Doctoral theses at NTNU, 2018:10

Yingguang Chu

Virtual Prototyping for Marine Crane Design and Operations

Doctoral thesis

Yingguang Chu

ISBN 978-82-326-2832-2 (printed ver.)
ISBN 978-82-326-2833-9 (electronic ver.)
ISSN 1503-8181

Doctoral theses at NTNU, 2018:10

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Engineering
Department of Marine Technology

NTNU
Norwegian University of
Science and Technology

NTNU

NTNU
Norwegian University of
Science and Technology

Yingguang Chu

Virtual Prototyping for Marine Crane Design and Operations

Thesis for the Degree of Philosophiae Doctor

Trondheim, January 2018

Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

NTNU
Norwegian University of
Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the Degree of Philosophiae Doctor

Faculty of Engineering
Department of Marine Technology

ISBN 978-82-326-2832-2 (printed ver.)
ISBN 978-82-326-2833-9 (electronic ver.)
ISSN 1503-8181

Doctoral theses at NTNU, 2018:10

Printed by NTNU Grafisk senter

Abstract

Marine crane system design is an interdisciplinary process involving such as mechanical design, kinematics, multi-body dynamics, hydraulics, and operational control-related tasks. Marine crane operations are inherently challenging due to system stiffness, heavy loading, unstable working platform, and external disturbances, especially under harsh weather conditions in rough sea fields. This dissertation introduces virtual prototyping (VP) for marine crane system design and operations, such as produce design space exploration, analytical study, risk finding, and training. Modeling and simulation in a virtual environment provides the user comprehensive time- and cost-efficient insights to the behaviors of complex dynamic systems. The proposed VP system for modeling, simulation and visualization not only supports the product and system design process, but also adds physics and dynamics to real-time simulations of crane operations.

Despite the prevalent use of various computer-based tools, model development and handling the simulation of the various dynamic models in different domains simultaneously presents non-trivial complications. Currently, modeling and simulation of complex engineering systems is carried out domain-specifically and application-dependently focusing on the most interested and critical subsystem or operation phase. This is partly due to the fact that the behaviors of these dynamic subsystems in different domains are purposefully described mathematically based on their constitutive laws. What's more, different users' preference for the software tools complicates the communication between them. Effective and efficient communication setup requires not only the data exchange between the interactive dynamic models using different software tools, but also the user interface for manipulation, control and views. Reusing the existing knowledge in modeling and simulation efficiently requires a common standard for model integration. Correspondingly, it is necessary to redefine the component model structure and interfaces to provide the flexibility for model modification and interaction at the system level.

The main objective of research is to develop an open, flexible, and efficient heterogeneous platform for the simulation of various interactive dynamic models, particularly models in different domains handled by different software tools. The proposed VP framework is based on the application of the functional mock-up interface (FMI) standard, which defines a shared format to support model exchange and co-simulation of dynamic models. With this common standard available, model development and handling can be performed separately with different domain-specific tools. Integration of the simulation only needs to take care of the data for interaction at a proper frequency. Therefore, modeling and simulation of the possibly stiff systems may be represented in different complexity levels and can be handled at their own time-steps. To support the integration of simulation and co-simulation using the VP framework, a component-based multi-objective approach is introduced based on the object-oriented modeling (OOM) method for model development of complex dynamic systems. The component library provides generalized basic models with different complexity levels for model integration and exportation depending on the purpose of the simulation.

The VP system is designed to bridge the following two gaps in the current marine crane system simulation. Firstly, the need for an open and flexible platform oriented to the overall product and system design, modeling, simulation and visualization. Secondly, the need to reinforce virtual crane operation simulators with high fidelity models of physics and dynamics. As a case study for verification, the VP system was tested on mechanical design, model development, and simulation of the knuckle boom crane (KBC) systems. The crane designer and crane operation simulator proved the effectiveness of the proposed VP system in solving the identified challenges regarding modeling and simulation of complex multi-domain systems.

Acknowledgement

The research work contained in this dissertation was carried out at the Department of Ocean Operations and Civil Engineering, Norwegian University of Science and Technology in Aalesund. The PhD position was financially supported by the Research Council of Norway.

First of all, I am very grateful for the opportunity to pursue a PhD degree under the supervision of Prof. Vilmar Æsøy, Prof. Houxiang Zhang, and Prof. Sören Ehlers. The guidance and support I received in the past four years has always been encouraging and resourceful. Each of my advisors has had a distinct influence on me, not only as a scientific researcher but also as an individual. It has been fascinating to work with them.

It is an absolute privilege to collaborate and share the Mechatronics Lab office with my colleagues and friends. Our discussions and conversations are always inspiring, whether work-related or not. I'd especially like to thank M.S. Lars Ivar Hatledal for his valuable input and significant contributions in implementing the VP framework in Chapter 3.3 and the crane operation simulator in Chapter 4.3; M.S. Birger Skogen Pederson for sharing the knowledge and implementation of the workspace editor in Chapter 4.1.1; M.S. Yuxiang Deng for his contributions in implementing the mechanical editor in Chapter 4.1.2. My gratitude also goes to Dr. Cong Liu, Dr. Siebe Bruno van Albada, Øyvind Bunes from Rolls-Royce Marine for their comments and advices; Guoyuan, Yushan, and many others from the university and the industry partners.

Last but not least, I give my special thanks to my family for their understanding over these years and getting used to my absence in many aspects of their lives. And my best friend in Norway Håvard, an unfailingly kind being, thank you!

Every PhD candidate leaves his or her own traces on the path. I feel I am merely a "ring bearer" on this journey that couldn't have been done without the others of the fellowship.

To the darkness of the Nordic winters, and those bright- bright summer days.

Summer, 2017

Ålesund

Contents

List of Publications

The research work has resulted in significant contributions to the publication of several articles. The following papers are appended as part of this dissertation (in the order of the publication date).

I. Chu, Y., Æsøy, V., Ehlers, S. and Zhang, H., 2015. Integrated multi-domain system modelling and simulation for offshore crane operations. *Journal of Ship Technology Research,* 62(1), pp.36-46.

II. Chu, Y. and Æsøy, V., 2015. A Multi-Body Dynamic Model Based on Bond Graph for Maritime Hydraulic Crane Operations. In *proceedings of ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering*, St. John's, Newfoundland, Canada, p. V001T01A010.

