

**FMH606 Master's Thesis 2023  
Industrial IT and Automation**

**Introduction, summary and references from  
Master thesis "Line of sight stabilization  
using direct drive actuators in a gyro  
stabilized sensor system." (Non-classified  
information)**

Eirik Engen

Faculty of Technology, Natural Sciences and Maritime Sciences  
Campus Porsgrunn

**Course:** FMH606 Master's Thesis 2023

**Title:** *Introduction, summary and references from Master thesis "Line of sight stabilization using direct drive actuators in a gyro stabilized sensor system." (Non-classified information)*

**Pages:** 142

**Keywords:** *Stabilization, Direct drive, Harmonic Drive, Line of sight stabilization, Gyro, LQR, LQG*

**Student:** *Eirik Engen*

**Supervisor:** *David Di Ruscio*

**External partner:** *Rheinmetall Norway AS, Report: Confidential*

### **Summary:**

Line of sight stabilization is about keeping the line of sight in a sensor (camera, laser) towards an object of interest while being exposed to external disturbances. A military vehicle may in some cases be equipped with a long-range observation sensor platform. The sensor platform must be capable of observing with a steady and accurate line of sight during its mission, which can be achieved by mounting the sensors on a stabilized pan tilt platform. This thesis documents a concept study where a direct drive concept has been evaluated against a gear box drive for a stabilized elevation axis on the long-range observation platform Vingtaqs II. A prototype was developed and used as reference, where an optimal linear quadratic controller, LQR, together with a linear quadratic optimal state estimator, a Kalman filter, was used as an LQG stabilization controller.

Models of the drive were developed and implemented in Matlab for simulation and for design, and the results from the simulations and implementation can be viewed in detail in the result chapter 4.

# Contents

<b>Contents</b>	<b>5</b>
List of Figures . . . . .	8
List of Tables . . . . .	9
<b>1 Introduction</b>	<b>13</b>
<b>2 Problem Formulation</b>	<b>15</b>
<b>3 Methods</b>	<b>16</b>
3.1 Definitions . . . . .	17
3.1.1 Coordinate frames . . . . .	17
3.1.2 Notations . . . . .	19
3.2 Mathematical model development . . . . .	19
3.2.1 Discretization . . . . .	23
3.2.2 Model analysis . . . . .	24
3.3 direct drive prototype . . . . .	24
3.4 System identification . . . . .	25
3.4.1 Frequency response calculation from test data . . . . .	26
3.4.2 Model estimation using frequency response data object . . . . .	26
3.5 Control design . . . . .	26
3.5.1 Drive controller . . . . .	28
3.5.2 LQ optimal controller - LQR . . . . .	29
3.5.3 Design discrete LQR . . . . .	31
3.5.4 State estimator . . . . .	36
3.5.5 Controller robustness and performance . . . . .	38
3.6 Implementation in Matlab / Simulink . . . . .	38
3.6.1 Model implementation . . . . .	38
3.6.2 Test signal implementation . . . . .	39
3.6.3 System identification implementation . . . . .	39
3.6.4 LQR design implementation . . . . .	39
3.6.5 Kalman filter implementation . . . . .	40
3.6.6 LQG implementation . . . . .	41
3.6.7 System simulator implementation in Simulink . . . . .	41
3.6.8 Prototype controller compilation in Simulink . . . . .	41

3.6.9	Simulink solver . . . . .	41
3.7	Simulations . . . . .	42
3.8	System tests . . . . .	43
<b>4</b>	<b>Results</b>	<b>46</b>
4.1	Mathematical models results . . . . .	46
4.1.1	Servo drive axis with Harmonic Drive gear . . . . .	47
4.1.2	Servo drive axis with direct drive . . . . .	50
4.1.3	Model analysis results . . . . .	54
4.2	Designing the direct drive prototype . . . . .	61
4.2.1	Motor drive specification . . . . .	61
4.2.2	Direct drive prototype design and manufacturing . . . . .	64
4.2.3	Integration and test setup . . . . .	71
4.2.4	Functional testing . . . . .	73
4.3	System identification results . . . . .	75
4.3.1	Test setup to collect frequency response data . . . . .	76
4.3.2	FRD objects in Matlab . . . . .	80
4.3.3	Identification script in Matlab . . . . .	80
4.4	Design of stabilization system controllers . . . . .	84
4.4.1	Elmo Platinum drive controller design . . . . .	84
4.4.2	Optimal stabilization controller design . . . . .	92
4.4.3	Optimal estimator design - Kalman filter . . . . .	96
4.4.4	Implementation of the LQG controller . . . . .	99
4.5	Simulation and measurement results . . . . .	102
4.5.1	Simulink model - simulation . . . . .	102
4.5.2	Stabilization frequency response . . . . .	104
4.6	System tests . . . . .	107
4.6.1	Test configuration and setup . . . . .	107
4.6.2	Stabilization performance . . . . .	108
<b>5</b>	<b>Discussions and Conclusion</b>	<b>115</b>
5.1	Conclusion . . . . .	116
	<b>References</b>	<b>117</b>
<b>A</b>	<b>Master Thesis description</b>	<b>119</b>
<b>B</b>	<b>Matlab scripts</b>	<b>122</b>
B.1	Create FRD-object from iba-data . . . . .	122
B.2	Model estimation function . . . . .	124
B.3	LQR analysis script . . . . .	125
B.4	LQR + Kalman filter analysis script . . . . .	127
B.5	LQG simulate frequency response measurement . . . . .	130

