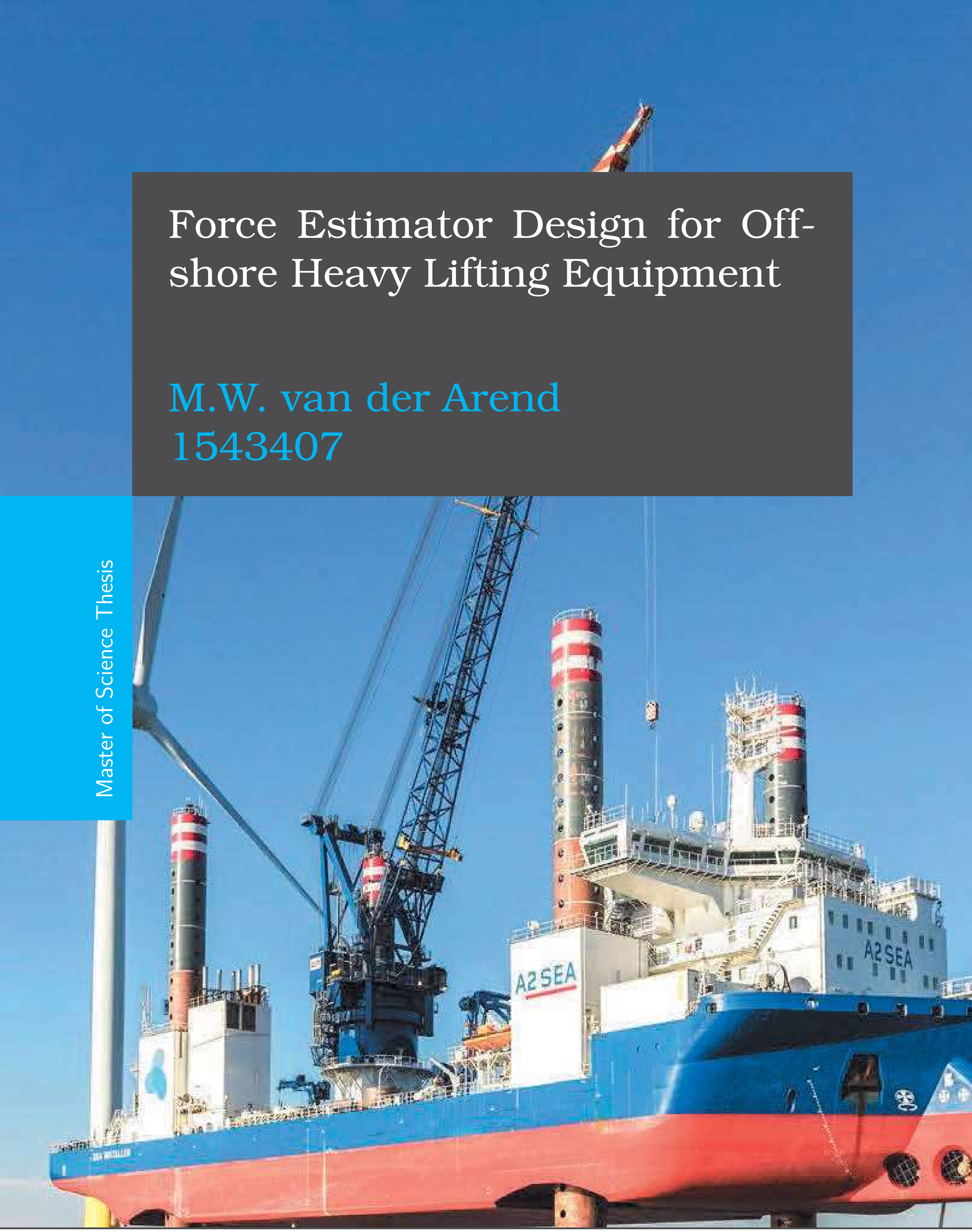

Force Estimator Design for Offshore Heavy Lifting Equipment

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Master of Science Thesis

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Abstract

One of the phases of the installation of Offshore Wind Turbines is the installation of the foundation for the turbine. Herein, a monopile is one of the most frequently used foundation-types. This monopile is a high steel cylinder, over 60 meters high, which supports the wind turbine to the seabed. Currently, monopiles are lifted with large boom cranes on jack-up ships. SeaState5 has developed a more efficient method for monopile installation by using the Grasshopper-T (GH-T), a new crane which skids the monopiles from the deck and places it onto the seabed. The system reduces the weight and footprint for jack-up ships.

