Control of the NANOMEFOS

Naus, G.J.L.

Published: 01/01/2006

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the author's version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal?

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 11. Dec. 2018
Control of the NANOMEFOS
An introductory survey

G.J.L. Naus

DCT Report no: 2006.060
24th of March, 2006
## Contents

Nomenclature and parameters ........................................ iii

1 Introduction ........................................................... 1

2 IO of the NANOMEFOS ............................................... 3

3 Machine functions .................................................. 5
   3.1 Following the product surface (measurement run) ............ 5
   3.2 Following CAD-data (testing the functional character of the machine) .... 6
   3.3 Calibration functions ........................................... 7
      3.3.1 One-time calibration of systematic errors ............... 8
      3.3.2 Every day calibration ...................................... 8
      3.3.3 Before a measurement run ................................ 9
      3.3.4 After a measurement run - data post processing ....... 9
   3.4 Initialization setpoints ......................................... 9
   3.5 Separate control of all stages and movements ............... 10

4 Control stages of the NANOMEFOS ............................... 11
   4.1 Probe stroke control ........................................... 11
      4.1.1 focusing .................................................. 11
      4.1.2 stroke control ........................................... 12
      4.1.3 light source power ...................................... 12
   4.2 Probe angle control ............................................ 12
   4.3 R-stage control ................................................ 13
   4.4 Z-stage control ................................................ 13

5 Control of the spindle .............................................. 15
   5.1 Controller specifications ...................................... 15
      5.1.1 constant speed ........................................... 15
      5.1.2 indexing ................................................... 16
   5.2 Spindle set-up .................................................. 16
      5.2.1 Break-out box ............................................ 17
   5.3 Erroneous behaviour ............................................ 17
   5.4 Identification of the spindle set-up .......................... 18
      5.4.1 Step response measurements .............................. 18
      5.4.2 Transfer function estimate measurements ............... 20
   5.5 Controller design ............................................... 23

6 Conclusions and recommendations ................................ 25

A IO of the NANOMEFOS ............................................. 29
# CONTENTS

**B Overview of data acquisition and controller boards** 33

- **C Spindle set-up specifications** 37
  - C.1 Block-Head air bearing spindle 37
  - C.2 Permanent Magnet Synchronous Brushless Motor 38
  - C.3 The LA-2000 motor drive 38
  - C.4 The Renishaw RGH20F readhead 39
  - C.5 The ERP 880 Heidenhain angular encoder 39

- **D Break-out box** 41

- **E Simulation model of the NANOMEFOS** 43
  - E.1 Simmodel.m 43
  - E.2 Specifications 44

- **F Commutation problems** 47
  - F.1 Built-in speed controller 47
  - F.2 Open loop measurements 49
### Nomenclature and parameters

<table>
<thead>
<tr>
<th>symbol</th>
<th>range</th>
<th>unit</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_R(t)$</td>
<td>1/0</td>
<td>–</td>
<td>I/O brake on the R-stage</td>
</tr>
<tr>
<td>$B_Z(t)$</td>
<td>1/0</td>
<td>–</td>
<td>I/O brake on the Z-stage</td>
</tr>
<tr>
<td>$B_\psi(t)$</td>
<td>1/0</td>
<td>–</td>
<td>I/O brake on the $\psi$-axis</td>
</tr>
<tr>
<td>$C(t)$</td>
<td>±2.5</td>
<td>$mm$</td>
<td>probe stroke</td>
</tr>
<tr>
<td>$d_p$</td>
<td>1.5 to 2</td>
<td>$mm$</td>
<td>focus distance between (the lens of) the probe and the product surface</td>
</tr>
<tr>
<td>$d_r$</td>
<td>0.5 to 2</td>
<td>$mm$</td>
<td>size of the radial steps (spacing between the tracks)</td>
</tr>
<tr>
<td>$d_s$</td>
<td></td>
<td>$m$</td>
<td>diameter of the product surface</td>
</tr>
<tr>
<td>$FES(t)$</td>
<td>±1·10^{-6}</td>
<td>$m$</td>
<td>focus error signal of the probe photo diodes</td>
</tr>
<tr>
<td>$n_m$</td>
<td>5</td>
<td>–</td>
<td>number of times the same track is measured</td>
</tr>
<tr>
<td>$n_t$</td>
<td></td>
<td>–</td>
<td>total number of tracks</td>
</tr>
<tr>
<td>$P_{LS}(t)$</td>
<td></td>
<td>$V$</td>
<td>power of the light source</td>
</tr>
<tr>
<td>$r_s$</td>
<td></td>
<td>$m$</td>
<td>radius of the product surface</td>
</tr>
<tr>
<td>$R(t)$</td>
<td></td>
<td>$m$</td>
<td>radial movement of the R-stage</td>
</tr>
<tr>
<td>$Z(t)$</td>
<td></td>
<td>$m$</td>
<td>vertical movement of the Z-stage</td>
</tr>
</tbody>
</table>

**Greek letters**

<table>
<thead>
<tr>
<th>symbol</th>
<th>range</th>
<th>unit</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{CAD}$</td>
<td>0.1 to 0.01</td>
<td>$mm$</td>
<td>error of the CAD-data with respect to the product surface</td>
</tr>
<tr>
<td>$\epsilon_f$</td>
<td></td>
<td>$m$</td>
<td>focus error</td>
</tr>
<tr>
<td>$\epsilon_{f,max}$</td>
<td>±1.0</td>
<td>$\mu m$</td>
<td>maximum focus error</td>
</tr>
<tr>
<td>$\theta(t)$</td>
<td></td>
<td>$rad$</td>
<td>spindle rotation</td>
</tr>
<tr>
<td>$\psi(t)$</td>
<td></td>
<td>$rad$</td>
<td>probe angle ($\psi$-axis)</td>
</tr>
<tr>
<td>$\omega(t)$</td>
<td></td>
<td>$rads^{-1}$</td>
<td>spindle rotational speed</td>
</tr>
<tr>
<td>$\omega_m(t)$</td>
<td>2$\pi$</td>
<td>$rads^{-1}$</td>
<td>spindle rotational speed when measuring</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Part of the PhD thesis of Ir. R. Henselmans titled *the design, development and testing of a machine for measurement of lens surfaces* [7] is to develop and build the actual measurement machine. The machine is called the NANOMEFOS. To this point the design is entering its final stadium, whereas the actual development still is in a very preliminary stadium. However, a clear overview of the functions of the machine is already present. Consequently, most of the requirements for the controllers for the different machine parts can be defined. This report aims to provide an introduction to the control parts of the machine. Elaboration on the exact working of the machine can be found in [7].

The NANOMEFOS consists of several stages each containing a specific controller. Depending on the function the machine is executing, these controllers cooperate and can be dependent on each other. Consequently the inputs that are used depend on the executed function also. In Chapter 2 the IO of the NANOMEFOS is discussed. An overview of all inputs and outputs is given in Appendix A. Next, the functions of the machine and the corresponding input control signals are discussed, focusing on the control goals: which variables have to be controlled and what are the requirements (Chapter 3). Per stage a controller is present, using the feedback signals as input. The controllers including the corresponding requirements are discussed in Chapter 4. Finally the spindle part of the machine is elaborated on in Chapter 5. The data processing afterwards and one-time calibration are not discussed in this report.
Chapter 2

IO of the NANOMEFOS

In Figure 2.1 an overview of all inputs and outputs (sorted by function) of the NANOMEFOS is given. Distinction is made between the output signals:

- signals that are used for online control (feedback);
- signals that are measured (buffered) but processed only afterwards. The results are used for data processing, calibration and synchronization;
- signals both used for online control as well as measured for afterwards processing;
- emergency feedback signals, which will get a separate control scheme;
- calibration signals, which will not be incorporated in the regular control scheme.

Figure 2.1: IO of the NANOMEFOS

In Appendix A an overview of all inputs and outputs per stage as well as the various parts the NANOMEFOS consists of is given. In Figure A.2 the inputs and outputs are shown.

Furthermore to this point a final overall data acquisition and controller board is missing yet.

3
### Variable Description Parameter

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_\Theta$</td>
<td>spindle rotation</td>
<td>$\Theta (t)$</td>
</tr>
<tr>
<td>$A_\Psi$</td>
<td>probe angle (Ψ-axis)</td>
<td>$\Psi (t)$</td>
</tr>
<tr>
<td>$B_\Psi$</td>
<td>brake on the Ψ-axis</td>
<td>$B_\Psi (t)$</td>
</tr>
<tr>
<td>$A_P$</td>
<td>probe stroke</td>
<td>$S (t)$</td>
</tr>
<tr>
<td>$P_{LS}$</td>
<td>power of the light source</td>
<td>$P_{LS}$</td>
</tr>
<tr>
<td>$A_R$</td>
<td>radial movement of the probe</td>
<td>$R (t)$</td>
</tr>
<tr>
<td>$B_R$</td>
<td>brake on the R-stage</td>
<td>$B_R (t)$</td>
</tr>
<tr>
<td>$A_Z$</td>
<td>vertical movement of the probe</td>
<td>$Z (t)$</td>
</tr>
<tr>
<td>$B_Z$</td>
<td>brake on the Z-stage</td>
<td>$B_Z (t)$</td>
</tr>
</tbody>
</table>

**Table 2.1: Overview of the control variables in the NANOMEFOS.**

Choosing an appropriate board, the inputs and outputs are divided into digital I/O, A/D inputs, D/A outputs and encoder outputs, see Figure A.1. A detailed overview is given in the table in Appendix A. The Heidenhain IK220 counter card mentioned in Figure A.1 and Appendix A may be omitted if an appropriate data acquisition board is chosen, e.g. a dSpace board (see Appendix B).

![Figure 2.2: Overview of I/O, A/D, D/A and encoder signals of the NANOMEFOS.](image)

Before choosing an appropriate board, an overview of several practical possibilities is made (see Appendix B and 2). In this way the advantages and disadvantages of the various boards can be compared relatively easily. To this point no definitive choice is made. However in choosing an appropriate board the main points of attention are

- the right number and kind of inputs and outputs;
- the highest controller bandwidth desired (see Chapter 4);
- simplicity of development and implementation of the controllers, such that it is relatively easy for new cooperating people to get involved in the project;
- the total costs of the board.
Chapter 3

Machine functions

Depending on the moment of operation, the NANOMEFOS executes various functions. These functions can be divided into 6 main groups:

1. Following the product surface (measurement run);
2. Following CAD-data (testing of the functional character of the machine);
3. Calibration functions;
4. Initialization setpoints;
5. Emergency stops;
6. Separate control of all stages and movements.