III. Chu, Y., Deng, Y., Pedersen, B.S. and Zhang, H., 2016. Parameterization and Visualization of Marine Crane Concept Design. In *proceedings of ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering*, Busan, South Korea, p. V007T06A095.

IV. Chu, Y., Hatledal. L. I., Æsøy, V., Ehlers, S. and Zhang, H., 2015. Virtual prototyping for marine crane design and operations, *Journal of Marine Science and Technology*, first online Nov, 2017.

V. Chu, Y., Hatledal. L. I., Æsøy, V., Ehlers, S. and Zhang, H., 2015. An Object-Oriented Modeling Approach to Virtual Prototyping of Marine Operation Systems Based on Functional Mock-up Interface Co-simulation, *Journal of Offshore Mechanics and Arctic Engineering*, 140(2), first online Nov, 2017.

The following papers are not included in the dissertation, but considered as relevant to the research.

i. Chu, Y., Æsøy, V., Zhang, H. and Bunes, O., 2014. Modelling and Simulation of an Offshore Hydraulic Crane. In *proceedings of 2014 28th European Conference on Modeling & Simulation (ECMS),* Brescia, Italy, pp. 87-93.

ii. Aarseth, J., Lien, A.H., Bunes, O., Chu, Y., Æsøy, V., Marine, R.R. and Helge, A., 2014. A Hardware-In-The-Loop Simulator for Offshore Machinery Control System Testing. In *proceedings of 2014 28th European Conference on Modeling & Simulation (ECMS),* pp. 57-63.

iii. Chu, Y., Sanfilippo, F., Æsøy, V. and Zhang, H., 2014. An effective heave compensation and anti-sway control approach for offshore hydraulic crane operations. In *proceedings of 2014 IEEE International Conference on Mechatronics and Automation (ICMA),* Tianjin, China, pp. 1282-1287.

iv. Chu, Y., Hatledal, L. I., Sanfilippo, F., Æsøy, V., Zhang, H. and Schaathun, H. G., 2015. Virtual prototyping system for maritime crane design and operation based on functional mock-up interface, in *proceedings of MTS/IEEE OCEANS 2015*, Genova, Italy, pp. 1-4.

v. Chu, Y., Æsøy, V., Bunes, Y. and Pedersen, E. (2016) 'Modeling and simulation of the accumulator during active heave compensation operations', in *proceedings of ASME 2016 35th International Conference on Offshore Mechanics and Arctic Engineering*. Busan, South Korea, p. V001T01A007.

vi. Chu, Y., Zhang, H. and Wang, W. (2016) 'Enhancement of Virtual Simulator for Marine Crane Operations via Haptic Device with Force Feedback', in *proceedings of EuroHaptics 2016 10th International Conference, Lecture notes in computer science: Haptics: Perception, Devices, Control, and Applications,* London, UK, Springer International Publishing, pp. 327–337.

List of Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
AHC	Active Heave Compensation
BG	Bond Graph
CAD	Computer-Aided Design
CPS	Cyber-physical System
DoF	Degree of Freedom
DP	Dynamic Positioning
FMI	Functional Mock-up Interface
FMU	Functional Mock-up Unit
KBC	Knuckle Boom Crane
OpenGL	Open Graphics Library
OSG	OpenSceneGraph
RMI	Remote Method Invocation
RMSE	Root-Mean-Square Error
RTF	Real-Time Factor
Three.js	JavaScript 3D library
URV	Underwater Robotic Vehicle
VP	Virtual Prototyping
VRML	Virtual Reality Modeling Language
WebGL	Web Graphics Library

List of Tables

List of Figures

Chapter 1

1 Introduction

1.1 Background

Marine cranes are equipped on many types of vessels and offshore platforms performing operational tasks such as lifting, towing, and transferring goods and personnel from shore to deck or deck to deck. In general, marine crane systems are large and have low speed manipulations with heavy loading conditions. Unlike land-based cranes with fixed working platforms, marine cranes operate in unstable environment and are subject to unneglectable impacts from waves, currents, and winds, despite of the dynamic positioning (DP) of the vessel. Due to these issues, both the working safety and efficiency are hard to achieve, especially in sea areas where calm weather conditions are rare (Christou and Konstantinidou, 2012). As a result, marine crane operations rely on robust design of mechanical structure and hydraulic power systems that potentially over-dimensioned. Remote control of marine cranes is usually realized through direct feedforward control and is highly dependent on the skills of the operators. Advanced control algorithms have been proposed for heave compensation and anti-sway operations in offshore and subsea applications (Skaare and Egeland, 2006; Parker *et al.*, 2007; Küchler *et al.*, 2011; van Albada *et al.*, 2013; Chu, *et al.*, 2014). However, offshore training in operations of various types of cranes to accomplish a variety of operational tasks is expensive and time-consuming with physical systems or prototypes.

Supported by virtual reality technology, marine crane operation simulators have been developed for risk-finding and training to reduce the potential dangers and cost of human-caused accidents. Among many other solutions presented in literature, the leading commercial simulation centers in the world include Kongsberg maritime simulators (Kongsberg, 2017), Vortex simulators by CM Labs (Vortex, 2017), and Offshore Simulator Center (OSC, 2017) as shown in Fig. 1.1. Crane operators can perform real-time manipulations of cranes in virtual scenarios with "realistic" visual effects. However, handling high fidelity dynamic models of all the physical systems in real-time simulation is non-trivial for such large scale simulators, as is the communication of large data sets for visualizations. Consequently, the physics and dynamics of the simulation models are usually simplified in order to achieve the requisite simulation efficiency.

Fig. 1.1 Crane Operation Simulator at Offshore Simulation Center Ålesund Norway

The simulation of marine carne operations currently in existence suggest the following research questions:

- ***How might accurate and efficient dynamic models of the physical systems enhance the simulation of marine crane operations?***
- ***Is it possible to reuse the existing available models from product design and system engineering?***

To address these research questions, it is necessary first to study the role of modeling and simulation in the current product and system development process. As shown in Fig. 1.1, marine crane system design is an interdisciplinary process involving mechanical design, kinematics, multi-body dynamics, hydraulic system engineering, and operational control-related activities. Many computer-aided software tools have proven very useful in several stages for design, modeling, analytical simulation, and 3D visualization. But the various modeling methods and simulation tools also present many challenges for integration and communication. Currently, modeling and simulation start after the substantial completion of design, even though the essential functional parameters (e.g., physical dimensions, work capacity, and limitations) are known from the beginning of the design process. Granted, systematic design approaches don't necessarily contain the answers to all the questions that implementation requires (Pahl *et al.*, 2007). Model-Based Design/System Engineering (MBD/MBSE), for example, is highly dependent on the models of the physical systems (Estefan, 2008; Jensen, Chang and Lee, 2011). Simulations of various sub-models are hard to integrate due not only to the complexities of the physical sub-systems in different domains, but also the interfacing between the domain-favored software tools.

