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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

**University of South-Eastern Norway**

www.usn.no

**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.

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# 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 |

| **Symbol** | **Explanation** |
|---|---|
| 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 stabilizes 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) 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. 104 122, 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 (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 (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).