In the following subsections all functions of the NANOMEFOS are arranged in these groups and as far as useful to this point for some of them the corresponding setpoints for the outputs are defined already. For the design of the reference trajectories, 3rd-order trajectories have to be used, hence the jerk energizes the mechanical vibrations in a motion system (as do derivatives of lower order). Consequently the jerk has to be limited, which yields the use of 3rd-order trajectories. To gain better understanding in the actual working of the overall control system, a model is designed using Matlab / Simulink. This model contains all stages and several functions discussed in this section:

- a measurement run (following the product surface);
- separate control of all stages;
- following of CAD-data (testing of the functional character of the machine).

This model is further discussed in Appendix E of this report and can be used as a basis in testing the functional character of the NANOMEFOS and as a starting point in developing the overall control software of the machine.

3.1 Following the product surface (measurement run)

Output control signals:

a. Spindle rotation $\Theta(t)$
b. Probe stroke $C(t)$
c. Probe angle $\Psi(t), B_\Psi(t)$
d. R-stage $R(t), B_R(t)$
e. Z-stage $Z(t), B_Z(t)$

The main function of the NANOMEFOS is to measure the height variation in a product surface. The spindle on which the product is mounted rotates with constant speed. The probe stroke is used to follow the surface in $C$-direction while focusing on the surface. The
angle of the probe and the R,Z-stage are used to position the probe stepwise over the entire surface.

1. Start: The measurement run starts after the probe is brought into focus on the rotating product surface using an initialization setpoint. The measurement starts when all signals are synchronized by the spindle encoder, which indexes every revolution of the spindle (zero-crossing of $\Theta(t)$).

2. Using the focus error signal ($FES$) of the photo diodes in the probe as a feedback signal, the probe is held in focus (see Section 4.1.1).

3. Variation in the surface height is within the range of the probe stroke and is covered by $C(t)$ (check at beforehand by verification of the CAD-data if this is true).

4. The R,Z-stage and $\Psi$-stage are used to position the probe at a track. While measuring a track, all three stages are held: $B_R(t) = 1$, $B_Z(t) = 1$ and $B_{\Psi}(t) = 1$;

5. The surface is measured stepwise from the rotational center to the edge of the product via $n_t = \frac{r_s}{d_r}$ tracks (with $r_s$ the radius of the surface and $dr$ the size of the radial steps). So $R(t) = R_k$ with $k$ from 0 to $n_t$ the number of the track currently measured. The spacing between the tracks $d_r$ is in the range of 0.5 to 2 mm. Stepping to a new track takes about 1 sec and starting the measurement of a new track, again synchronized using the zero-crossing of $\Theta(t)$;

6. Every track is measured multiple times: $n_m = 5$. Afterwards, the measurements are averaged for a more accurate determination of the surface.

7. Two options for setting the rotational speed of the spindle are possible:
   a. a constant speed $\omega_m$
   b. a variable speed $\omega_m(R_k)$ depending on the radial position of the probe to provide a tangential measurement speed that is relatively constant. This means that $\omega_m(R_k)\mid_{k=1} = \omega_{max}$ and $\omega_m(R_k)\mid_{k=n_t} = \omega_{min}$. However, this may result in longer measurement times than intended.

8. The spindle rotates CCW to be able to see the surface move towards the probe.

9. The error between the CAD-data and the actual product surface is assumed to be approximately 0.01 to 0.1 mm. The distance between (the objective lens of) the probe and the surface is approximately 1.5 to 2.0 mm (1.56 mm for the lens currently under investigation). The focus range equals $\pm 1 \ \mu \text{m}$, so if the probe gets out of focus, a safe solution would be to instantaneously control (retract) the probe to the CAD-data plus a certain bias. This bias minimally equals the maximal assumed error between the CAD-data and the product surface. Next focus has to be regained by crossing the range of the CAD-data plus the bias to the CAD-data minus the bias. The track that was measured at that moment should be measured again.

10. An accurate measurement of the actual height of the surface is determined afterwards using interferometers, which use the rotation axis of the probe as a reference and buffer measurement data during the measurement run. (This accurate measurement is then being adjusted by the measured calibration signals.)

An example of this function is included in the model of the system discussed in Appendix E.

3.2 Following CAD-data (testing the functional character of the machine)

Output control signals:
3.3. CALIBRATION FUNCTIONS

a. probe stroke \( C(t) \)
b. probe angle \( \Psi(t), B_\Psi(t) \)
c. R-stage \( R(t), B_R(t) \)
d. Z-stage \( Z(t), B_Z(t) \)
optional:
e. spindle rotation \( \Theta(t) \)

The function ‘following the CAD-data’ is used to test the functional character of the machine. Furthermore the CAD-data is used to ‘find’ and ‘check’ the surface and thus define the initial starting position when starting a measurement, to keep track of the surface when not in focus and as a reference for the resulting measured surface (see the calibration functions).

1. Start: After moving to the initial position and synchronized by the Z-index signal of the spindle, following of the CAD-data starts. This is only allowed when no product is present. The Z-index signal of the spindle may be replaced by a virtual signal, while no actual rotation of the spindle is needed. Consequently the spindle rotational signal is an optional output signal.

2. Variation in the surface height is within the range of the probe stroke and is covered by \( C(t) \).

3. The R,Z-stage and \( \Psi \)-stage are used to position the probe at a track. While measuring a track, all three stages are held: \( B_R(t) = 1, B_Z(t) = 1 \) and \( B_\Psi(t) = 1 \);

4. The CAD-data is measured stepwise from the rotational center to the edge of the product via \( n_t = r_s/d_r \) tracks (with \( r_s \) the radius of the virtual surface and \( d_r \) the size of the radial steps). So \( R(t) = R_k \) with \( k \) from 0 to \( n_t \) the number of the track currently measured. The width of a track \( d_r \) is in the range of 0.5 to 2 mm. Stepping to a new track takes about 1 sec and starting the measurement of a new track is synchronized using the virtual zero-crossing of \( \Theta(t) \);

5. The probe stroke is measured (using an interferometer) and used as a feedback signal to control the probe stroke \( C(t) \).

6. Two options for setting the virtual rotational speed of the CAD-data are possible (see the function ‘measurement run’), which will be set in accordance with the function ‘measurement run’.

7. The CAD-data virtually rotates CCW (in accordance with the ‘measurement run’ function).

An example of this function is included in the simulation model of the system discussed in Appendix [E]

### 3.3 Calibration functions

Output control signals:

a. spindle rotation(al speed) \( \Theta(t), \omega(t) \)
b. probe stroke \( C(t) \)
c. probe angle \( \Psi(t), B_\Psi(t) \)
d. R-stage \( R(t), B_R(t) \)
e. Z-stage \( Z(t), B_Z(t) \)

For calibration purposes (see [S]) the probe tip has to be able to move throughout its complete working range. Besides that, the spindle has to be able to rotate over a certain angle or with certain rotational speed (both in CW and CCW) direction. This is comparable to the
CHAPTER 3. MACHINE FUNCTIONS

separate control of the spindle of Section 5.1. The calibration functions can be divided into 4 main groups:

1. one-time calibration of systematic errors;

2. every day calibration;

3. calibration functions before a measurement run is executed;

4. calibration functions after a measurement run is completed.

For this purpose 2D-trajectories and corresponding setpoints for the before mentioned output control signals have to be defined. All calibration functions are categorized into these main groups. As far as useful to this point some of the sub-functions are discussed in more detail already.

3.3.1 One-time calibration of systematic errors

One-time calibrations of systematic errors are executed now and then to calibrate the NANOMEFOS. They are executed without a product present. The results are saved in calibration tables, which are used to adjust the measured data of a measurement run afterwards.

1. Start: All functions start at the hold position of the probe (see Section 3.4).
   
   - Z mirror alignment relative to spindle axis (0.1 \( \mu \text{rad} \) accuracy)
   - R mirror alignment relative to spindle axis (0.1 \( \mu \text{rad} \) accuracy)
   - Z mirror straightness (10 nm accuracy)
   - R mirror straightness (10 nm accuracy)
   - spindle error motion (5 nm / 0.1 \( \mu \text{rad} \) accuracy)
   - \( \Psi \)-axis encoder (5 \( \mu \text{rad} \) accuracy)
   - \( \Psi \)-axis roundness (10 nm accuracy)
   - spindle encoder (2 \( \mu \text{rad} \) accuracy)
   - probe tip guidance straightness
   - probe distance - tilt dependency (10 nm \( \text{deg}^{-1} \) dependency)
     - proof of principle - mirror on spindle
   - real probe calibration
     - off-machine (an extra PSD is needed)
     - on-machine

3.3.2 Every day calibration

Every day calibration functions are executed every day to calibrate parts of the NANOMEFOS. They are executed without a product present. The results are saved in calibration tables, which are used after a measurement run to adjust the measured data.
3.4. **INITIALIZATION SETPOINTS**

1. **Start**: All functions start at the hold position of the probe (see Section 3.4).

   - Y-position of the probe (tip) (0.1 µm / 1 µ rad accuracy)
     1. use a PSD, an interferometer and laser beam data
   - calibration of the probe PSD, \( PSD_p \)
     1. horizontal and vertical
        → position the probe horizontally and measure the position of a rotating vertical mirror on the spindle
     2. angle
        → position the probe under an angle and compare the \( PSD_P \) and encoder outputs

3.3.3 **Before a measurement run**

The 'before a measurement run' calibration (nulling) functions are executed preliminary to a measurement run, primarily to identify the product surface, but also for momentarily calibration of the machine and its stages. Consequently most of the functions are executed with the product present and some of them aren’t. If a product is present, always check if a generated trajectory doesn’t collide with the product or the machine before actually implementing it in a function. The results are used for the initialization functions (see Section 3.4).

1. **Start**: All functions start at the hold position of the probe (see Section 3.4).