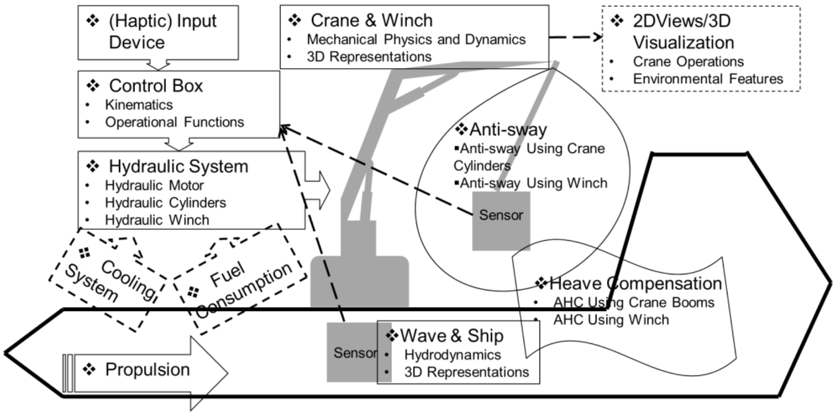


Fig. 1.2 Modeling and simulation of marine crane operations

The goal of applying VP to product and system design is to provide a modeling and simulation platform for the whole system. Thus it would represent the real physical system and permit analysis and testing just like a real physical prototype (Wang, 2002). To date, the development of VP (including virtual reality) technology in marine industry is in its infancy compared to other engineering fields such as aerospace and automobile industries (Chatterjee *et al.*, 2005; Amditis, Karaseitanidis and Mantzouranis, 2008). Thus, addressing the role of VP in product and system design raises the following research questions:

- ***How might VP improve the current product and system design process of marine crane systems?***
- ***How might it be possible to develop and integrate the dynamic models in different domains effectively and efficiently?***

It is necessary to develop models with proper fidelities to simulate and visualize the interested behaviors of the systems within short timeframes. Enabling the modeling and simulation tools in the overall design process will support the designers through collaborations with customers and system engineers, making it possible to determine the results of any change before implementing it. Further, the virtual operation simulators with full dynamic models would also enhance the fidelity of the operation simulators for training purposes. However, the plethora of modeling tools within different disciplines perform very significant functions, and no single method or software tool is suitable for every stage of the design process.

1.2 Objectives

This dissertation deals with the development of the VP system for both marine crane design and simulations of operational tasks with physics and dynamic models of involved physical systems. In order to reuse the existing knowledge in current domain-specific modeling and simulation, the research has the following main objective:

- **To develop a tool-independent VP framework providing an open, flexible and efficient simulation platform that allows for design visualization, analysis, pre-testing, verification, and training.**

Both physical mock-ups and digital models are simplifications of real physical systems. The accuracy and efficiency of simulation rely on complex models of the physical systems, as well as equally complex models of the interaction environment. To support model development of complex dynamic systems, it is necessary and beneficial

- **To introduce a flexible approach to support model development providing different detail levels for different simulation purposes.**

As mentioned, marine crane operations are inherently challenging. Virtual crane simulators with physics and dynamics provide realistic and risk-free assessment for testing and training. As a case study for verification, the design, modeling, and implementation of a crane operation simulator is presented

- **To illustrate the process of mechanical design, model development of dynamic systems, and simulations of crane operations based on the proposed VP system.**

1.3 Structure of the Dissertation

The rest of the dissertation is organized as follows. Chapter 2 discusses the challenges and findings in existing work on product and system design, modeling and simulation of complex multi-domain systems, and virtual prototyping simulators of operation systems. Chapter 3 introduces the proposed virtual prototyping system for general product and system design, model development, simulation, and visualization for operations. Chapter 4 presents the implementation of the virtual crane prototyping simulator and results of simulations. Chapter 5 summarizes the contributions and limitations of current research and directions for future work. The references and appendices conclude this document.

Chapter 2

2 Literature Review

This chapter provides an overview of existing research and applications related to this project in the marine industry and other sectors. Section 2.1 investigates the role of modeling and simulation for product and system design. Section 2.2 discusses the known challenges with complex system modeling and integration of simulations, especially beyond the mechanical domain. Section 2.3 introduces the utilization of virtual prototyping for design and operations through modeling and simulation. Section 2.4 discusses the state-of-the-art of modeling methods and tools for dynamic systems, focusing on model modularization, classification, and interfacing.

2.1 Model-Based Design and System Engineering

In general, design of engineering systems originates from concept alternatives, through representations in the form of digital models or physical prototypes for evaluation and optimization, until it can be realized into the product that fulfills certain functions (Suh, 1990). As illustrated in Fig. 2.1, the conventional design process starts with customer requirements, concept design, and embodiment design, continues to modeling and simulation for testing and evaluation, and finally physical prototype testing and verification (Bordegoni and Rizzi, 2011). Simulations in a virtual environment not only save the time and cost associated with physical prototypes, but also allow the designers to predict and prevent inadequate design as early as possible.