B.6	Mathematical model of direct drive VTII elevation axis . . . . .	134
B.7	Mathematical model of Harmonic Drive VTII elevation axis . . . . .	136
<b>C</b>	<b>Elmo Platinum configuration settings</b>	<b>139</b>
C.1	Platinum drive settings . . . . .	139
C.1.1	Axis configuration . . . . .	139
C.1.2	Motor settings . . . . .	140
C.1.3	Feedback settings . . . . .	140
C.1.4	Limits and protections . . . . .	141
C.1.5	Commutation . . . . .	142

# List of Figures

1.1	Vingtaqs II product . . . . .	13
3.1	Flow diagram of the direct drive concept study . . . . .	16
3.2	Line of sight . . . . .	17
3.3	General dynamic system description. . . . .	19
3.4	System identification methods . . . . .	20
3.5	System Identification toolbox (Matlab System Identification Toolbox GUI)	25
3.6	General description of measuring an open loop response on a system. . . .	26
3.7	Block Diagram of the conceptual control architecture . . . . .	27
3.8	Flow diagram of the control design process . . . . .	27
3.9	Block diagram of autonomous state feedback system . . . . .	30
3.10	LQR with integral action conceptual diagram . . . . .	33
3.11	Conceptual architecture of LQR with integral action and Kalman filter . .	36
3.12	Simulink solver used in the simulations . . . . .	42
3.13	Vingtaqs II Stabilization control loops . . . . .	42
3.14	Motion simulation platform, (Rheinmetall Norway, 2010) . . . . .	44
4.1	Vingtaqs II sensor head components (Rheinmetall Norway 2021) . . . . .	46
4.2	Cradle section view . . . . .	46
4.3	Physical model of elevation axis with Harmonic Drive gear . . . . .	47
4.4	Pan & tilt mechanical stiffness . . . . .	47
4.5	Harmonic Drive stiffness and damper . . . . .	47
4.6	Free body diagrams of the Harmonic Drive elevation axis . . . . .	48
4.7	Physical model of the direct drive . . . . .	51
4.8	Free body diagrams of direct drive system . . . . .	52
4.9	Harmonic Drive Open Loop - Compare measured response and mathem- atical model . . . . .	56
4.10	Harmonic Drive Closed Loop - Compare measured response and mathem- atical model . . . . .	57
4.11	Harmonic Drive closed loop - step response . . . . .	57
4.12	Direct drive Open Loop - Compare measured response and mathematical model . . . . .	59
4.13	Direct drive Closed Loop - Compare measured response and mathematical model . . . . .	60
4.14	Direct drive closed loop - step response . . . . .	60