   - position of the intermediate body with respect to the metrology frame
     1. measure points on the intermediate body and on the metrology frame
   - nulling of the R-interferometer on the PSD in the middle of the spindle
     1. move the probe in R-direction over the PSD at 0° and at 180°
        → the Y-offset is measured and the R-offset can be calculated and used afterwards
     2. position a tilted flat on the spindle and measure at 0° and at 180°
        → the crossing of the two measured lines is the spindle axis
     3. measure the center of the surface twice
        → using a least-squares fit, the radial position can be corrected
   - nulling of the Z-interferometer (1 µm accuracy)
     1. position horizontal mirrors on the spindle center, on the intermediate body, on
        the reference rim, on top of the product and on the metrology frame and combine
        position measurements of these mirrors with the Z-stage linear scale reading.
   - nulling of the probe interferometer on a frame-fixed mirror
   - Calibration of the starting position via a PSD: calibration of the mid-position and the
      height of the product surface at the mid-position
   - Check distance to the product surface at various points

3.3.4 **After a measurement run - data post processing**

   - Measure points on the intermediate body and on the metrology frame again and re-
     measure the first track / radial cross-section to determine drift in the measurements
   - Calculate surface from combination of slope (from deflectometer / probe-PSD measure-
     ment data) and position data
   - Calculate shape from sheared or multi-step data sets / average over multiple rotations
     per track

3.4 **Initialization setpoints**

Output control signals:
CHAPTER 3. MACHINE FUNCTIONS

a. spindle rotation(al speed) $\Theta(t)$, $\omega(t)$
b. probe stroke $C(t)$
c. probe angle $\Psi(t)$, $B_\Psi(t)$
d. R-stage $R(t)$, $B_R(t)$
e. Z-stage $Z(t)$, $B_Z(t)$

The probe tip has to be able to move throughout its complete working range following a user-defined trajectory:

1. for calibration purposes;
2. to move to initial positions and in between various machine options;
3. user-defined to test the machine;
4. separate control of all stages and movements.

For this purpose 2D-trajectories and corresponding setpoints for the before mentioned output control signals have to be defined.

1. with and without a product present (for initial calibration / checking of the product or calibration / checking of the machine and stages); Always check if a generated trajectory doesn’t collide with the product or the machine before implementing it.
2. All setpoints start at the same ’initial position’. Hold position is the standard position of the probe when not active. Every time a new setpoint is defined, start from this hold position to make sure the product is never touched, except for setpoints of the same group, which incorporate the same conditions.

- Go to initial position
- Switch between user-defined trajectories
- Go to hold position

3.5 Separate control of all stages and movements

Output control signals:

a. spindle rotation $\Theta(t)$
b. spindle rotational speed $\omega(t)$
c. probe stroke $C(t)$
d. probe angle $\Psi(t)$, $B_\Psi(t)$
e. R-stage $R(t)$, $B_R(t)$
f. Z-stage $Z(t)$, $B_Z(t)$
g. power of the light source $PLS$

It should be possible to execute all movements of each stage separately (user-defined) for inspection of all movements, boundary tests, trajectory tests and manual calibrations. Consequently the corresponding reference trajectories are user-defined, bounded by the physical bounds of the machine and the (possibly present) size of the product, which has to be checked / calculated before a movement is applied. Furthermore the stages that aren’t used are braked ($B_Z(t) = 1$, $B_R(t) = 1$ and $B_\Psi(t) = 1$);
Chapter 4

Control stages of the NANOMEFOS

For every stage a separate controller has to be developed. Depending on the generated setpoints, these controllers are working together (see Chapter 3). The controller of a stage may have various modes depending on the machine function and the corresponding setpoints (e.g. the controller for the probe stroke can be dependent on a user-defined trajectory for the stroke or on the Focus Error Signal (FES) of the probe photo diodes). In this chapter per stage an overview of the specifications of the corresponding controllers as determined to this point is given. Controller specifications of the spindle are discussed in Chapter 5.

4.1 Probe stroke control

The probe stroke is used to focus and follow trajectories with an amplitude within the range of the stroke \((\pm 2.5 \cdot 10^{-3} \text{ m})\). The displacement is measured using an interferometer. For focusing, the output of 2 photo diodes is used. Depending on the surface of the product the power of the light source may have to be adjusted to optimize focusing. Consequently the controller consists of three parts.

4.1.1 focusing

When to control

During a measurement run continuous focusing is required, starting when the probe is in focus. Furthermore focusing is used for calibration and test purposes (e.g. to identify the product surface).

IO

Input: normalized Focus Error Signal of the probe photo diodes, \(FES (\pm 5 \text{ V})\).
Output: control signal to the amplifier \(A_P\) of the probe stroke actuator (this probably will be a linear motor).

Requirements

- the distance between the lens and the surface is 1.5 a 2 \(\text{ mm}\) (1.56 \(\text{ mm}\) for the set-up currently selected) and the error in the surface with respect to the CAD-data is 0.01 to 0.1 \(\text{ mm}\), so a little overshoot is allowed;
- the in-focus range of the photo diodes limits the static error to \(\epsilon_{P,\text{max}} = \pm 1 \mu\text{m}\);
- The error of the focus error signals is limited to $1 \, \mu\text{m}$ ($|FES| \leq 1 \, \mu\text{m}$). Consequently tracking of the surface has to have an accuracy of $\pm 1 \, \mu\text{m}$. To be able to accurately measure the height of the surface, a maximal disturbance-slope of 5 deg is allowed. If the disturbances are assumed to be triangular shaped the tangential error length thus becomes $2 \times 11.4 \, \mu\text{m} = 23 \, \mu\text{m}$. At the maximum rotational measuring speed $\omega_{\text{m,max}} = 2\pi \, \text{rad s}^{-1}$ and simultaneously measuring at the maximum radius of 250 mm, this results in a maximum frequency for the disturbances in the surface to be followed of 34 kHz. This off course is not a feasible controller bandwidth. However, it indicates first of all that a controller bandwidth as high as possible is required and secondly that the rotational speed of the spindle is limited by this controller bandwidth.

- the controller should be 'faster' than the probe stroke controller so that focusing is able to take over control immediately when in focus;
- every track is measured multiple times and the measurement results can be averaged afterwards. Consequently the controller may benefit from iterative learning feedforward control.

4.1.2 stroke control

**When to control**

Follow trajectories (in C-direction) with an amplitude within the range of the stroke of the probe (e.g. follow CAD-data, find the point of focus and for calibration and test purposes).

**IO**

Input: interferometer position signal of the probe objective.
Output: control signal to the amplifier $A_P$ of the probe stroke actuator (this probably will be a voice coil).

**Requirements**

- overshoot, bandwidth and accuracy correspond to the requirements of the focusing controller;
- feedforward control can be used to optimize the controller.

4.1.3 light source power

**When to control**

Depending on (the reflectivity of) the surface of the product, the intensity of the light source may have to be varied for optimal focusing. After one time calibration of a surface, the power of the light source is set (e.g. before a measurement run).

**IO**

Input: intensity of the reflected light beam, which may vary in between 5% for glass and 99% for mirrors for example.
Output: power of the light source of the photo diodes $P_{LS}$.

**Requirements**

- vary open-loop in e.g. 20 steps;
- further requirements depend on the final design.

4.2 Probe angle control

**When to control**

During a measurement run, when checking the CAD-data and for positioning, calibration and test purposes the $\Psi$-axis is used.
4.3 R-STAGE CONTROL

IO
Input: the angle of the probe \( \Psi(t) \), measured by the encoder \( E_{\Psi} \). The same signal is used for exact calibration and data acquisition afterwards.
Output: control signal to the amplifier \( A_{\Psi} \) of the \( \Psi \)-axis actuator as well as the control signal to the brake \( B_{\Psi} \) of the \( \Psi \)-axis.

Requirements
- the same data is used for online control and data acquisition afterwards, which leads to an accuracy of 5 \( \mu \) rad or 5 nm;
- while measuring a track, the \( \Psi \)-angle is held constant. Consequently the bandwidth of the controller does not depend on the measuring speed. The total range of \(-0.25 \pi \) rad to \(0.75 \pi \) rad should be covered in about 1 sec, which is also the settling time in between 2 tracks;
- implementation of feedforward control may provide great benefits in optimizing the controller.

4.3 R-stage control

When to control
During a measurement run or the scanning of CAD-data, the \( R \) position of the probe tip has to increase step-wise. Furthermore for positioning, calibration and user-defined test purposes, the complete working range of the R-stage is used.

IO
Input: position of the R-stage is measured by \( E_{R} \), the exact position of the probe tip is measured using an interferometer and the \( \Psi \)-axis as a reference axis.
Output: control signal to the amplifier \( A_{R} \) of the R-stage actuator as well as the control signal to the brake \( B_{R} \) of the R-stage.

Requirements
- the R-stage is used to position the probe, so the allowed overshoot is minimal (see Section 4.1.1);
- the total stroke of the R-stage is 400 mm. Depending on the mass of the final design, the stage should be able to move over this range in 5 sec. During a measurement run stepping to the next track may take 1 sec including focusing with an accuracy of 5 \( \mu \) m;
- depending on the position of the Z-stage different dynamical behaviour will be present (this depends on the final design);
- implementation of feedforward control may provide great benefits in optimizing the controller, taking into account the changing dynamical behaviour.

4.4 Z-stage control

When to control
During a measurement run or the scanning of CAD-data, variation in the \( C \) direction of the probe tip (parallel to the probe tip) is covered by the probe tip stroke. Then, the Z-stage is held by its brake \( B_{Z} \). For positioning, calibration and user-defined test purposes, the complete working range of the Z-stage is used.

IO
Input: position of the Z-stage, measured by \( E_{Z} \). The exact position of the probe tip is measured using an interferometer with the \( \Psi \)-axis as a reference axis (accuracy of 1 \( \mu \) m).
Output: control signal to the amplifier \( A_{Z} \) of the Z-stage actuator as well as the control signal to the brake \( B_{Z} \) of the Z-stage.
Requirements

- the Z-stage is used both when a product is present and no product is present, so the allowed overshoot is minimal (see Section 4.1.1);
- depending on the encoder used, the accuracy is determined to be 1 \( \mu \text{m} \) or 0.1 mm. This is not clear yet and depends on the final requirements to the Z-stage.
- the total stroke of the Z-stage is 150 mm. Depending on the mass of the final design, the stage should be able to move over this range in 2 sec;
- depending on the position of the R-stage different dynamical behaviour will be present;
- implementation of feedforward control may provide great benefits in optimizing the controller, taking into account the changing dynamical behaviour.
Chapter 5

Control of the spindle

To this point the spindle is the only hardware of the NANOMEFOS that is actually bought. Consequently the control of the spindle can be elaborated on already. Analogous to the controller specifications for the other stages discussed in Chapter 4, the specifications for the spindle controller will be discussed first, after which an overview of the set-up of the spindle is given. Before the identification of and controller design for the spindle that are already performed are described, the erroneous behaviour of the amplifier, limiting this identification and controller design is mentioned. As a result only a layout for the modelling of the system and a first intent to show the possibilities for controller design are given.

5.1 Controller specifications

Analogous to the controller specifications for the other stages of the NANOMEFOS discussed in Section 4, the specifications for the control of the spindle are discussed in this section. The controller of the spindle consists of two parts with various requirements and IO: rotating at constant speed and indexing. Input of both controllers is the same, the Renishaw encoder \( E_\Theta_R \) is used as control input. The Heidenhain encoder \( E_\Theta_H \) is used afterwards for exact determination of the actual \( \Theta(t) \) during a run.