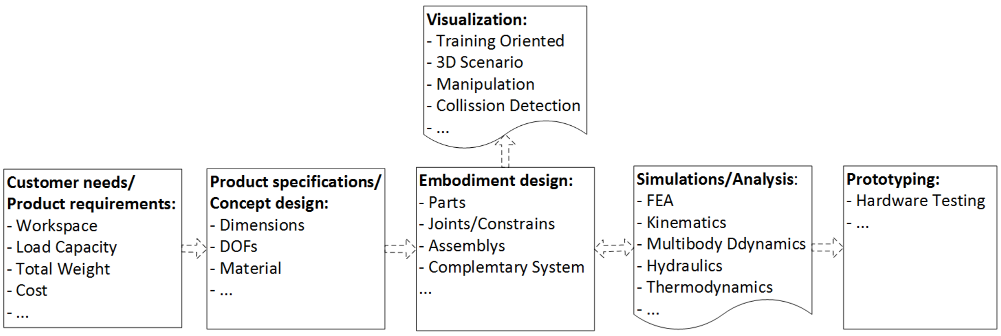


Fig. 2.1 Conventional sequential model of the product development process of marine cranes

Systematic approach such as MBD/MBSE is defined as a model-centric approach for the design and engineering processes for complex, multi-domain systems and systems of systems (Ramos, *et al.*, 2012). Currently, simulations of the physics and dynamics of multi-domain systems are carried out separately and supported by different software tools. The decomposition benefits the modeling and simulation of the whole system, but offers more challenges for model integration. As a result, the mathematical models representing the interested behaviors of sub-systems in certain domains are usually simplified, while the effects of the rest are idealized or neglected. One of the main challenges with simulations of complex dynamic systems is to establish system models with a suitable level of complexity.

- ***MBD/MBSE as a general systematic approach to product and system design, simulation and visualization is still underdeveloped in the marine industry, especially for systems that exceed the mechanical domain.***

2.2 Modeling and Simulation of Multi-domain Systems

Modeling and simulation of marine operation systems is characterized by intricate interactions between a wide range of physical and engineering domains. The modeling and simulation capabilities of Computer-aided Design (CAD) tools and their user interfaces have improved significantly in the last few decades. Due to the increasing complexity of modern dynamic systems and interoperability of these various domain dependent software tools, interest has grown in integrated simulations of complex multi-domain systems such as mechatronic, mechanic-hydraulic, and hydro-thermal. And models with original detailed design from CAD tools are usually too complex to compute when the systems become complex and the real-time performance of the simulation must be guaranteed.

Generally speaking, there are two developing trends in modeling of complex multi-domain systems from the industrial perspective (Bertsch and Schulmeister, 2014). First, modeling the entire system with one consistent method, language and software tool. This has advantages in supporting deep understanding of the modeling of systems that have growing complexity. Modeling and simulation of multi-domain systems in a homogeneous environment has led to the development of software packages, extensions, and toolboxes such as Matlab®/Simulink®, SimulationX, 20-sim, and OpenModelica. This approach requires the modeling language to be suitable for various physical domains. In theory, multi-domain dynamics models can be assembled because they use the same general state variables. However, the efficiency of the simulation falls off, in particular, for strongly-coupled systems and systems with nonlinearities. For example, Bak presented research on MBD of electrical-hydraulic motion control systems for offshore crane operations (Morten K. Bak and Hansen, 2013; Bak, 2014). A system model of the electro-hydraulic crane was developed includes the most important characteristics of both mechanical and hydraulic components. Model implementation and simulation was handled by MapleSim™ and SimulationX, both provide several predefined model libraries in different physical domains. The model is used to optimize the crane performances of initial design by minimizing oscillations, maximizing the load range and maintaining operational reliability. Skjong and Pedersen presented model-based design for evaluating the control algorithms of offshore hydraulic winch systems (Skjong and Pedersen, 2016). The authors developed dynamic models of the winch system using the Bond Graph (BG) method, which is an equation-based graphical modeling technique based on the energetic structure of physical dynamic systems. Using the models, the proposed sliding-mode back-stepping control was evaluated and compared with regular PID-control.

The second developing trend is to decompose the whole system into sub-systems and components for modeling, distribute the handling of these sub-models, and define a unified interface standard for model exchange or co-simulation. This approach facilitates model modularization and allows for the use of specialized methods and tools for different sub-systems. However, it also poses challenges on the interaction between different sub-models and the communication between different simulation tools. Due to the system complexity and presentations in modeling, the sum of all the models of all sub-systems is not necessarily a proper model for the simulation of the whole system. Assembling and handling these simulations is even more difficult when the real-time performance is required. It requires a heterogeneous platform for model integration, coupling of simulation, and management of visualization.

Related to hybrid simulations of marine operation systems, Li and Wang presented a visual simulation system for shipborne crane control using the open graphics library (OpenGL) and VC++ (Li and Wang, 2009). Chin presented DP of a drill ship for thrust optimization design and control under environment disturbances using Matlab®/Simulink® (Chin, 2012). Further, Prats *et al.* developed an open source tool called UWSim for the simulation of URV applications (Prats et al., 2012). The simulator is implemented in C++ and uses the OpenSceneGraph (OSG) and osgOcean libraries to render visualization. It also provides interfaces to external architectures such as control programs and dynamic models in Matlab® through the robotic operating system (ROS). Physics of contact is supported by the game engine Bullet wrapped in osgBullet. Thekkedan *et al.* presented simulations of underwater positioning controls using Matlab®/Simulink® (Thekkedan, Chin and Woo, 2015). It included a dynamic model of the 6-DoF URV and the Fuzzy logic controller for the positioning of the URV. The 3D visualization was developed using the virtual reality modeling language (VRML), which can import CAD models to create a virtual scenario. The output data from Simulink© is connected to the VRML model via the virtual reality sink block.

Heavy lifting crane operations have significant impacts on DP of floating vessels and barges as well, in particular, for lightweight class vessels with slender hulls and low transverse stability (Halse *et al.*, 2014; Hatecke *et al.*, 2014). Simulation coupling of hydrodynamics of the vessel and crane operation with a suspended load is particularly computation-demanding. Terashima *et al.* presented a virtual plant of a shipboard crane that combines computational fluid dynamics (CFD) with mechanical dynamics (Terashima et al., 2010). The virtual plant model, however, is complex enough that requires an enormous time to compute. Lee presented the dynamic response of a floating crane and a suspended heavy cargo considering the nonlinear effect of hydrostatic force (Lee, Cha and Park, 2010). Ku *et al.* developed a dynamics kernel for multi-body systems considering the external hydrostatic and hydrodynamic effects for offshore crane operations (Ku, Ha and Roh, 2014). The equations of motion for the multi-body system consisting of the ship, crane and load were derived using recursive formulation which is declared as more computational-efficient. The hydrostatic force and linearized hydrodynamic force are considered as the external forces acting on the floating crane. For design optimization of heavy lifting crane vessels and hazard assessment of crane lifting operations, a time-domain simulation method was developed to simulate the coupled motions of the ship and the suspended load (Vorhölter, Hatecke and Feder, 2015), see also (Hatecke, 2016). In order to reduce the computational effort, the equations of motions are separately solved considering the external hydrostatic and hydrodynamic forces, and then integrated in the time domain. Specifically, the heave, sway, yaw and pitch motions are assumed to be small and less influenced by nonlinear effects. Therefore these motions are computed in the frequency domain by means of a linear strip method. The roll and load motions are strongly-coupled and depend much more nonlinearly on the wave and motion amplitude, and thus are computed nonlinearly.