4.15	Angular and velocity profile required for the system to move to any angle within 3 seconds. . . . .	63
4.16	Direct drive torque-speed curve . . . . .	65
4.17	Heidenhain absolute encoder (Heidenhain catalogue - Rotary Encoders) . .	67
4.18	Mounted direct drive, showing the encoder sensor . . . . .	68
4.19	Gyro mounted on prototype . . . . .	68
4.20	Direct drive motor section view with labels . . . . .	70
4.21	Direct drive motor exploded view . . . . .	70
4.22	Rotor assembly . . . . .	71
4.23	Stator assembly . . . . .	71
4.24	direct drive prototype . . . . .	71
4.25	direct drive prototype . . . . .	71
4.26	Prototype hardware communication block diagram . . . . .	72
4.27	direct drive test setup layout . . . . .	73
4.28	EAS II software from Elmo motion control . . . . .	74
4.29	TwinCAT in Visual Studio . . . . .	75
4.30	Frequency response setup for the Gyro Open Loop . . . . .	76
4.31	Prototype electronic setup . . . . .	77
4.32	Prototype measurement setup . . . . .	77
4.33	Prototype measurement setup on the motion platform . . . . .	77
4.34	Frequency response excitation signal . . . . .	79
4.35	Frequency as a function of time of the sine sweep excitation signal . . . . .	79
4.36	Frequency response from velocity reference to measured gyro rate . . . . .	83
4.37	Block Diagram of the Control Architecture . . . . .	84
4.38	Block Diagram of the Drive Torque Control Architecture . . . . .	85
4.39	Platinum drive torque control implementation (Elmo Motion Control, 2022)	86
4.40	Current plant identification . . . . .	86
4.41	Current control design . . . . .	87
4.42	Current control verification . . . . .	88
4.43	Block Diagram of the Drive Velocity Control Architecture . . . . .	88
4.44	Harmonic Drive velocity plant . . . . .	89
4.45	Platinum drive velocity control implementation (Elmo Motion Control, 2022)	90
4.46	Velocity plant identification . . . . .	90
4.47	Velocity control design . . . . .	91
4.48	Drive velocity control measured closed loop response . . . . .	92
4.49	System with process and measurement disturbance . . . . .	93
4.50	Logged sinusoidal closed loop tracking . . . . .	94
4.51	LQR with integral action conceptual diagram(as also shown in chapter 3.5.3)	95
4.52	Simulation result from LQR closed loop step response . . . . .	96
4.53	Simulation result from LQR + Kalman filter closed loop step response . .	98
4.54	Simulation result from LQR + Kalman filter closed loop step response, but with noisy feedback signal . . . . .	99

4.55	Zoomed in on feedback signal, to observe the filtered Kalman estimate $\bar{y}$	99
4.56	Simulink model - LQR with Kalman filter	100
4.57	Implemented LQG on prototype Beckhoff IPC	101
4.58	Implemented LQR in LQG on prototype Beckhoff IPC	101
4.59	Simulink model simulation disturbance	103
4.60	Simulink model stabilization error computation	103
4.61	Simulink model simulation stabilization error	104
4.62	Frequency response measurement of conservative vs aggressive LQR	105
4.63	Frequency response measurement of simulated LQG vs aggressive LQR	106
4.64	Frequency response comparison of stabilization closed loop	107
4.65	Motion platform	108
4.66	Motion platform test facility	108
4.67	Test setup view	108
4.68	Test overview	108
4.69	Stabilization error comparison between Harmonic Drive and direct drive	109
4.70	direct drive prototype stabilization test, Excitation 1	110
4.71	direct drive prototype stabilization test, Excitation 2	110
4.72	direct drive prototype stabilization test, Excitation 3	111
4.73	direct drive prototype stabilization test, Excitation 4	111
4.74	direct drive prototype stabilization test, Excitation 5	112
4.75	direct drive prototype stabilization test, Excitation 7	112
4.76	direct drive prototype stabilization test, Excitation 8	113
4.77	direct drive prototype stabilization test, Excitation 9	113
4.78	direct drive prototype stabilization test, Excitation 10	114
C.1	Direct drive axis configuration	139
C.2	Direct drive motor settings	140
C.3	Absolute encoder feedback settings	140
C.4	Direct drive current limit configuration	141
C.5	Direct drive position limit settings	142
C.6	Direct drive motor commutation process	142



# List of Tables

3.1	Coordinate frames used in this thesis. All of the coordinate frames are orthogonal and right handed. . . . .	18
3.2	Notations . . . . .	19
3.3	External motion excitation signals . . . . .	44
4.1	Elevation Harmonic Drive Axis Parameters . . . . .	48
4.2	Direct drive physical parameters . . . . .	51
4.3	Gyro sensor feedback delay . . . . .	69
4.4	Experimental stabilization performance measurement result . . . . .	109

# Listings

4.1	Direct drive motor parameters . . . . .	65
4.2	Frequency sweep signal . . . . .	78
4.3	Model estimator function . . . . .	80
4.4	script sequence estimating model . . . . .	81
4.5	script sequence - check controllability and observability . . . . .	93
4.6	script sequence - check closed loop stability . . . . .	94
4.7	script sequence - LQR main simulation loop . . . . .	95
4.8	Kalman filter function . . . . .	101
B.1	create Matlab frd-object . . . . .	122
B.2	Model estimation function . . . . .	124
B.3	LQR analysis . . . . .	125
B.4	LQR + Kalman filter analysis . . . . .	127
B.5	LQG simulate frequency response measurement . . . . .	130
B.6	Mathematical model of direct drive VTII elevation axis . . . . .	134
B.7	Mathematical model of Harmonic Drive VTII elevation axis . . . . .	136