5.1.1 constant speed

When to control
Rotating the spindle at constant speed is used when a measurement run is performed, for calibration and for test purposes. No rotation is required when following the CAD-data. However, for calculation of the momentary position with respect to the CAD-data as well as for synchronisation of all measured signals, a virtual rotation signal and Z-index signal are required.

The LA2000 amplifier \( A_\Theta \) has a built-in speed controller using a frequency train. This controller can also be used in combination with an external frequency input. However, the controller is designed specifically for rotational speeds up to about 20,000 rev/min. For low rotational speeds (e.g. for 0 to 0.5 rad/s) the controller becomes unstable and a speed ripple is present on top of the desired speed. Consequently the external input has to be used in combination with the output of the Renishaw encoder in controlling the spindle.

IO
Input: Renishaw encoder (TTL, 16,384 lines).
Output: external input control signal of the amplifier \( A_\Theta \) (± 10 V).

Requirements
- due to the limitations of the built-in speed controller of the LA2000 amplifier, a position controller in combination with a position ramp as setpoint will be used to control the speed $\dot{\Theta} = \omega$ of the spindle;
- within 1 revolution the reference speed has to be reached with 20 $\mu$rad accuracy;
- maximum speed during a measurement run is $\omega_{m,max} = 2\pi \text{ rad s}^{-1}$;
- maximum speed for calibration and test purposes (not during focusing or during probe stroke control) is $\omega_{c,max} = 5\pi \text{ rad s}^{-1}$ (this is limited by the IK220 Heidenhain encoder);
- minimum speed for calibration and test purposes is $\omega_{min} = 0\pi \text{ rad s}^{-1}$;
- within 0.5 revolution the spindle has to be slowed down to standstill;
- in case of an emergency stop the spindle has to be slowed down as fast as possible to prevent damaging its air bearing;
- a negative input to the LA2000 amplifier corresponds to CCW rotation;
- depending on the mass of the product, the dynamics will change;

5.1.2 Indexing

When to Control
For calibration and test purposes as well as to identify the product surface (e.g. the initial position or the accurateness of the corresponding CAD-data) indexing is used. With respect to the null-position of the spindle, the spindle can be forced to rotate over a user-defined angle (when starting up the machine, one of the main functions is to detect the Z-index / calibrate the null-position).

IO
Input: Renishaw encoder (TTL, 16,384 lines);
Z-index of the Heidenhain encoder (1 Vpp, 90,000 lines, 0.1 $\mu$rad / 5 nm accuracy).
Output: external input control signal of the amplifier $A_{\Theta}$ ($\pm$ 10 V).

Requirements
- when used for calibration, the distance between a vertical mirror mounted on the spindle and the probe has to be measured. The distance between the lens of the probe and a measurable surface is 1.5 to 2 mm, so little overshoot is allowed;
- within 1 to 2 sec the minimum accuracy of 20 $\mu$rad has to be reached (the resolution of the Renishaw encoder is 0.5 $\mu$rad);
- user defined clockwise (CW), counter-clockwise (CCW) or shortest-path rotation;
- optional: rotation over a user-defined number of revolutions with a user-defined speed;
- depending on the mass of the product the dynamics change;
- one-time commutation using the Hall sensors and definition of the Z-index; from then on keep in memory this position and use the Renishaw encoder;
- feedforward control taking into account the changing mass of the product is useful for optimizing the controller.

5.2 Spindle Set-up

The spindle concerned is a Block-Head air bearing spindle, driven by a permanent magnet synchronous brushless motor of Motion Control Systems [10]. The motor has an embedded Hall effect array and a built-in Renishaw RGH20F readhead with 16384 line counts. Furthermore an ERP 880 Heidenhain angular encoder with 90000 line counts is built-in as to attain the desired accuracy in determining the exact position of the product surface with respect to the probe. The motor is controlled via a LA-2000 amplifier, which enables control of the spindle via a built-in speed controller or direct control of the input current via an analog input. More details about these hardware components is listed in Appendix C.

In the set-up of the spindle (see Figure 5.1) an AQI is used to provide the analog input to the amplifier. To this point the Heidenhain encoder is only tested, while the output of the Renishaw
5.3. ERRONEOUS BEHAVIOUR

The encoder is used as input of the AQI. Furthermore a break-out box is developed to be able to bypass the signals from the spindle to the amplifier neatly (see also Section 5.2.1).

5.2.1 Break-out box

The spindle is actually intended for application in high speed precision milling machines. Consequently the standard accompanying controller is a speed controller that assures very accurate and constant speed control. This speed controller is built-in in the LA2000 amplifier and cannot be adjusted. However, it is also possible to get around this built-in controller by bypassing the control cable of the motor to the amplifier via an external input. In order to do this neatly, a break-out box is developed. The layout is shown in Appendix D. The break-out box incorporates:

- a 25 pin D connector on the motor side for the input from the spindle
- a switch and / or a BNC connector to enable the external input
- a BNC connector for application of the external torque
- a 9 pin D connector for the encoder output signals in accordance with the TUeDAC and AQI encoder inputs
- a BNC connector for bypassing of the air fault system
- a 25 pin D connector for user-defined application (e.g. controlling measurements) incorporating all input signals
- a 25 pin D connector on the amplifier side for the output to the amplifier

5.3 Erroneous behaviour

Due to erroneous commutation behaviour of the spindle, determination of the static behaviour of the spindle appeared to be impossible. Despite regular contact with the supplier and even after sending back the amplifier, the erroneous behaviour still is present to this point. However, fixing the commutation problem has to be done before continuing the controller design. In Table 5.1, an overview of the spindle set-up history to this point is given. In Appendix F measurement examples clearly showing the commutation problem are presented.
Chapter 5. Control of the Spindle

Spindle set-up history

<table>
<thead>
<tr>
<th>date</th>
<th>description</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>01-05</td>
<td>purchase of the spindle set-up</td>
<td>RH</td>
</tr>
<tr>
<td>06-05</td>
<td>testing the spindle set-up</td>
<td>RH</td>
</tr>
<tr>
<td></td>
<td>wrong settings changed after consulting Bob Dapper of MCS, however</td>
<td></td>
</tr>
<tr>
<td></td>
<td>commutation problems seem to be present when starting to turn</td>
<td></td>
</tr>
<tr>
<td></td>
<td>from standstill. Rest of the set-up works fine.</td>
<td></td>
</tr>
<tr>
<td>12-05</td>
<td>testing the spindle set-up</td>
<td>GN, RH</td>
</tr>
<tr>
<td></td>
<td>contacted Bob Dapper about the commutation problems.</td>
<td></td>
</tr>
<tr>
<td>12-05</td>
<td>testing the spindle set-up combined with TUeDAC / AQI hardware</td>
<td>GN, RH</td>
</tr>
<tr>
<td></td>
<td>tests with TUeDAC went ok, after successful replacement of the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TUeDAC by the AQI and increasing the input voltage to 4 V, the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>motor drive blows. Besides that, the commutation problems are still</td>
<td></td>
</tr>
<tr>
<td></td>
<td>present.</td>
<td></td>
</tr>
<tr>
<td>12-05</td>
<td>return of the motor drive to MCS</td>
<td>RH, GN</td>
</tr>
<tr>
<td>02-06</td>
<td>got back the motor drive</td>
<td>RH, GN</td>
</tr>
<tr>
<td>02/03-06</td>
<td>testing the spindle set-up</td>
<td>GN, RH</td>
</tr>
<tr>
<td></td>
<td>same commutation problems as before, (re)checked all signals, better</td>
<td></td>
</tr>
<tr>
<td></td>
<td>integration of the AQI into the system via the break-out box.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Performed measurements to indicate the commutation problems in a clear</td>
<td></td>
</tr>
<tr>
<td></td>
<td>way to be sent to MCS (see Appendix F). Performed identification of the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>spindle set-up and performed a preliminary controller design.</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: overview of the problems with the spindle set-up, RH, GN indicating R. Henselmans and G. Naus respectively.

5.4 Identification of the spindle set-up

The erroneous commutation behaviour of the amplifier (see Section 5.3) has limited identification of and controller design for the spindle set-up. However, to be able to make a first step in the design of a controller, a model is developed nevertheless. The emphasis in modeling lies on (relatively) easy blackbox modeling, because of the changes that will be applied yet. Step response measurements are performed, a Transfer Function Estimate (TFE) is determined and a simulation model to validate the measurement results is made.

5.4.1 Step response measurements

The transfer gains and the largest time constants determining the time to steady-state of the system can be determined using step response measurements. Consequently staircase tests are performed to get an idea of these characteristic system parameters. The set-up shown in Figure 5.1 is used, using an AQI in combination with Matlab / Simulink to control the spindle via the external input of the amplifier.

In Figure 5.2 the result of a staircase test is shown. In the upper plot the input voltage signal of the motor drive is shown and in the lower plot the resulting rotational speed of the spindle. The peaks in the lower plot correspond to the indexing signal of the encoder, which is measured every revolution. Next, per step, first order exponential fits are made as is shown in Figure 5.3. The fits correspond to

$$\omega(t) = k (1 - \exp(-(t - \tau_d)/k \tau))$$

(5.1)

with $\omega$ the rotational velocity, $t$ the time, $\tau_d$ the time delay, $\tau$ the time constant and $k$ the increase
5.4. IDENTIFICATION OF THE SPINDLE SET-UP

Figure 5.2: staircase test measurement results; in the upper plot the input signal to the amplifier and in the lower plot the resulting speed of the spindle is shown.

Figure 5.3: staircase test measurement results; in the upper plot the input signal to the amplifier and in the lower plot the resulting speed of the spindle is shown.

in speed. This yields for the steady state gain $g_{ss}$

$$g_{ss} = \frac{k}{g_i}$$  (5.2)
Table 5.2: parameter values for the first order model of the spindle set-up, derived by staircase tests and simulations.

<table>
<thead>
<tr>
<th>description</th>
<th>variable</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>time delay</td>
<td>$\tau_d$</td>
<td>0</td>
<td>sec</td>
</tr>
<tr>
<td>time constant</td>
<td>$\tau$</td>
<td>13.7</td>
<td>sec</td>
</tr>
<tr>
<td>steady state gain</td>
<td>$g_{ss}$</td>
<td>-22.6</td>
<td>rad/s/V</td>
</tr>
<tr>
<td>”damping”</td>
<td>$\beta$</td>
<td>-0.044</td>
<td>V/s/rad</td>
</tr>
<tr>
<td>”total inertia”</td>
<td>$J$</td>
<td>3.3</td>
<td>V s^2/rad</td>
</tr>
</tbody>
</table>

with (in this case) $g_i = -0.2$ V the input gain used. The time delay $\tau_d$ from the input voltage to the output torque is negligible, which yield a first order model

$$ J\dot{\omega}(t) = u - \beta \omega(t) \quad (5.3) $$

with $u$ the input voltage, $\beta = 1/g_{ss}$ and $J = 1/3\tau$. The parameters $\beta$ and $J$ can be interpreted as some sort of damping and inertia of the spindle respectively. However, the model describes the dynamical behaviour of the set-up including the spindle as well as the amplifier and the brushless DC motor. Consequently, $\beta$ and $J$ do not correspond exactly to the damping and inertia of the spindle as is shown by the corresponding units (see Table 5.2). The total drive is designed for usage in a high speed milling application. Consequently in this case the drive will be employed in a region in which it is assumed to be linear still (when employing the drive at the maximum of its application region, nonlinear behaviour becomes significant).