This thesis consists of mechanical modeling the GH-T for the purpose of estimating the forces within the lifting system. A non-linear modeling method; Euler-Lagrange (EL) method with constraints is used to capture the systems dynamic, non-smooth and non-linear behavior over the entire range of motions of the upending process. Secondly, for the purpose of simplification, yet capturing the mentioned behavior, the system is linearized around several areas of operation, analyzing local detectablity and observability. Thirdly, attempts are made to design linear observers and disturbance estimator to both estimate the states of the system and any disturbance applied on the monopile, like hydrodynamic forces. Finally, a non-linear observer is proposed to estimate the states along the entire upending process of the monopile. Experiments for model validation are performed on SeaState5's 1:25 scale prototype for which a sensor setup has been designed.

Simulations show that linear observers based on the linearized model are able to estimate the states, and compute forces of interest, within a very small area of operations. The designed linear disturbance estimator proves to be ineffective in estimating disturbances and is only valid for the same small neighbourhood around the equilibrium point. This motives the need for an observer capable of estimation over a broad range of motions. Therefor, a non-linear observer is designed. For the non-linear observer, the state recovery proves to be efficient and robust enough to cope with sensor noise and the high range of motions of the upending procedure. Experimental results show the model is able to capture the non-linear behavior of the real system and estimate forces of interest within acceptable margins, showing promises for an online state estimation using the non-linear observer.

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Chapter 1

Introduction

Motivation

Wind turbines provide a viable alternative for fossil fuels and sustainable energy resources such as solar and hydro power. Methods like hydro-power and solar energy are already gaining a higher share on the global energy market, yet are currently not able to provide energy on a large scale, while demand is growing. This is where wind turbines are introduced. Estimates say that by 2020 a total amount of 75 GW of offshore wind energy will be installed worldwide [1, 2], which is a massive increase of 2011's 3.16 GW. In addition, by 2050, roughly 50% of Europe's electricity demand comes from wind energy [3]. Since wind energy on land is facing limitations in terms of available space, noise and visual pollution, the focus of high power wind turbines is offshore, where a large amount of wind turbines are placed in open sea with increased efficiency and power. In addition, not only the efficiency of the wind turbines increases over time, the size of the wind turbines increases as well [4]. This forms a challenge with installing the wind turbines and their foundations, since with their size, the weight also increases. This causes challenges in a critical phase of the life cycle of a wind turbine, especially compared with onshore wind turbines, which are less intensive from a financial and engineering aspect.

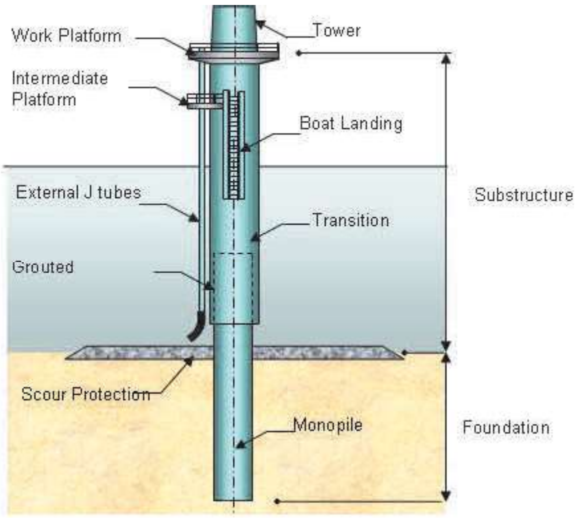

Figure 1-1: Schematic overview of monopile-based tower structure *(source: wind-energy-the-fact.org)*

In Europe, most of the wind parks are build in relative shallow parts of the North Sea, with up to 40 meters depth. In these waters, like the North Sea, monopile foundations (Fig. 1-1) are a relative cheap and easy solution to place the turbines, with the ratio installed foundation in 2015 of 97% monopiles and 3% jacket structure [5], showing a clear interest in these type of foundations. In shallow waters, monopiles are the most frequent used foundation-type [6], which can reach a height of 60 meters and weigh over 1000 metric ton. 80% of the already installed wind turbines has a monopile-like foundation [5]. One of the main reasons for this is the availability of shallow water. However, it is predicted that for deeper waters, monopiles will be used as well due to its simple production and installation properties [7]. For installation in deeper waters, larger and heavier monopiles are required, and estimates show the piles may grow up to 2000 tons.