# Nomenclature

Symbol	Explanation
6DOF	6 Degrees Of Freedom
DD	Direct drive
DFT	Discrete fast Fourier Transform
EAS	Elmo Application Studio
EMF	Electromotive force
EMI	Electromagnetic Interference
EMO	Elevation actuator / motor
Ex( $n$ )	Excitation number $n$
FFT	Fast Fourier Transform
FOV	Field of View
FRD	Frequency Response Data
HD	Harmonic Drive
IEC	International Electrotechnical Commission
IPC	Industrial PC
LOS	Line of Sight
LQ	Linear Quadratic
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
LRF	Laser Range Finder
LTI	Linear Time-Invariant
MEMS	Micro-Electro-Mechanical Systems
mRad	Milliradians
NRMSE	Normalized Root Mean Squared Error
PID	Proportional Integral Derivative
RMS	Root Mean Square
RPM	Rounds Per Minute

<b>Symbol</b>	<b>Explanation</b>
SCU	System Control Unit
TIM	Thermal Imaging Module (thermal camera)
VIM	Visual Imaging Module (day camera)
VINGTAQS	Vinghøg Target Acquisition System

# 1 Introduction

Rheinmetall Norway AS is a sub-division of the company Rheinmetall AG, a leading European systems supplier for defence and security technology. It has been an established player in the Nordic region for over half a century, located in Tønsberg. The company specializes in high-tech products for dismounted soldiers as well as sensor and observation systems, reconnaissance and fire control systems. One of the most advanced products at Rheinmetall Norway, is the observation system Vingtaqs II, which is a high-end long range observation system, that can be mounted on different types of military vehicles. The sensor platform (Figure 1.1) is gyro stabilized, which means that it stabilizes the camera line of sight towards an observed scene or object.

Along with the camera line of sight, the system uses also other types of high-end electro-optical sensors to calculate coordinates at long distances up to 10 km, where all of the sensors must be co-aligned in order to give this functionality. As the market becomes more and more demanding, it is of interest to investigate how the performance of the stabilization may be improved by replacing the gear box drive to direct drive in the pan and tilt platform.



Fig. 1.1: Vingtaqs II product

## Background

Rheinmetall is a large international company with the technology and experience required to design systems that stabilize a two axis gimbal with electro-optical sensors. Internal articles and reports within the company are company confidential and cannot be used as reference in this paper, however, several public books and articles describe and discuss the subject. The paper "Inertial stabilization, estimation and visual servoing for aerial surveillance" [1] gives a complete system perspective of a line of sight stabilized system, and covers many experimental test results together with theoretical explanations. Stabilizing a two axis gimbal system requires a cross discipline engineering focus. The book "Stabilizing the line of sight" [2], describes many technological considerations that

must be made when designing a LOS stabilized system and focuses especially on using direct drive actuators for high performance stabilization. An article in the Control Engineering magazine ([controleng.com](http://controleng.com)) presents a direct drive vs. geared servo motor study on a general basis [3]–[5] , but with some focus on positioning an axis precisely for an indexing table. Modelling positioning error of the gear [6], non-linear friction [7]. Some of the articles are too detailed for the scope of this project, but gives an overview of the complexity of using the Harmonic Drive gear in high dynamic servo control.