A simulation model of this first order system is developed using Simulink, which yields the same output as the actual measurements (when the correct starting conditions are implemented). The resulting parameter values of the system are given in Table 5.2. Due to the use of an air bearing, no friction and only a small amount of damping as a result of the EMF in the motor will be present. Consequently the value of $\beta$ is small. Furthermore the time delay is negligible and the high total inertia of the system explains the relatively large time constant. These results yield a transfer function from the input voltage $U$ of the amplifier to the rotational velocity $\Omega$ of the spindle

$$ \frac{U}{\Omega} = \frac{1}{Js^2 + \beta} \quad (5.4) $$

of which a plot is shown in Figure 5.4

5.4.2 Transfer function estimate measurements

In order to validate the transfer function derived in Section 5.4.1, which is shown in Figure 5.4, a transfer function estimate of the system is derived via direct measurements to the system. To be able to derive this transfer function estimate, the same set-up as used with the staircase tests is used (see Figure 5.1). Only now as an input signal a sinusoidal signal varying in frequency from $1 \cdot 10^{-3}$ Hz to 5 Hz is used. Using the same frequencies, a fit over the resulting output signal is made, starting at the point where the system reaches steady state behaviour. Comparing this fit to the input signal, the amplitude ratio and phase difference are determined. This yields the transfer function estimate shown in Figure 5.5 in which the measured points are indicated by the red circles.

Combining the transfer function resulting from the modeling after the staircase tests with this transfer function yields the plots in Figure 5.6 As can be concluded from this figure, the first order model as well as the black box model of the system result in the same linear model for the spindle set-up. Consequently a model for the transfer from input voltage to rotational speed of the spindle is determined. Addition of one integrator to this model yields a model for the transfer from the input voltage to the rotation of the spindle. The drive is designed for usage in e.g. a high speed milling application. When employing the drive at the maximum of its application region,
5.4. IDENTIFICATION OF THE SPINDLE SET-UP

Figure 5.4: transfer function from the input voltage $U$ to the rotational velocity $\Omega$ of the spindle system, resulting from staircase tests and simulation results.

Figure 5.5: transfer function from the input voltage $U$ to the rotational velocity $\Omega$ of the spindle system, resulting from frequency response measurements. The red circles indicate the measurement points.

nonlinearities will become more important. In this case however, the drive will be employed in a region in which it may be assumed to behave in a linear manner \[4\]. Consequently this model can
be used for further controller design

\[
\frac{U}{\Omega} = \frac{1}{s (J s^2 + \beta)}
\]  

(5.5)

Figure 5.6: transfer function from the input voltage \( U \) to the rotational velocity \( \Omega \) of the spindle system; the thin plot results from staircase tests, while the thicker (red) plot results from frequency response measurements.

### 5.4.3 The load

To this point no load is present on the spindle. However, for modeling in the simulation model described in Appendix E it will be discussed briefly at this point.

The load of the spindle consists of a free-form optics, which is mounted directly onto the rotor of the spindle. The free-form optics consists of flat, spherical, aspherical axis-symmetric and off-axis surfaces. For uniformity and simplicity of modeling, the free-form optics is approached by an axis-symmetric solid cylinder. This simplification is justified only if the off-axis mass of the load is relatively small and if the center of mass of the cylinder is relatively close to the central axis of the free-form optics used. However, the variation in mass and geometry is only used to explore the working range in simulations, so in this way a relatively good estimation of the load can be made.

The load is mounted directly onto the rotor of the spindle, hence only the increase of the moment of inertia of the moving mass has to be taken into account (no additional damping, stiffness of friction is added to the system). The moment of inertia of a solid cylinder or disc around the symmetry axis is given by

\[
I = \frac{1}{2} m r^2 \quad [\text{kgm}^2]
\]  

(5.6)

Considering

- a load mass \( m_l \) in the range of 0 to 50 kg
- a load diameter \( d_l \) in the range of Ø0 to Ø500 mm
- a load thickness \( t_l \) in the range of 0 to 100 mm
and assuming a linear dependency of $d_l$ and $t_l$ with respect to $m_l$ yields

\[
\begin{align*}
    d_l &= \frac{d_{l,max}}{m_{l,max}} m_l \\
    t_l &= \frac{t_{l,max}}{m_{l,max}} m_l
\end{align*}
\]

with $d_{l,max}$, $t_{l,max}$ and $m_{l,max}$ the maximum values of the corresponding before-given ranges. So variation of the load mass $m_l$ results in a moment of inertia for the load of

\[
I_l = \frac{1}{8} \frac{d_{l,max}^2 m_{l,max}^3}{m_l^3}
\]

with $I_l$ in the range of 0 to $1.56 \text{ kg m}^2$. This approximation is used in the simulation model discussed in Appendix E.

### 5.5 Controller design

Based on the controller specifications as discussed in section 5.1 and the model of the system derived in Section 5.4, a controller can be designed. However, due to the problems with the set-up (see Section 5.3), controller design is only addressed briefly to this point.

Based on the previously derived velocity transfer function, a position transfer function shown in Figure 5.7 is defined. From this plot it follows immediately that the open-loop bandwidth (zero-crossing of the magnitude of the open-loop (see Figure 5.7)) is limited by the phase of the system. Consequently a PD-controller is applied. The open-loop frequency domain results for three different gains are shown in Figure 5.7, 5.8. Especially from the Nyquist figure it can be seen that increasing the gain of the PD-controller has positive influence on the phase margin at first, which clearly is limited, as for higher gains, the phase margin deteriorates again. This demands application of a more sophisticated controller development if higher bandwidths are required.

The controllers corresponding to the open-loop transfer functions shown in the plots are implemented and tested briefly. However, at prescribing a constant position with zero rotational speed as a reference trajectory, the amplifier seems to loose notion of the position of the spindle at standstill. As a result the electronic commutation fails, which yields drifting of the spindle. Consequently no further controller design is addressed to this point.
Figure 5.7: Bode plots of the position transfer function (the utmost left plot) and open loop frequency responses; from left to right corresponding to an increasing gain.

Figure 5.8: Nyquist plots of the position transfer function (the top plot) and open loop frequency responses; from top to bottom corresponding to an increasing gain. The dotted circle represents the 6 dB sensitivity bound.
Chapter 6

Conclusions and recommendations

A preliminary survey to the IO and control of the NANOMEFOS has been performed. This has resulted in

- an overview of the IO of the machine
- an overview of its functions with respect to the IO of the machine
- an overview of controller boards from which one can be chosen based on the IO of the machine
- survey to the controller structure of the machine, resulting in a first design of a model using Matlab / Simulink to simulate the (controlled) machine
- an overview of the various controllers including their requirements
- a first design for the controller of the spindle based on a validated model of it, which, due to commutation errors, not yet functions as it should and therefore isn’t elaborated and optimized yet

On the short term recommendations for further research considering the control of the NANOMEFOS are

- choose control board
- fix the commutation of the spindle and finish the design of the controller for it
- extend the Matlab / Simulink model to gain insight in the overall control structure of the machine by expanding the functional character of the machine
- elaboration of all functions of the machine when the final design of the machine is ready

On the long term, the total control structure of the NANOMEFOS has to be developed stage-wise and optimized by extended testing. Emphasis will lie firstly on the correct processing of the various succeeding functions, while the controllers will function merely independently. Secondly emphasis will lie on the development of a correct data handling during operation of the machine and data processing afterwards.
Bibliography


Appendix A

IO of the NANOMEFOS

In Figure A.1 an overview of all inputs and outputs of the NANOMEFOS is given (see also Section 2). The outputs are sorted by function. In Figure A.2 an extended overview of the various parts of the NANOMEFOS is given. All parts as well as the input and output signals are labeled. In the following table some specifications of the various parts and an explanation for the labels is given.

