your solutions and your overall results.

15 Homework 5 (H5): Final Documentation

15.1. Goals

You write one self-contained final document of the whole laboratory course.

Subgoals and Tasks

- You reflect the laboratory as a whole and draw conclusions about your approach and the resulting solution.
- You document your result such that the reader of the final document can review your solution.
- The final document follows the rules and guidelines as described in [10].
- Make obvious how you followed the guidelines for a systematic approach to solve control problems given in Section 2 of this document.

15.2. Hints and Remarks

The abstract and conclusion is the most important part of the final document. They should motivate the reader to carefully read the document. The abstract should describe the addressed problem, the main result and a major conclusion. The conclusion should summarize your main results. In contrast to the abstract, the reader should be familiar with the previous discussion. Therefore, you can be more specific in the conclusion.

Make sure to put emphasis on explaining why you executed certain single steps during the labcourse. This means, not only list step by step what you did during the labcourse but also address in what way these steps are target-aimed and why you performed them.

The final document may be based on your previous protocols. You can even reuse parts of your previous protocols. But the final document has to be *self-contained*. This requires:

- Pay attention to a comprehensible line of thought conveying your main results.
- Reference your previous protocols or other work only for supplementary results or to

support your thoughts.

- Include an abstract, introduction and conclusion in your final document.

15.3. Deliverables Checklist

Documents

A report over the whole laboratory course has to be written. This final document may have up to 8 pages and it has to contain
☐ the results of your work,
☐ your approaches on a more abstract level, such that the reader can understand your results and
☐ a well-written abstract and conclusion summarizing your results.

For the submission deadlines of the document, see Section 3 of this handbook.

Files

☐ Simulink and Matlab files containing your final controller and
☐ everything needed to fulfill the control task using your solution.

Miscellaneous

None.

A Vocabulary list for technical terms

Table A.1 contains some technical terms needed for the lab course.

Table A.1.: Vocabulary list for technical terms.

English term	German term
angle encoder resolution	Winkelenkoder Auflösung
controllability	Steuerbarkeit
controlled output	Regelgröße
elevation angle	Steigwinkel
law of conservation of angular momentum	Drehimpulserhaltungssatz
law of conservation of momentum	Impulserhaltungssatz
manipulated variable	Stellgröße
measured output	Messgröße
observability	Beobachtbarkeit
plant	Regelstrecke
pitch angle	Nickwinkel
steady state, equilibrium	Ruhelage
travel angle	Schwenkwinkel

References

[1] S. Skogestad and I. Postlethwaite, *Multivariable Feedback Control: Analysis and Design*. Wiley-Blackwell; 2nd Edition edition, 2005.

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[3] H. Hahn, *Rigid body dynamics of mechanisms*. Springer, 2003.

[4] "3-DOF Helicopter: User Manual," Quanser Inc., Markham, ON, Canada., Tech. Rep., 2010.

[5] "Quanser QUARC: Short Introduction," IST, Tech. Rep., 2011.

[6] "Q8-USB Data Acquisition Board: User Manual," Quanser Inc., Markham, ON, Canada., Tech. Rep., 2012.

[7] "VoltPAQ X2/X4: User Manual," Quanser Inc., Markham, ON, Canada., Tech. Rep., 2012.

[8] "CAD drawings of the Quanser 3 DOF helicopter," IST, Tech. Rep., 2011.

[9] "Quarc Online Help," Markham, ON, Canada., 2010. [Online]. Available: https://docs.quanser.com/quarc/documentation

[10] "How to write a protocol for the MSc laboratory course "Concepts of Automatic Control" at the IST," IST, Tech. Rep., 2011.