## References

- [1] M. Řezáč, ‘Inertial stabilization, estimation and visual servoing for aerial surveillance,’ 2014.
- [2] P. J. Kennedy and R. L. Kennedy, *Stabilizing the Line of Sight*. Laurin Publishing Co. Inc., 2018.
- [3] D. Miller and B. Knight. ‘Direct drive vs. geared rotary servomotor: A quantification of design advantage: Part 1.’ Place: Downers Grove Publisher: Control Engineering. (2020), [Online]. Available: <https://www.controleng.com/articles/direct-drive-vs-geared-rotary-servomotor-a-quantification-of-design-advantage-part-1/>.
- [4] D. Miller and B. Knight. ‘Direct drive vs. geared rotary servomotor: A quantification of design advantage: Part 2.’ Place: Downers Grove Publisher: Control Engineering. (2021), [Online]. Available: <https://www.controleng.com/articles/direct-drive-vs-geared-rotary-servomotor-a-quantification-of-design-advantage-part-2/>.
- [5] D. Miller and B. Knight. ‘Direct drive vs. geared rotary servomotor: A quantification of design advantage: Part 3.’ Place: Downers Grove Publisher: Control Engineering. (2021), [Online]. Available: <https://www.controleng.com/articles/direct-drive-vs-geared-rotary-servomotor-a-quantification-of-design-advantage-part-3/>.
- [6] H. Jia, J. Li, G. Xiang, J. Wang, K. Xiao and Y. Han, ‘Modeling and analysis of pure kinematic error in harmonic drive,’ *Mechanism and Machine Theory*, vol. 155, p. 104122, 2021, ISSN: 0094-114X. DOI: <https://doi.org/10.1016/j.mechmachtheory.2020.104122>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0094114X20303402>.
- [7] B. Han, J. Ma and H. Li, ‘Research on nonlinear friction compensation of harmonic drive in gimbal servo-system of DGCMG,’ *International Journal of Control, Automation and Systems*, vol. 14, no. 3, pp. 779–786, 1st Jun. 2016, ISSN: 2005-4092. DOI: 10.1007/s12555-014-0430-8. [Online]. Available: <https://doi.org/10.1007/s12555-014-0430-8>.
- [8] K. Gade, *Inertial navigation — theory and applications*, Book Title: Inertial Navigation — Theory and Applications ISBN: 9788232628711 ISSN: 1503-8181, 2018. [Online]. Available: <http://hdl.handle.net/11250/2491714> (visited on 03/05/2022).

- [9] Mathworks. ‘Continuous-discrete conversion methods - MATLAB & simulink - MathWorks nordic.’ (), [Online]. Available: <https://se.mathworks.com/help/control/ug/continuous-discrete-conversion-methods.html> (visited on 07/05/2022).
- [10] *Bilinear transform*, in *Wikipedia*, Page Version ID: 1084036855, 22nd Apr. 2022. [Online]. Available: [https://en.wikipedia.org/w/index.php?title=Bilinear\\_transform&oldid=1084036855](https://en.wikipedia.org/w/index.php?title=Bilinear_transform&oldid=1084036855) (visited on 06/05/2022).
- [11] D. Di Ruscio and H. i Telemark, ‘System theory state space analysis and control theory,’ *Lecture notes, Telemark University College, Porsgrunn, Norway*, 1996.
- [12] Beckhoff Automation GmbH. ‘EtherCAT,’ Beckhoff Automation. (), [Online]. Available: <https://www.beckhoff.com/en-en/products/i-o/ethercat/> (visited on 06/05/2022).
- [13] Mathworks. ‘Frequency response data (FRD) models - MATLAB & simulink - MathWorks nordic.’ (), [Online]. Available: <https://se.mathworks.com/help/control/ug/frequency-response-data-frd-models.html> (visited on 07/05/2022).
- [14] Elmo Motion Control. ‘Platinum solo twitter.’ (), [Online]. Available: <https://www.elmomc.com/product/platinum-solo-twitter/> (visited on 07/05/2022).
- [15] D. Di Ruscio and H. i Telemark, ‘Optimal model based control: System analysis and design,’ *Forelesningsnotater, Institutt for prosessregulering, Avdeling for teknologiske fag, Høgskolen i Telemark*, 2004.
- [16] David Di Ruscio, ‘Discrete LQ optimal control with integral action: A simple controller on incremental form for MIMO systems,’ *Modeling, identification and control*, vol. 33, no. 2, pp. 35–44, 2012, Place: Kristiansand Publisher: Norsk Forening for Automatisering NFA, ISSN: 0332-7353. DOI: 10.4173/mic.2012.2.1.
- [17] J. C. Doyle, ‘Guaranteed margins for lqg regulators,’ *IEEE Transactions on automatic Control*, vol. 23, no. 4, pp. 756–757, 1978.
- [18] F. Whitepaper, ‘Motor calculations for coreless brush DC motors,’ p. 11, 2021. [Online]. Available: [https://www.faulhaber.com/fileadmin/user\\_upload\\_global/support/MC\\_Support/Motors/Tutorials\\_Motors/dff\\_200276\\_whitepaper\\_motorcalculation\\_fin.pdf](https://www.faulhaber.com/fileadmin/user_upload_global/support/MC_Support/Motors/Tutorials_Motors/dff_200276_whitepaper_motorcalculation_fin.pdf) (visited on 14/05/2022).
- [19] ‘Swept-frequency cosine - MATLAB chirp - MathWorks nordic.’ (), [Online]. Available: <https://se.mathworks.com/help/signal/ref/chirp.html> (visited on 05/05/2022).