To improve the efficiency on financial aspect, SeaState5 has developed a tool (the Grasshopper-T (GH-T)) and method for placing monopiles, in a more efficient way, allowing for placement from smaller ships and reduces the total installation time. This contributes to a reduction of installation cost and therefore the Levelized Cost of Energy (LCoE), which is currently the main goal in the wind industry, especially in offshore. These installation and foundation costs are significantly higher in offshore wind turbines (21%) than in onshore wind turbines (8%) [8].

Figure 1-2: Jack-up ship the SeaJack's Zaratan *(source: HeavyliftSpecialist.com)*

Compared to traditional cranes, the new system is lighter and has a smaller footprint, while it is able to lift the same monopile weight and size. This reduces the limit on the jack-up ships (Figure 1-2) currently used in the upending process in terms of weight and available space on deck. For a more detailed look at the monopile installation process from a jack-up vessel, the reader is directed to [9] or Figure 1-3. Conventional cranes can be up to 100 meters high, while the Grasshopper-T spans a height of maximum 50 meters. Also, the upending motion of the monopile of the GH-T differs from that of conventional cranes, which involves lifting entire monopiles in the air. The Grasshopper-T skids, or glides, the monopile along a roller construction into the sea, resulting in less counterweight or balance-keeping structures needed. Taking into account the ever increasing size of monopiles, this potentially means more monopiles can be placed on the ship, which results in a more efficient schedule for the installations. After all, the jack-up ship does not need to return to shore to refill on monopiles that often.

During the operation of the GH-T, SeaState5 desires to acquire an on-line evaluation of structural forces and states of the system, for which there are three motives:

1. Operators on deck should be able to assess the state of the system and be informed if current conditions are within safe operation limits [10].
2. A specific accuracy is required for placing monopiles, external forces ought to be understood to estimate the motions in the system.
3. For life-time and maintenance purposes, the amount of lifting operations with related forces must be known.

Figure 1-3: QR code, referring to a video of a monopile installation process [9]

Problem statement

For the Grasshopper-T, critical joints and connections of the crane, see Fig. 1-4, need to be investigated, e.g., for safety monitoring. One of the most vulnerable joints, while also being one of the most critical, is the connection piece or the clamp, linking the monopile to the crane itself and showing the actual weight the GH-T is carrying. Other critical locations in the crane are the wires, setting the system in motion. Tensile forces are required to be under a certain value in order to maintain safety [11]. Even though the system is set in motion by these forces, or control inputs, monitoring these tensile forces will help getting insight into the entire system.

During the upending process. the monopile is loaded onto a roller, helping to skid the monopile into the sea. Not only does this roller need to be able to carry the weight of the monopile while being upended, but additional forces are introduced with the hydrodynamic interaction with the sea. It must be ensured that the experienced loads are within limits. Slamming of the monopile into the roller is an example of a critical situation.

Potential benefits

In addition, the downside of using mooring vessels or jack-up ship is the installation time [10], of which over 8 hours can be spend to the anchor-procedure and measuring the sea-state. These methods are used, due to stability during the upending process. More versatile systems, such as DP systems, use thrusters for maintaining position on sea, yet these systems are not powerful enough to counter a toppling monopile, making them currently unfit for these type of operations. Being able to measure and predict hydrodynamic disturbances on the monopile could create the foundation for using Dynamic Positioning (DP) in the installation of offshore wind turbines. This

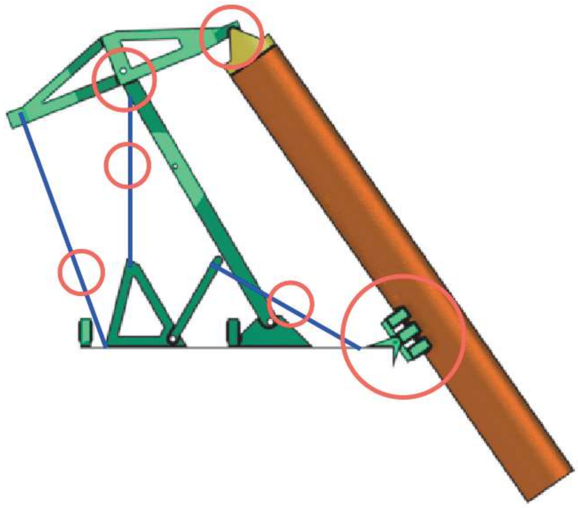

Figure 1-4: Impression of the Grasshopper-T with the location of the most critical points (red circles) in the crane.

could significantly decrease the installation time and therefore the cost, as DP systems no longer require to anchor before installation.