Some of the above solutions have developed their own systems for model integration and rendering visualization. Several are based on, for example, Matlab®/Simulink® which is designed for modeling and simulation of control systems and provides diverse supports for communication to external software and hardware. These simulations and simulators were nicely developed based on the models of the interested sub-systems. Different approaches were adopted to reduce the computational efforts to improve the simulation efficiency and obtain the accuracy at the same time. Instead of modeling with one consistent method and simulating by one single simulator, it seems natural to find or establish a unified standard for interfacing supported by the software tools for a complex multi-domain dynamic system. Decomposition and modularization also facilitate model modifications, exchange and reuse of the sub-models, and collaborations between departments and companies considering business confidentiality issues.

- ***Model integration, simulation coupling, and visualization requires a universal standard for interfacing, data exchange and communication.***

2.3 Virtual Prototyping of Dynamic Operation Systems

In contrast to the sequential design process, Fig. 2.2 shows a conceptual diagram of the VP system for dynamic operation systems. VP is essentially modeling and simulation of all the related aspects of a product; it also exceeds the traditional term of modeling and simulation to embrace the environment and human interactions including hardware-in-the-loop, visuals, tactile, and haptic/force feedbacks (Ha *et al.*, 2009; Aarseth *et al.*, 2014; Chu, Zhang and Wang, 2016). The integration of modeling and simulation in a virtual environment brings the customers, designers, engineers and other relevant partners to work together on the same matter. VP entails the integration of modeling and simulation of dynamic systems during the product development process to analyze the effects of design trade-offs on the overall system performance. The digital models in the virtual environment permit the simulation of an infinite number of what-if scenarios, thereby reducing the dependence on intuition-and-empiricism and trial-and-error.

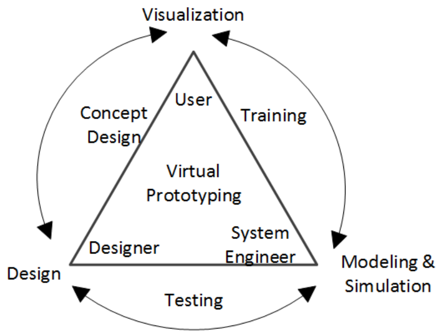


Fig. 2.2 VP for product and system design, modeling and simulation, and visualization

A prototype is an early embodiment of a design concept (Budde, R., Kautz, K.Kuhlenkamp, K., Zlighoven, 1992). Rapid prototyping using CAD data has replaced raw material prototypes, especially the fast development of 3D printing technology using layered manufacturing in recent years. However, virtual prototyping has superseded the efficiency of physical prototypes in terms of both time and cost. The aerospace and automobile industries have played leading roles in utilizing VP technology for product design, manufacturing, and simulation and visualization (Bennett, 1997; Lau, Mak and Lu, 2003). Recently, the automotive industry has been particularly innovative; for example the European Modelisar project which led to the establishment of the FMI standard among other things (Blochwitz *et al.*, 2012). The FMI standard defines a tool-independent format to support the integration of simulations for multi-domain dynamic systems. To date, the FMI standard for model exchange and co-simulation is supported by over 150 software tools. The main difference between model exchange and co-simulation is that co-simulation requires the compilation of the functional mock-up unit (FMU) together with a numeric solver (slave clients), while an FMU for model exchange only implements the model itself and the computation relies on the solver of the integration tool (master).

The FMI standard solved the long existing challenge in system model integration and, hence, was quickly adopted by the industry. It has shown that significant computation time speed-ups can be regained at the price of a moderate loss of accuracy for strongly-coupled systems using FMI co-simulation (Viel, 2014). Among many other case studies, Erdelyi *et al.* presented their implementation of FMI on an application of vehicle dynamics (Erdelyi *et al.*, 2012). An air-spring FMU is compiled from Modelica code for model exchange with the front suspension of a vehicle modelled in LMS Virtual.Las Motion. Neema *et al.* presented a model-based integration platform called C2WT using FMI co-simulation for the vehicle thermal management system (Neema *et al.*, 2014). Drenth *et al.* and Henningsson *et al.* implemented an engine model and an engine cooling system model of a vehicle in the FMI toolbox for Matlab® (Drenth *et al.*, 2014; Henningsson *et al.*, 2014). Both systems are modeled in Dymola and imported as FMUs and simulated in Matlab® coupled with the controllers.

- ***Handling of integrated dynamic models of strongly-coupled multi-domain systems is difficult, especially when real-time capability of the simulation must be guaranteed. Simulation coupling through co-simulation is promising, but a universal standard such as the FMI for interfacing between different sub-simulators is required.***

2.4 Model Development for Complex Dynamic Systems – Methods, Languages and Tools

The models representing the physical systems are decisive to support decision-making through simulations. As a prototype is defined as a representation of a class of design, a virtual prototype should include all the functional aspects as a physical prototype could offer. However, model development for complex dynamic systems is inherently complex and usually simplified only reflecting certain aspects of the problem (Slomka *et al.*, 2011). The purpose of introducing the OOM method for engineering systems is to facilitate the modularization and integration of model development. It allows all different users to form an understanding of the same matter (model) and contribute their expertise on one sub-system without worrying about the others.