Figure A.1: IO of the NANOMEFOS
Figure A.2: schematic overview of the inputs and outputs of the NANOMEFOS per stage. All abbreviations are listed in Table A.
<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Purpose</th>
<th>Accuracy / bitrate</th>
<th>Device</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enc1</td>
<td>Enc1</td>
<td>Renishaw encoder unit a-x-i-s</td>
<td>feedback + computation</td>
<td>0.1 (µrad) (6 mm)</td>
<td>Renishaw PBR1</td>
</tr>
<tr>
<td>Enc2</td>
<td>Enc2</td>
<td>Renishaw encoder</td>
<td>feedback</td>
<td>5 µrad</td>
<td>350 mm</td>
</tr>
<tr>
<td>Enc3</td>
<td>Enc3</td>
<td>2-stage linear encoder</td>
<td>feedback</td>
<td>7</td>
<td>1.25 mm</td>
</tr>
<tr>
<td>(Enc4)</td>
<td>Enc4</td>
<td>Renishaw encoder input</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Haldeman (220) encoder input signals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enc5</td>
<td>Enc5</td>
<td>Denken RK: encoder on 9-a-x-i-s</td>
<td>measurement</td>
<td>0.1 (µrad) (6 mm)</td>
<td></td>
</tr>
<tr>
<td>Enc6</td>
<td>Enc6</td>
<td>Denken RK: encoder on 9-a-x-i-s</td>
<td>feedback + measurement</td>
<td>5 µrad</td>
<td>0.75π rad / 1 (µpp)</td>
</tr>
<tr>
<td><strong>AD input signals (12)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A01</td>
<td>A01</td>
<td>intensity of falling PSD on spindle</td>
<td>calibration</td>
<td></td>
<td>Philips: PSD unit 1</td>
</tr>
<tr>
<td>A02</td>
<td>A02</td>
<td>normalized X of PSD</td>
<td>calibration</td>
<td></td>
<td>Philips: PSD unit 1</td>
</tr>
<tr>
<td>A03</td>
<td>A03</td>
<td>normalized Y of PSD</td>
<td>calibration</td>
<td></td>
<td>Philips: PSD unit 1</td>
</tr>
<tr>
<td>A04</td>
<td>A04</td>
<td>intensity of probe deflection meter (PSD)</td>
<td>measurement</td>
<td></td>
<td>Philips: PSD unit 2</td>
</tr>
<tr>
<td>A05</td>
<td>A05</td>
<td>X of PSD</td>
<td>measurement</td>
<td></td>
<td>Philips: PSD unit 2</td>
</tr>
<tr>
<td>A06</td>
<td>A06</td>
<td>Y of PSD</td>
<td>measurement</td>
<td></td>
<td>Philips: PSD unit 2</td>
</tr>
<tr>
<td>A07</td>
<td>A07</td>
<td>PSD feedback</td>
<td>feedback</td>
<td></td>
<td>Philips: PSD unit 2</td>
</tr>
<tr>
<td>A08</td>
<td>A08</td>
<td>intensity of probe photodiode 1</td>
<td>feedback</td>
<td></td>
<td>Philips: PSD unit 3</td>
</tr>
<tr>
<td>A09</td>
<td>A09</td>
<td>intensity of probe photodiode 2</td>
<td>feedback</td>
<td></td>
<td>Philips: PSD unit 3</td>
</tr>
<tr>
<td>A10</td>
<td>A10</td>
<td>sum of the probe photodiodes</td>
<td>feedback</td>
<td></td>
<td>Philips: PSD unit 3</td>
</tr>
<tr>
<td>A11</td>
<td>A11</td>
<td>(PSD)</td>
<td>(extra AD input 1)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A12</td>
<td>A12</td>
<td>(PSD)</td>
<td>(extra AD input 2)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Agilent Technologies PCI N1231 B Three-Axis High Performance Laser Board with External Sampling: Interferometer signals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A13</td>
<td>A13</td>
<td>probe objective displacement</td>
<td>measurement</td>
<td>10 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>A14</td>
<td>A14</td>
<td>R-spindle displacement interferometer</td>
<td>measurement</td>
<td>5 μm</td>
<td>5 mm</td>
</tr>
<tr>
<td>A15</td>
<td>A15</td>
<td>Z-displacement interferometer</td>
<td>measurement</td>
<td>1 μm</td>
<td>5 mm</td>
</tr>
<tr>
<td><strong>I/O input signals (2)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi1</td>
<td>I/Oi1</td>
<td>top limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi2</td>
<td>I/Oi2</td>
<td>bottom limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi3</td>
<td>I/Oi3</td>
<td>GW limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi4</td>
<td>I/Oi4</td>
<td>CW limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi5</td>
<td>I/Oi5</td>
<td>CW limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi6</td>
<td>I/Oi6</td>
<td>CCW limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi7</td>
<td>I/Oi7</td>
<td>left limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi8</td>
<td>I/Oi8</td>
<td>right limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi9</td>
<td>I/Oi9</td>
<td>top limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi10</td>
<td>I/Oi10</td>
<td>bottom limit switch on the spindle drive</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi11</td>
<td>I/Oi11</td>
<td>air pressure check</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi12</td>
<td>I/Oi12</td>
<td>manual emergency stop</td>
<td>emergency feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oi13</td>
<td>I/Oi13</td>
<td></td>
<td>extra AD input 1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>I/Oi14</td>
<td>I/Oi14</td>
<td></td>
<td>extra AD input 2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>DA output signals (8)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DA1</td>
<td>DA1</td>
<td>amplifier of M1</td>
<td>feedback</td>
<td></td>
<td>MDC LA 100N</td>
</tr>
<tr>
<td>DA2</td>
<td>DA2</td>
<td>amplifier of M2</td>
<td>feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DA3</td>
<td>DA3</td>
<td>amplifier of M3</td>
<td>feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DA4</td>
<td>DA4</td>
<td>amplifier of M4</td>
<td>feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DA5</td>
<td>DA5</td>
<td>amplifier of M5</td>
<td>feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DA6</td>
<td>DA6</td>
<td>power of the light source for the probe photodiodes</td>
<td>feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DA7</td>
<td>DA7</td>
<td>(PSD)</td>
<td>(extra AD output 1)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DA8</td>
<td>DA8</td>
<td>(PSD)</td>
<td>(extra AD output 2)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>I/O output signals (8)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oo1</td>
<td>I/Oo1</td>
<td>probe objective</td>
<td>feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oo2</td>
<td>I/Oo2</td>
<td>Z-stage brakes</td>
<td>feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oo3</td>
<td>I/Oo3</td>
<td>Z-stage brakes</td>
<td>feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I/Oo4</td>
<td>I/Oo4</td>
<td></td>
<td>(extra I/O output)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hall</td>
<td>Hall</td>
<td>Hall sensors in spindle for electr. commutation</td>
<td>feedback</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS4</td>
<td>PS4</td>
<td>calibration PSD</td>
<td>one time calibration</td>
<td></td>
<td>Philips: PSD unit 4</td>
</tr>
<tr>
<td>AC0</td>
<td>AC0</td>
<td>calibration on autocollimator</td>
<td>one time calibration</td>
<td></td>
<td>automation electronics</td>
</tr>
<tr>
<td>IR0</td>
<td>IR0</td>
<td>calibration on interferometer</td>
<td>one time calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR1</td>
<td>IR1</td>
<td>calibration on interferometer</td>
<td>one time calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR2</td>
<td>IR2</td>
<td>calibration on interferometer</td>
<td>one time calibration</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix B

Overview of data acquisition and controller boards

In Figure B.1 an overview of the input and output signals of a control board accompanying the NANOMEMFOS is given. In the following table on the next page, an overview of possible control boards and their main specifications is given: Quanser [12], TUDACCS/3 and TUDACCS/6 [13] and dSpace [5]. The specifications of the Compact Rio system are discussed in more detail by [2]. A good indication of the prices to compare the various boards could not be put together and is therefore omitted.

![Diagram of control board signals](image)

Figure B.1: Overview of the I/O, A/D, D/A and encoder input and output signals of a control board accompanying the NANOMEMFOS.

Furthermore a table including specifications of the data acquisition boards currently kept in mind as possible solutions for parts of the data acquisition (see Figure B.1 A.2) is included at the end of this appendix: the Heidenhain IK220 [6], an Agilent Laser Board [1], a Zygo Measurement Board [14] and a Lion Capacitive Probe Driver [9].
## APPENDIX B. OVERVIEW OF DATA ACQUISITION AND CONTROLLER BOARDS

<table>
<thead>
<tr>
<th>CONTROLLER BOARDS</th>
<th>I/O accuracy</th>
<th>conversion time &amp; sampling frequency</th>
<th>interface, sample rates</th>
<th>counter-timer</th>
<th>software</th>
<th>various</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quanser: Q8 High-Performance H.I.L. Control Board</strong></td>
<td>32 digital I/O</td>
<td>0.18-0.79µs</td>
<td>PCI, 32 bit, 33MHz</td>
<td>2 counter-timers</td>
<td>Quanser WinCon</td>
<td>simultaneous sample &amp; hold A/D</td>
</tr>
<tr>
<td></td>
<td>8 A/D +/-10V</td>
<td>17.8µs / 56kHz</td>
<td>32 bit, 3.0ns resolution</td>
<td>Mathworks xPC Target</td>
<td></td>
<td>simultaneous output D/A</td>
</tr>
<tr>
<td></td>
<td>8 D/A +/-0V, +/-10V, 0-10V</td>
<td>0.62-1.35µs</td>
<td>24 bit counter size</td>
<td>LabVIEW RTX</td>
<td></td>
<td>simultaneous sampling Enc.</td>
</tr>
<tr>
<td></td>
<td>8 encoder inputs</td>
<td>2-50-4.72µs / max. input freq.: 2-15MHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TueDACS/3</strong></td>
<td>32 digital I/O lines</td>
<td>800µs</td>
<td>PCI, 32 bit, 33MHz</td>
<td>2 counter-timers</td>
<td>Mathworks xPC Target</td>
<td>external trigger can be assigned</td>
</tr>
<tr>
<td></td>
<td>2 digital I/O lines</td>
<td>20MHz master clock output</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 digital I/O lines</td>
<td>programmable clock output</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>32 digital I/O lines</td>
<td>max. sample rate 1MHz</td>
<td></td>
<td></td>
<td>2 memories of 512k samples</td>
<td></td>
</tr>
<tr>
<td><strong>TueDACS/6</strong></td>
<td>4 A/D +/-10V</td>
<td>100kHz</td>
<td>PCI, 32 bit, 33MHz</td>
<td>2 counter-timers</td>
<td>Mathworks xPC Target</td>
<td>external trigger / gate input</td>
</tr>
<tr>
<td></td>
<td>12 bit</td>
<td>20MHz master clock output</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 bit</td>
<td>programmable clock output</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Compact Rio van National Instruments</strong></td>
<td>4 A/D BNC channels +/-2.5V, +/-5V, +/-10V, 0-10V</td>
<td>max. sample rate 1MHz per channel</td>
<td>PCI, 32 bit, 33MHz</td>
<td>2 counter-timers</td>
<td>Mathworks xPC Target</td>
<td>external trigger / gate input</td>
</tr>
<tr>
<td></td>
<td>16 bit</td>
<td>max. sample clock signal</td>
<td></td>
<td></td>
<td>2 memories of 512k samples</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>external trigger input</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>max. sample clock signal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>dSpace: DS1103 PPC Controller board</strong></td>
<td>8 D/A +/-10V</td>
<td>5-20MHz</td>
<td>external trigger</td>
<td>Mathworks xPC Target</td>
<td>external trigger, 256k samples buffer per channel</td>
<td>software or external trigger, 512k samples buffer per D/A channel</td>
</tr>
<tr>
<td></td>
<td>12 bit</td>
<td>ext. sample clock input</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 bit</td>
<td>ext. clock input</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 bit</td>
<td>ext. clock input</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 bit</td>
<td>ext. clock input</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16 bit</td>
<td>ext. clock input</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

I/O accuracy conversion time & sampling frequency interface, sample rates counter-timer software various

### TueDACS/3

- **MSI**
  - 4 A/D
  - 12 bit
  - 100kHz
  - 20MHz master clock output
  - programmable clock output
  - external trigger can be assigned

- **DIO**
  - 32 digital I/O lines
  - 12 bit
  - max. sample rate 1MHz per channel
  - max. sample clock signal external trigger input
  - 1MHz
  - 2 memories of 512k samples

### TueDACS/6

- **ASR**
  - 2 A/D +/-1V (per module)
  - 12 bit
  - max. input freq.: 5-20MHz
  - ext. sample clock input
  - 5-20MHz sample rate
  - external trigger / gate input
  - external trigger, 256k samples buffer per channel