Method

The main objective in this thesis will be to compute a mechanical model of the Grasshopper-T and design an observer to estimate forces in the crane, using a non-linear design method. This estimator needs to be robust to handle model mismatch, parameter inaccuracy and sensor noise. For this, an analysis of a linearized model description will be performed, after which linear observers will be designed around several linearization points. Afterwards, a non-linear observer is designed for the entire range of motion and tested on an experimental scale-model. These observer will finally be extended with disturbance estimation, to cope with possible hydrodynamic influences on the monopile.

Preliminary work

In offshore applications, research has been done to design non-linear observers and estimators for ships [12]. Kalman filters are generally applied to estimate model states and are often required and applied for Dynamic Positioning (DP) problems. In [13], disturbances including wave filtering properties, bias state due to current, low frequency motion components and non-measured vessel velocities are attempted to be estimated. For that, a passive nonlinear observer was designed and tested using simulations, showing a convergence commercial Kalman based DP systems cannot reach. Others [14] proposed a non-linear observer for a class of fully actuated Euler-Lagrange system, suitable for vessels. Here, the stability of error dynamics between the real and estimated states of the system is the foundation for the requirements of the observer gains.

Outside the field of offshore, non-linear observer and disturbance estimators have been designed for robotic manipulators [15], where a non-linear function must be found to guarantee stable error dynamics.

[16, 17] construct an Immersion and Invariant observer, where a manifold is defined that should be rendered attractive and invariant. The goal is to design a non-linear speed observer a general class of mechanical systems. High gain terms are introduced to dominate sign-indefinite terms in a Lyapunov-like analysis and is tested on a Chaplygin Sleigh.

Organization

The organization of the thesis report is as follows. First, in Chapter 2, a general Euler-Lagrange modeling approach with Lagrange multipliers is provided. This modeling technique is applied to the Grasshopper-T, after which the derived model is linearized. Chapter 3 provides a method to design linear observers, based on the linearized model. Additionally, a non-linear observer for a class of Euler-Lagrange systems is proposed. The observers are extended with a disturbance estimation in Chapter 4, for the linear observer case. Also, methods for non-linear disturbance estimators are reviewed. Simulation results are shown in Chapter 5 in which both the linear and non-linear estimators are tested with the non-linear model. In Chapter 6, an experimental setup is designed for measurements on the 1:25 scale model. The prototype and measurements are then used for validation of the model. Finally, in Chapter 7 the thesis objectives are reviewed and future recommendations are presented.

Chapter 7

Conclusions and recommendations

This chapter finalized this thesis, with a review of the thesis objectives and contributions of the work done in Section 7-1, followed up by Section 7-2, in which topics for future research are proposed.

7-1 Conclusions

In this thesis, research was performed on the topic of modeling and observability of the offshore heavy lifting crane Grasshopper-T. Observers were designed to estimate states and forces, based on minimal or available information, for safety and monitoring reasons. If successful, sensor hardware could be adjusted or even removed to reduce the cost of operations.

A dynamical model was established using a general Euler-Lagrange modeling approach with Lagrange multipliers, which where eliminated by transforming the model into independent state coordinates. The system model was linearized around several operating points, in order to design linear observers for the neighbourhood of these operating points. The goals were to investigate the observability of the linear system, which translates into insight in the non-linear case. It was shown that state feedback, with possible force feedback, was sufficient for a completely observable system. This resulted in linear Luenberger observers for each linearizaton point.

Open-loop simulations show the linear observers are effective within a very small neighbourhood around the linearization point. When the system moved away from the linearization point, the observer becomes more unstable. The linear observers are effective on stagnant systems, yet require a relative long time to converge to the real state coordinates of the system. When a disturbance is added, linear disturbance estimators are ineffective and computationally intensive when the used constraint forces are used for output injection. Without the force injection, the estimator act as an observer. For disturbance estimation, at least 2 constraint forces are required in order to have a detectable system. However, even with constraint forces as output injection, the estimator fails to estimate disturbances.

The non-linear observer proves to be effective when applied on noised outputs of a non-linear system. Adding constant disturbances or model mismatch removed the Universally Globally Asymptotic Stable (UGAS) property of the non-linear observer, showing the need for a non-linear disturbance estimator or an extended observer able to deal with uncertainty or disturbances. Closed-loop performance of the non-linear observer shows good convergence for measurements with added white Gaussian noise.