OOM originated from software model development and resulted in the establishment of the unified modeling language (UML) in the 1990s (Völter *et al.*, 2013). During the past years, Modeling and Analysis of Real-Time Embedded Systems (MARTE) has extended it to real-time embedded systems (Object Management Group, 2011), and SysML has extended it to complex engineering systems (Friedenthal, Moore and Steiner, 2011; Holt and Perry, 2013). Many functional diagrams are defined in both MARTE and SysML. For example, in total nine diagrams are used in SysML based on what known as the four pillars of SysML: the requirements, the behavior, the structure and the parametric. Recently, the INTO-CPS project developed INTO-SysML models for co-simulation of cyber-physical systems (CPS) (Amálio *et al.*, 2016). The INTO-SysML profile customizes SysML for architectural modeling in a setting of multi-modeling and FMI co-simulation. It introduces specializations of SysML blocks to represent different types of CPS components, constituting the building blocks that enable a hierarchical description of the CPS architecture. SysML is a powerful, but formidable, technical language to master, especially for the designers and system engineers. Its extensions, such as INTO-SysML, could be a better alternative for modeling if matured in the next years.

More recently, Modelica has drawn the attention of both the academy and industry users. Modelica is a non-proprietary, object-oriented, equation-based language designed for the convenient modeling of complex physical systems (Modelica Association, 2000). Basic models of physical components are defined in a declarative way by their constitution equations and connected with the outside world without implied causality. This makes the description of the physical systems more flexible and understandable than using causal or block-oriented modeling languages. Modelica is also easier to use than directly writing simulation code using procedural languages like C or FORTRAN (Pulecchi, Casella and Lovera, 2010). Complex models can be built by connecting the basic models where the physical connections exist. Since the models are written in terms of generic differential-algebraic equations, components that define interactions between different physical domains can be combined without any restriction.

Before the presence of OOM and Modelica, the BG method was one of the most effective approaches for modeling multi-domain dynamic systems. It describes a physical system by identifying its energetic structure and represents the energy flow using generalized energy variables. The BG elements provide a generalized form of representations of the basic components across different energy domains. BG can actually be seen as a special form of OOM modeling (Borutzky, 1999). Broenink and Cellier developed a Modelica BG library that is, in effect, a translation of BG elements in Modelica (Broenink, 1997; Cellier and Nebot, 2005). Later, an export filter for BG models implemented in 20-sim was developed to generate Modelica code (Broenink, 1999). The generation of Modelica code from existing basic BG elements and block diagram appears quite straight forward. In fact, the BG method shares the following features of the OOM paradigm:

- *A-causal modeling:* Computation causality is not needed in modeling, but needs to be decided in compiling the model into computable code. A-causal modeling means that the equations are written as true equations that state the mathematical principles rather than determining the actual computational sequence. In this way, the interfaces of the sub-model can be defined by variables that are not committed to any role for computation. This feature of the OOM modeling approach is essential if the internals of the sub-models are to be completely encapsulated.

- *Encapsulation:* The interaction with a model is only accessible via well-defined interfaces with its outside world. The use of the model is not constrained by the internal specifications. This allows for the reuse of the model or certain parts of the model while keeping the rest untouched.
- *Hierarchy:* A physical system is hierarchical in nature and can be decomposed into sub-systems. Thus, the model of a system is composed of sub-models that may contain lower level of sub-models.
- *Inheritance:* Based on a hierarchical relationship, the properties of a sub-model are inherited by its upper class of sub-models and shared by the lower class of sub-models.

Modelica is a textual modeling language, while BG elements are equation-based graphical representations of certain physical properties and phenomena. In this sense, neither Modelica nor BG provide easy comprehension for those who are not familiar with the modeling language or graphical diagrams. Modelica allows for more flexibility than BG in terms of variable structure systems. Currently, many Modelica-based software programs are in use such as SimulationX, MapleSim™, JModelica, OpenModelica. For system engineers, graphical modeling tools provided well-defined model libraries take less effort to master.

- ***The component model libraries build the foundation of the VP simulators. Developing such libraries requires intensive collaborations of different users over time. Model development must conform to the requirements for modularization, classification, interfacing, and reusability.***

2.5 Summary

Following the research questions, the above sections discussed the related work on modeling and simulation for design and system engineering, virtual prototyping of operation systems, and model development for complex dynamic systems. These research gaps and challenges are identified, and the promising research that could be utilized to fulfill our objectives are highlighted:

- ***MBD/MBSE for product and system design in marine industry is immature, especially beyond the mechanical domain.***
- ***Crane operation simulators need the support of effective and efficient models of physics and dynamics.***

- **The objective of VP for dynamic operation systems such as marine cranes is to provide an open, flexible, and efficient platform for design, system engineering, and operations through modeling, simulations, and visualizations.**

- ***Currently, modeling and simulation of complex dynamic systems are carried out domain-specifically by a plethora of software tools. Handling of integrated dynamic models of strongly-coupled multi-domain systems is difficult, especially when real-time simulations are required.***

- **Simulation coupling by means of co-simulation not only facilitates reuse of models but also enhances the simulation efficiency.**

- ***An open, flexibles and efficient standard for interfacing between the simulation tools is required for model exchange and co-simulation of various dynamic models.***

- **The FMI standard offers a tool-independent format for both model exchange and co-simulation, which the academic and industrial users increasingly embrace and most of the widely used modeling and simulation tools increasingly support.**

- ***It is necessary to standardize the model architecture in different levels for model development oriented to different purposes of simulations.***

- **The OOM approach defines the architecture of a component model in different layers. Model classification is based on the complexity level of each model implementation. Model structure and behaviors are separated to support model modularization and integration.**

Chapter 3

3 Virtual Prototyping System for Dynamic Operation Systems

This chapter describes the methods and tools to develop the VP system for marine crane design and operations. Section 3.1 presents the scope of work, limitations and assumptions of this dissertation. Section 3.2 presents the crane designer tool for mechanical design space exploration, specifically, to visualize the design concepts and generate 3D models for simulations. Section 3.3 introduces the component-based multi-objective approach to model development of dynamic systems. Section 3.3 describes the software architecture of the proposed VP framework based on the FMI standard.