- **TRC**
  - 2 A/D channels +/-1V
  - 12 bit
  - max. input freq.: 5-20MHz
  - ext. clock input
  - 5-20MHz sample rate
  - external trigger / gate input
  - external trigger, 256k samples buffer per channel

- **ASG**
  - 4 D/A BNC channels +/-2.5V, +/-5V, +/-10V, 0-10V, 0-5V
  - 12 bit
  - max. input freq.: 5-20MHz
  - ext. clock input
  - 5-20MHz sample rate
  - external trigger / gate input
  - external trigger, 256k samples buffer per channel

### Compact Rio van National Instruments

- **RS232 serial port**
  - 200kHz motion control
  - 1MHz closed loop digital control
  - LabVIEW RTX

### dSpace: DS1103 PPC Controller board

- **A/D: 16 multiplexed / 4 parallel +/-10V**
  - 16 bit
  - 1µs / 800µs
  - 1 sampling rate timer, 32 bit, 15ns resolution
  - ControlDesk; Simulink interface, graphical interface for operator version or common version management system
  - Options for experiment control and data acquisition with Matlab (Mlib/Mtrace)
  - PLL-driven UART for accurate baud rate selection
  - additional I/O via subsystem possible: Texas Instruments TMS320F240 DSP; 20MHz, 16 A/D, 10 PWM outputs, 4 capture inputs, 2 serial ports, 18 D/I/O

- **8 D/A +/-10V**
  - 16 bit
  - 5µs (14 bit)
  - 1 time base counter, 64 bit, 30ns
  - Options for experiment control and data acquisition with Matlab
  - 32k samples buffer per D/A channel

- **6 independent digital incremental encoder channels**
  - 24 bit resolution
  - max. input freq.: 1.65GHz
  - PLL-driven UART for accurate baud rate selection

- **1 analog incremental encoder interface**
  - 32 bit loadable position counter (analog enc.), 6 bit
  - A/D conversion performance
  - max. input freq.: 0.6MHz
  - PLL-driven UART for accurate baud rate selection

- **32 digital I/O**
  - CAN and serial, 1GHz
  - CPU clock
  - 2 general purpose timers, 32 bit, 15ns resolution
  - DS1103 Real-Time Library and Real-Time Interface
  - possibility to synchronize A/D, D/A and position of incremental encoder with internal PWM signal or external trigger
  - digital incremental encoder interface, graphical interface for operator version or common version management system
  - Options for experiment control and data acquisition with Matlab
  - PLL-driven UART for accurate baud rate selection

- **A/D: 16 multiplexed / 4 parallel +/-10V**
  - 16 bit
  - 1µs / 800µs
  - 1 sampling rate timer, 32 bit, 15ns resolution
  - ControlDesk; Simulink interface, graphical interface for operator version or common version management system
  - Options for experiment control and data acquisition with Matlab
  - 32k samples buffer per D/A channel

- **8 D/A +/-10V**
  - 16 bit
  - 5µs (14 bit)
  - 1 time base counter, 64 bit, 30ns
  - Options for experiment control and data acquisition with Matlab
  - 32k samples buffer per D/A channel

- **6 independent digital incremental encoder channels**
  - 24 bit resolution
  - max. input freq.: 1.65GHz
  - PLL-driven UART for accurate baud rate selection

- **1 analog incremental encoder interface**
  - 32 bit loadable position counter (analog enc.), 6 bit
  - A/D conversion performance
  - max. input freq.: 0.6MHz
  - PLL-driven UART for accurate baud rate selection
### DATA PROCESSING BOARDS

**Heidenhain IK220**

- **44 bit measured value**
- **40kHz measuring**
- **PCI**
- **4096-fold signal subdivision**
- **Access to the measured data with 3.5 to 28.5kHz**
- **Driver software and demonstration program for Windows NT/95/98 in Visual C++, Visual Basic and Borland Delphi**
- **Adjustment of offset, phase and amplitude by software / online**
- **Internal memory for 8192 position values**

**Agilent Technologies N1231B PCI Three-Axis High Performance Laser Board with External Sampling**

- **36-bit axis position data**
- **Up to 20MHz measuring**
- **PCI**
- **Programming API (Windows NT4/2000/XP)**
- **On board programmable sample/hold clocks**
- **Position and velocity output**

**Zygo Corporation ZMI 4004 Measurement Board**

- **0.15nm resolution (2-pass)**
- **0.3nm for 1-pass**
- **10MHz**
- **Parallel, VME, high speed serial**
- **4 axes per board**
- **0.2 nsec data age uncertainty, synchronisation of axes**

**Lion Precision CPL190/290 Capacitive Probe Driver**

- **1, 2, 3, 6 and 8 channel drivers, +/-10V**
- **0.004% F.S. RMS**
- **Up to 15kHz bandwidth**
- **Virtual instrument driver using LabVIEW RTX**
- **Easy connection to National Instruments data acquisition hardware**

**Specifications**

- **Heidenhain IK220**
  - Encoders with 1Vpp (500kHz max input), 11µApp (3kHz max input), EnDat or SSI
  - 32-bit value of period counter and 12 bit interpolation value
  - Access to the measured data with 3.5 to 28.5kHz

- **Agilent Technologies N1231B PCI Three-Axis High Performance Laser Board with External Sampling**
  - 36-bit axis parallel or 36-bit multiplexed interface
  - 4 external sample inputs: 3 axis of laser measurement and 1 system sample for synchronisation.
  - 4 external data hold inputs for hardware position outputs
  - 0.15nm (λ/4096)

- **Zygo Corporation ZMI 4004 Measurement Board**
  - 4 axes per board
  - 0.15nm resolution (2-pass)
  - 0.3nm for 1-pass
  - 10MHz parallel, VME, high speed serial

- **Lion Precision CPL190/290 Capacitive Probe Driver**
  - 1, 2, 3, 6 and 8 channel drivers, +/-10V
  - 0.004% F.S. RMS
  - Up to 15kHz bandwidth
  - Virtual instrument driver using LabVIEW RTX
  - Easy connection to National Instruments data acquisition hardware
Appendix C

Spindle set-up specifications

In this appendix specifications of the Block-Head air bearing spindle and its accompanying hardware components, i.e. its driving permanent magnet synchronous brushless motor, the LA-2000 motor drive, the Renishay RGH20F readhead and the ERP 880 Heidenhain angular encoder are listed.

C.1 Block-Head air bearing spindle

Specifications of the Block-Head Air Bearing Spindle 10R are given below.

- total weight 680 $N$ (spindle only; excluding motor and encoders)
- rotor weight 320 $N$
- rotor inertia 0.254 $kgm^2$
- maximum speed 1800 rpm
- air consumption $< 85 L/min$

<table>
<thead>
<tr>
<th>load capacity</th>
<th>ultimate</th>
<th>working</th>
<th>(at 10 bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>radial</td>
<td>1780 $N$</td>
<td>890 $N$</td>
<td></td>
</tr>
<tr>
<td>axial</td>
<td>10700 $N$</td>
<td>5350 $N$</td>
<td></td>
</tr>
<tr>
<td>tilt</td>
<td>680 $Nm$</td>
<td>340 $Nm$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>stiffness</th>
<th>(at 10 bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>radial</td>
<td>350 $N/m$</td>
</tr>
<tr>
<td>axial</td>
<td>1750 $N/m$</td>
</tr>
<tr>
<td>tilt</td>
<td>11.3 $Nm/rad$</td>
</tr>
</tbody>
</table>

- load capacity and stiffness are approximately linear with the air pressure

<table>
<thead>
<tr>
<th>error motion</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>radial</td>
<td>$&lt; 25 nm$</td>
</tr>
<tr>
<td>axial</td>
<td>$&lt; 25 nm$</td>
</tr>
<tr>
<td>tilt</td>
<td>$&lt; 0.1 rad$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>eigen frequencies (derived from combination of the weight, inertia and stiffness per direction)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>radial</td>
<td>526 $Hz$</td>
</tr>
<tr>
<td>axial</td>
<td>1.17 $kHz$</td>
</tr>
<tr>
<td>tilt</td>
<td>1.35 $kHz$ (total inertia equals 0.157 kgm²)</td>
</tr>
</tbody>
</table>
C.2 Permanent Magnet Synchronous Brushless Motor

The spindle is driven by a permanent magnet synchronous brushless motor (or AC-synchronous servo motor), i.e. the B20-13 A3281 custom wound motor of Motion Control Systems (MCS). Specifications of this motor are given below.

- number of poles: 16
- $K_e$: 86.3 $V/1000rpm$
- $R_t$: 5 $\Omega$
- $L_t$: 8.73 $mH$
- electrical time constant $\tau$: 1.7 $mH/\Omega$ $(L_t/R_t)$
- weight: 140 kg (motorized spindle; including stator)

The motor incorporates an embedded Hall effect array of 3 Hall effect sensors, which are used for the electronic commutation. In between the Hall sensors, the motor drive examines the Renishaw readhead to gain a higher resolution and consequently reduce the torque ripple.

The motor is sinusoidally wound. This means that the voltage generated across each phase, which are placed under $120^\circ$ with respect to each other, by turning the rotor at a constant speed, has a sinusoidal waveform. Consequently the electrical current driving the motor should be sinusoidal and in phase with the voltages generated when injected into the corresponding motor phase windings. This means that the angular position of the rotor has to be known at all times, which is possible by the application of the Renishaw readhead.

The magnitude of the generated voltage is proportional to the angular velocity of the rotor.

![Figure C.1: Torque and Power vs rotational speed of the B20-13-HAH-136 motor.](image)

C.3 The LA-2000 motor drive

The LA-2000-62-B3031 motor drive is the amplifier accompanying the brushless motor of MCS. The main specifications of this motor drive are given below, see also the user’s manual.
C.4. THE RENISHAW RGH20F READHEAD

- analog input signal $\pm 10$ V
- analog output signal $\pm 10$ A
- it is a three phase drive
- no internal torque limiting (this has to be done by the controller)
- The drive has a built-in controller for the rotational speed. The control aims at (relatively) high constant rotational speeds with CW as well as CCW rotations. Acceleration and deceleration rates can be set in the range of 0 to 20000 rpm sec$^{-1}$. See [11] for detailed specifications.
- Control of the motor using the speed controller via RS232 or via an external analogue input in which the input voltage corresponds to the amplitude level of the electrical current in the motor (i.e. torque control); 1 V corresponds to 1 A with an input voltage $> 0$ for CW rotations and $< 0$ for CCW rotations

C.4 The Renishaw RGH20F readhead

Built-in in the spindle is a Renishaw RGH20F readhead in combination with a RGF2000, which are used by the LA2000 motor drive for the electronic commutation and can be used for angular position measurement as well. Specifications of the encoder are given below.