Experiments were performed on a 1:25 scale model, for which a sensor system was designed. Due to the structure of prototype and model/observer, experiments were performed in closed-loop and compared to static configurations of the model, which is feasible because of the slow system dynamics. The reason for this was a mismatch in the magnitude of the control input, which needs further investigation. Although it proved to be difficult to link the model/observer to the real prototype, the acquired results show a match in behavior of the model and the prototype, with an acceptable error (<15%) in magnitude of the acquired forces, corresponding to model mismatch and sensor inaccuracies. This shows model validation. As seen in the simulations, the observer is effectively applied to the model in closed loop. This indicates feasibility for the observer in real world applications.

With most state coordinates measurable, the question still arises why an observer is needed, since the system is relatively slow which shows in the state velocities. Due to the presence of noise and sensors faults, an observer can be made robust enough to cope with these factors. In addition, the winch states can be obtained, in theory, but in reality this proves to be a challenging task. The designed observers in this thesis are all model based and rely on model accuracy. Since the system is already known, this model can be computed accurately. Also, the need for an observer comes with the desire to have stable error dynamics for the accurate estimation/computation of the forces of interest, such as the constraint forces. This is especially the case when disturbances are present.

7-2 Recommendations

(1) Control input magnitude

During this thesis, it was established that the control input of the reality does not correspond to the magnitude of control input the model or observer needs, which is significantly lower. For slightly different control inputs, this could be caused by winch model mismatch. However, the control input required in reality can be a factor 1000 higher or more, which implies further investigations to this behavior is required, as it is unexplained.

One option is to have the non-linear sensors with hysteresis currently used in the feedback loop of the prototype match model states or parameters. As these sensors are correlated to the boom and strut wires, one can modify the controller to use the obtained or calculated wire tensile force in the control loop for the prototype or model/observer respectively.

(2) Extended model

Creating the model was done with a number of assumptions, such as neglecting specific pulley dimensions and frictions. As the friction between the monopile and the roller can be significant during an upending procedure, this might be modeled as set-value dry Coulomb friction.
In addition, one of the main motivations for this thesis was to help the installation of monopiles take place on DP based vessels, instead of jack-up ships. The main limitation with the used Euler-Lagrange modeling technique for the design of an observer is the use of holonomic constraints, forcing the monopile to be connected to the roller. In future work, models extended with non-holonomic constraints can be investigated. Astolfi [17] proposed a method of using an Immersion and Invariant speed observer for a general class of n-DoF mechanical system with non-holonomic constraints, which could be investigated.

(3) Online observer/estimator

In this thesis, the model and observer were tested offline, with acquired data from experiments. For practical applications, online performance is an important aspect, which depends on the model efficiency and computation time. Even though the system is relatively slow and the sample frequency is not required to be high due to the approximating of higher order dynamics, the computation time of an online observer needs to be low enough to still have an acceptable sampling frequency.

(4) (Extended) force/disturbance estimation

The design of a non-linear disturbance or force estimator was not achieved in this thesis. Therefore, investigations to the design of a non-linear disturbance estimator for a general class of mechanical Euler-Lagrange system is advised. Some preliminary work is performed by [23], who proposes a non-linear disturbance observer for Euler-Lagrange systems by assuming constant or linear disturbances. Others, [24, 15] propose a Non-Linear Disturbance Observer (NDO) in which the stability of the proposed observer is demonstrated by using Lyapunov's theorem for a two and n DoF link robot manipulator.
As a follow-up for estimating a class of disturbances where $\dot{\underline{d}} = 0$, more realistic cases of disturbances and its estimation can be investigated, such as waves. [13] proposes an estimator to estimate both the low frequent position and velocity of a ship from noisy position measurements, as well as environmental state estimation cause by the environment, and wave filtering. Investigating these methods into mechanical Euler-Lagrange methods might prove useful to handle realistic hydrodynamic disturbances on the monopile. This could lay the foundation for hydrodynamic force estimation,

which is interesting for a wide range of offshore application. For example, predicting abilities could improve DP safety on monopile installation vessels.

(5) Sensor fault detection

In addition to estimating forces and disturbances in the GH-T, the non-linear observer and estimator can be used as a base for fault detection and sensor fault detection as well. High offsets between the sensors and estimator, when the estimator is assumed to be functional, can be used to detect any defects in the sensors. As the area of operation is offshore, the hardware is subjected to harsh conditions, e.g., salt water. This can cause the lifespan of the sensors to decrease significantly. Investigations can be performed into the use of non-linear estimators to detect sensor faults.