3.1 Scope of work, limitations, and assumptions

The context of the research work is based on marine crane systems and operations, but the research findings and proposed solutions can be easily applied to a broader range of industrial sectors. The scope of developing the VP system for marine crane design consists of mechanical design of the crane structure, modeling and simulation of dynamic systems including kinematics and multi-body dynamics, hydraulic power systems and the interaction systems. VP for marine crane operations embraces features for human interactions like 3D visualization, haptic feedback, ergonomics and psychological effects. In this dissertation, several assumptions were made and time resources constraints created certain limitations, laid out as below:

- Chapter 4 presents the physics and dynamic models of the crane dynamic systems to implement the crane operation simulator. A tutorial for development of the hydraulic component library is provided, see Appendix B. However, creating generic component model libraries to aid the configuration of simulators is an extensive undertaking over time and needs continuous contributions and feedbacks from the users.
- Modeling of the interaction systems to the crane, such as the ship motions and environmental disturbances, were not elaborated. Related studies on hydrostatic and hydrodynamic effects on the DP of ships during heavy lifting crane operations can be found in Section 2.
- Assume the simulation results based on the mathematical analysis are trustworthy using the applied modeling methods and simulation tools. The co-simulation results also showed good characteristics compared to the integrated simulation results.

- Developing a graphical user interface would facilitate rapid prototyping in a convenient drag-drop-run manner. This was only partially done in the crane designer tool and the crane operation simulator for operations. The categorization of components, sub-systems, along with the model properties and interfaces requires extensive input from the users.
- Regarding human interactions with the simulator, the user interface mainly focuses on the possibilities for post-processing of analytical simulation results and views of plotting and visualization, especially 3D visualizations.
- The simulation stability depends on both the different types of sub-simulators setting the upper limits for the micro time-steps and the co-simulation manager (i.e., the VP system), which sets the lower limit of the macro time-step. In the case study, these time-steps were chosen based on the model complexity level to ensure the real-time capability of the simulation at a moderate loss of accuracy.

3.2 The Designer Tool for Mechanical Design

Mechanical design is mostly carried out using CAD software packages such as Solidworks©, NX©, and CATIA©. These programs make possible static analysis on, for example, loading effects on the mechanical structure. However, transferring the static models from mechanical design directly into real-time dynamic system simulations creates intractable problems. Henriksen *et al.* presented a finite segment model of a single crane boom to show the importance of structure flexibility in dynamic simulations (Henriksen, Bak and Hansen, 2011). A finite segment model is relatively less computational demanding than a finite element model providing roughly sufficient approximations of static structure deflections. The dynamic simulation results, however, are rather questionable showing totally different behaviors of the crane actuators. Currently, most CAD tools don’t provide interfaces to other simulation tools that were not purposefully developed. Manual transcriptions for model simplification are time-consuming and error prone (Choi and Cheung, 2008). During early design stage, a designer tool that can generate and visualize the design concepts is useful to evaluate the main geometrical and functional features, including the workspace and loading capability.

Previously, the author presented a numerical method for the computation and visualization of the workspace of offshore cranes (Hatledal *et al.*, 2015). A number of joint configurations are generated by using the Monte Carlo method, which are then mapped from joint to Cartesian space using forward kinematics. The bounding box of the workspace is then derived from these points, and the voxels are distributed on planes inside the box. Hameed et al. introduced an computer-automated tool for crane design optimization focusing on the working space and load capacity (Hameed *et al.*, 2016). It uses a genetic algorithm to optimize the dimension design of the crane structure. However, neither tool is made for mechanical design visualization nor includes the dynamics in the simulation except simple calculations of the joint torques in Hameed's approach. Therefore, a lightweight and flexible tool is developed based on the web graphics library (WebGL) to visualize the mechanical design, workspace, and load chart. The products from the designer tool can be used in the operation simulator by providing the data of physical properties. Details of implementations are presented in Section 4.1 through a case study; see also appended Paper III (Chu, Deng, *et al.*, 2016).

The crane designer tool consists of a workspace editor and a mechanical editor, as shown in Fig. 3.1. The workspace editor interprets the design requirements into initiative technical specifications including, e.g., DoF, workspace, and loading capability. The mechanical editor is a 3D scene editor using the Three.js library that uses WebGL to display 3D computer graphics in the web-browser. WebGL is a cross-platform JavaScript API for rendering 3D graphics inside of an HTML5 canvas element, without the use of plug-ins. WebGL is based on OpenGL ES 2.0, and Version 1.0 of the standard was released in 2011 and widely supported by modern browsers, including both desktop and mobile versions.

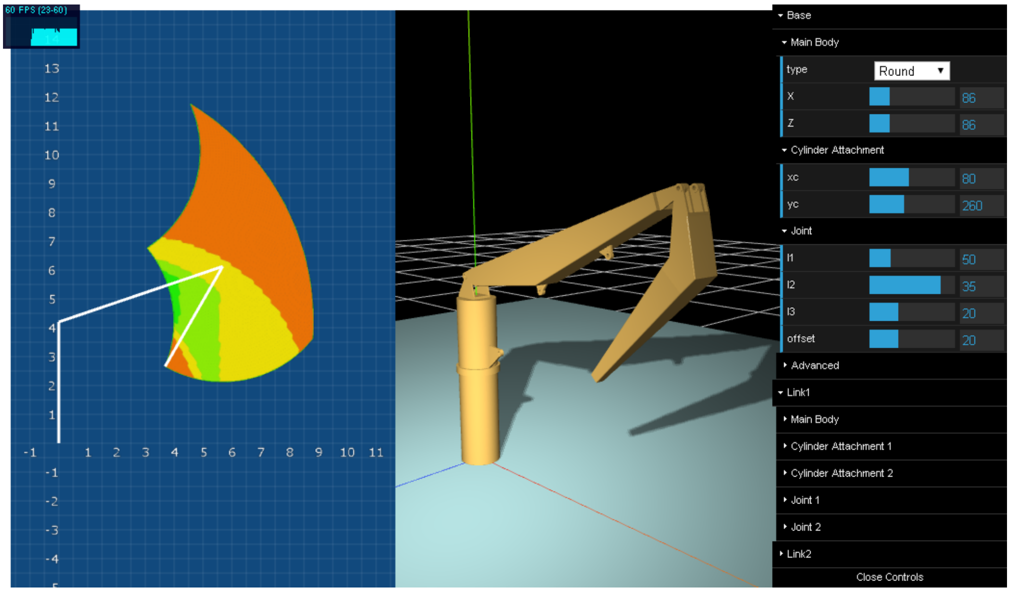


Fig. 3.1 Crane designer tool in a web-browser

A parametric component library containing a variety of basic components is developed, including the main bodies, joints, and cylinder attachments. These components in the library are 3D mesh models composed of vertices and faces. The arrangement of these vertices of a component is controlled by a set of parameters, which means manipulating those parameters will modify the shape of each component. The mechanical editor, together with the workspace editor, offers the users an efficient and intuitive tool for design space exploration during the early design stage.