- accuracy 1.5 arc second
- resolution 0.01"
- nom. external diameter 104 mm
- line counts 16384
- scale pitch $\mu m$
- mass 0.25 kg
- moment of inertia 550 kg mm$^2$
- system error $\pm 2.8$ " (for 20 $\mu m$ systems)
- graduation error $\pm 2.0$ " (for 20 $\mu m$ systems)
- output signal 1 Vpp

(i.e. 1 arc second resolution = $1.296 \cdot 10^6$ counts/rev = $2.778 \cdot 10^{-4}$ deg resolution)

C.5 The ERP 880 Heidenhain angular encoder

Besides the Renishaw encoder, the ERP 880 HeidenHain Modular angular encoder is built-in as to attain the desired accuracy in determining the exact position of the product surface with respect to the probe. Specifications for the Heidenhain encoder are given below.
APPENDIX C. SPINDLE SET-UP SPECIFICATIONS

- Line counts 90000 (180000 signal periods)

- Cut-off frequency
  - $-6 \text{ dB} \leq 1.3 \text{ MHz}$
  - $-3 \text{ dB} \leq 800 \text{ kHz}$ (equal to 266 rpm at 180.000 signals periods per rev.)

- Resolution 35 $\mu$rad ($8750 \text{ nm at } R = 250 \text{ mm};$ 200 fold interpolation yields a resolution of 0.175 $\mu$rad, respectively 45 nm at $R = 250 \text{ mm}$)

- One reference mark, the so-called Z-index

- Moment of inertia rotor $1.2 \cdot 10^{-3} \text{ kgm}^2$

- Weight 3.1 kg (3.0 kg without housing)

- System accuracy $\pm 1''$ ($= 5 \mu\text{rad} = 1.25 \mu\text{m}$ at $R = 250 \text{ mm}$ ($1.25 \cdot 10^{-6}/250 \cdot 10^{-3}$))

- Output signal 1 Vpp
Appendix D

Break-out box

On the next page in Figure D.1 an overview of the break-out box developed to neatly bypass the data cable from the spindle to the amplifier is given.
Figure D.1: Overview of the IO and connections of the break-out box used to enable external control of the spindle amplifier LA2000.
Appendix E

Simulation model of the NANOMEFOS

In this appendix a short overview of the simulation model `simModel.mdl` of the NANOMEFOS, designed using Matlab / Simulink is given. More details and information can be found in the accompanying files:

- `simModel.mdl` the Simulink model described in this appendix
- `MachineModes.m` the m-script driving the operator block ‘machine modes’
- `checkRange.m` the m-function used in evaluating feasibility of the user-defined setpoints set in the operator block

E.1 Simmodel.m

The model is designed to:

1. be able to test different machine functions, especially the combination and succession of the various setpoints
2. develop and simulate control strategies for each stage, which then can be tested and used in practice
3. gain better understanding in the working of the overall closed loop system

The model consists of:

1. a model of the hardware of the NANOMEFOS per stage
   a. spindle: attention is paid to correct modeling of the spindle parameters, an optional load consisting of a table and a load can be added and the Z-index signal provided by the HeidenHain ERP880 is modeled (see also Chapter E about modeling of the spindle).
   b. probe: a linear actuator and the confocal system are modeled, concerning the confocal system, the sinusoidal approximation has to be replaced by the method developed by L. Cacace (summation of two signals) [3]
   c. other stages: considering the R,Z-stage and Ψ-axis it isn’t sure to this point what actuators will be used and consequently they are modeled straightforward and analogous to the probe respectively the spindle.
2. a controller per stage
   a. spindle: a feedback PID controller is modeled, see Chapter 5 for more details on
      the design of a controller for the spindle
   b. probe: two separate feedback PID controllers, for the position tracking and the
      focusing part, a switching algorithm, which assures switching from position tracking
      to focusing when the probe comes in focus and an iterative learning feedforward
      controller for the focusing part, which has to be optimized yet such that it becomes
      a continuously learning controller
   c. other stages: no attention is paid yet to these controllers and thus a straightforward
      feedback gain is modeled for the R,Z-stage and the Ψ-axis to this point
3. an operator block, which is designed to be used as an user-interface to apply different
   machine modes to the NANOMEFOS.
   a. Per machine mode a logical scheme determines the sequence of stages that have to
      be controlled and the corresponding setpoints that have to be generated. This is
      done per stage such that per stage all possible setpoints can be generated, within
      predefined bounds and with user-defined characteristics.
   b. A 3-dimensional surface serving as the product surface defined by the given CAD-
      data is modeled and a 'real' product surface is derived from these 3D CAD-data.
      The height variation and diameter of the product are user-defined.
   c. To be able to measure a track multiple times the rotation of the spindle is converted
      to a number of tracks.

To this point three different machine modes are modeled; a measurement run because this
is the main function of the NANOMEFOS and because all stages have to cooperate and operate
successively, the test procedure 'following CAD-data - testing the functional character of the
machine' is modeled in analogy to the measurement run and the separate control of all stages
in order to be able to test all controllers and simulate all modeled stages separately. Using the
operator block 'machine modes' to start these functions, all characteristic control parameters can
be set up user-defined (see Figure E.1).

E.2 Specifications

Several more detailed specifications of the model needed in understanding some of the design
structures are given next.

Initial state of all stages is equal to the hold position. Can be set via masks of separate
stages in the NANOMEFOS block:

- $\Theta_h = 0; C_h = 0; \Psi_h = 0; R_h = 0; Z_h = 0$;
- automatically: $\omega = 0$;
- and consequently not in focus

With $S = 0$ the mid-position of the total stroke of the probe, $\Psi = 0$ the vertically pointing
down position of the probe, $R = 0$ the center of the spindle and $Z = 0$ the top of the spindle-
table. For focusing properties the probe stroke compensated for the position of the Z-stage is used.

The setpoint generators per stage are structured as:

- inputs:
  - setpoints
  - start; used only the first time the generator is invoked, after that a change in setpoint
    initiates a new trajectory
E.2. SPECIFICATIONS

Figure E.1: screenshot of the operator block’s user interface of the simulation model.

- outputs:
  - per machine function one trajectory
  - optionally a break
- if not started: break on
- if started: define trajectory and break off
- if ready: break on
- if break on and started and change in setpoint: define new trajectory and break off
- continue to next stage when break on and started

Probe stroke: setpoint is only used when not in focus. When in focus, setpoint is set to ready. Starting a measurement is only allowed after a minimum time of focusing in order to guarantee the probe following the surface using its focusing function accurately.

When a stage isn’t used no setpoint is generated and its controller isn’t used either (switched off) by the orange “<stageName>Control” blocks, which are set via the “useStage(i)” variable and determined in the Initialisation Dialog of the machine functions block. On top of that, the outputs of the machine functions block are set to the current value of all stages instead of zero setpoints by the switches after the setpoint generating blocks.

On breaking of a stage (Ψ-axis, R-stage or Z-stage), the corresponding controller is dis-
abled to prevent overheating. In the modeling of the stages the brakes are represented by memory blocks that store the actual position of a stage at the moment of braking. This is allowed if the brakes aren’t loosened before a new trajectory based on the (stored) actual position is defined. Otherwise the dynamical behaviour of the system while the break is on is stored as energy, which comes free when the brake is off.

Using the files surfaceTest.mdl and plotSurfaceTest.m, an example of the conversion from measurement to actual product surface data is demonstrated. Combining this method with the simulation model, the simulation test can be completed. In Figure E.2 an example result is shown.

Figure E.2: simulation test result of a product surface measurement.
Appendix F

Commutation problems

As mentioned in Section 5.3 several problems were encountered in controlling the Blockhead air bearing spindle 10R. The currently remaining problem involves the electronical commutation, which doesn’t seem to function as it should do:

- when starting the spindle from standstill, the spindle starts turning in the wrong direction initially or 'hesitates' to actually start rotating, regularly;
- when controlling the spindle via the analogue input port of the LA 2000 amplifier, control of the spindle at standstill seems to be impossible.

To subscribe the above mentioned problems, measurements using the ser_com program accompanying the LA 2000 amplifier and open loop measurements using the external input of the LA 2000 amplifier are performed. Set-up of the measurements and some of the erroneous results are presented in the following sections.

F.1 Built-in speed controller

To check the commutation at the start of a run using the built-in speed controller and RS-232 communication, the set-up as shown in Figure F.1 is used. The rotation of the spindle is user-

![Diagram](image)

Figure F.1: overview of the spindle set-up in performing tests using the amplifier built-in speed controller.

defined and set using the ser_con program running on the PC. Starting from standstill, the spindle should always start rotating in the desired direction due to the built-in Hall effect sensors (see [11], pg 22, which states that the absolute position of the spindle is always known after the 'power-up initialization period'). However, both for clockwise and counter clockwise rotations, regularly the spindle rotates in the wrong direction or hesitates to actually start rotating initially.
In the plots of Figure F.2 several examples of these phenomena are given. In every plot, the part of the measured position (in radians) from standstill (or almost standstill) to a constant speed is shown. Although the actual start commands aren’t triggered and thus aren’t shown, they can be distinguished clearly in the plots.

Figure F.2: measurement data illustrating the erroneous behaviour of the spindle commutation; in every plot the position (in radians) of the spindle is shown in time. The plots show measurement results of tests initiating the spindle from standstill to a constant rotational speed.
F.2 Open loop measurements

To test the open loop response and check the commutation of the spindle set-up, the analogue input mode of the LA2000 amplifier is used to impose a constant input voltage. Corresponding to

![Diagram of spindle set-up](image)

Figure F.3: overview of the spindle set-up in performing open-loop tests using the analog input of the amplifier.

the positive or negative sign of the input voltage, the spindle should rotate clockwise respectively counter clockwise. Starting from standstill the amount of times the spindle started turning in the right direction was compared to the amount of times the spindle initially rotated over a significant angle in the wrong direction or even hesitated for several seconds. Both for positive and negative input voltages, this erroneous behaviour occurred in almost 50% of the trials. Variation in the magnitude of the input voltage didn’t influence this behaviour.

In the plots of Figure F.4 some examples are given. The right figures are a magnification of the red encircled part in the corresponding figures to the left. It is clearly shown that the spindle starts rotating in the wrong direction over a significant angle or hesitates before starting to rotate regularly.
Figure F.4: Measurement data illustrating the erroneous behaviour of the spindle commutation; in every plot the position (in radians) of the spindle is shown in time. The left plots show measurement results of tests initiating the spindle from standstill to a constant rotational speed, the right plots are magnifications of the red encircled parts of the corresponding left plots.