3.3 Component-Based Multi-objective Object-Oriented Modeling

Depending on the modeling complexity, different implementations are configured with different sets of properties describing the behaviors of the component. The architecture of a component model based on the OOM paradigm for simulations of physical systems is shown in Fig. 3.2. The behavior model of an object is separated from the structure model. More specifically, the behavior model describes the dynamics of the model and the interfaces to other objects. The structure model defines the representation and properties of the object to the user for model manipulation. Model classification is based on the different complexity levels of the behavior model implementations. For one component model, several implementations share the same input and output to its outside world, but contain different behaviors. A complex implementation offers more accurate results reflecting the behaviors of the physical system, but also requires more parameters and state variables to compute. Consequently, the user interfaces become more complex and the simulation time increases which might be problematic for the entire simulation.

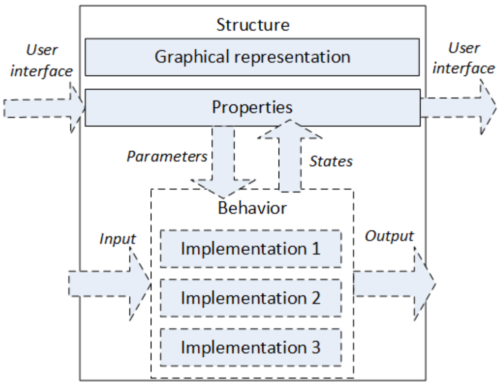


Fig. 3.2 Architecture of the component model based on the OOM paradigm

The abstraction of the user interfaces and simulation interfaces allows for flexible model modification and interaction. The user only needs to know the interactive relations between the component models. Thus, it requires less knowledge in comprehending all the implementation details of any specific sub-model. What's more, intellectual properties can be encrypted if a business desires. Based on the proposed VP framework, the main issue with co-simulations—especially, of strongly-coupled systems—is the weighting between the simulation accuracy and efficiency. On one hand, the simulation time-step (micro-step) sizes must be small for stiff systems to generate valid results. On the other hand, the co-simulation time-step (macro-step) size of the master algorithm has to be big, which means shorter simulation time, so that real-time simulations for operations can be achieved.

Paper V describes the development of the hydraulic component library based on the OOM approach, and presents comparisons and discussions of the results of using the FMI co-simulation (Chu, Hatledal, Æsøy, *et al.*, 2017). Model implantations of the hydraulic systems for co-simulation are presented in the case study in Section 4.2. Appendix B provides a tutorial for model development of the hydraulic component library using the BG method and implementation in 20-sim.

3.4 Virtual Prototyping Framework

The high-level architecture of the proposed VP framework is divided into three layers as shown in Fig. 3.3 (Chu, Hatledal, Sanfilippo, *et al.*, 2015; Chu, Hatledal, Zhang, *et al.*, 2017). It follows a standard model-view-controller pattern, which dictates a separation with low coupling between the logic (model), the presentation (view), and the input (controller) (Red and Green, 2011). Simulations of complex systems are treated by modularization and co-simulation to tackle the complexity and heterogeneity (Kübler and Schiehlen, 2000). Model exchange and co-simulation, that is, coupling of individual sub-system simulations using distinct software tools, underlie the FMI standard.

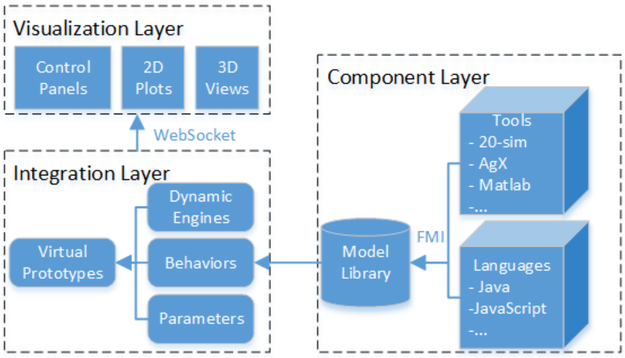


Fig. 3.3 High level software architecture of the VP framework

The component layer contains separate simulators for different components and sub-systems, and the integration layer implements the system model of the various components and sub-systems. The component models are created by a modeling tool and exported as FMUs for co-simulation, which could also be implemented using general purpose programming languages or other tools provided with compatible interfacing protocols other than the FMI standard. The case study described in the next chapter describes using a physics engine to handle the simulation of the mechanical physics and multi-body dynamics of the crane. 3D models from the crane designer tool are combined with physics properties and as well as materials and textures. Model development for the hydraulic power systems uses the BG method and is handled by 20-sim, which offers the basic BG elements and several domain-specific libraries and packages. One model or sub-model can have several implementations, allowing for the encapsulation of different alternatives of the behavior models of a component. Currently 20-sim supports the FMI standard for co-simulation exportation. As one of the benefits, comparisons can be made easily between the results of simulations in 20-sim and co-simulations in the VP simulator.

The integration layer implements the system model and acts as the master for co-simulations with the co-simulation slaves running in the component layer. The simulation manager is responsible for managing references to the available simulations. Initially, the clients must negotiate with the simulation manager to get the IP address of a simulation. After that, the clients can query the simulation directly. In the component layer, we use a thin Java wrapper around the FMUs to export the functionality via the remote method invocation (RMI). This allows the possibility to distribute FMUs on the network. Doing so also makes it possible to support FMUs with different compilation targets. For example, an FMU compiled for Linux would run in a Linux box and accessed over RMI by the VP system running in Windows.

The core of the VP framework is rendering agnostic and effectively decoupled from the visualization layer. This is important for the reuse of the simulation models with different views, and to use the visualization code with different models. Specifically, the user interface, including the views and controllers of the simulator, must be portable and accessible to many different platforms and operating control systems. This is facilitated by using the web technologies, which offers 3D visualization using WebGL and turns the web-browser into a powerful visualization vehicle.

Real-time bi-directional communication between the visualization and integration layer has been facilitated by using the TCP/IP or WebSocket protocols, while static files are served using HTTP. The JSON RPC standard has been used to facilitate data transmission between the clients and the server. Any tool or language that can communicate with the integration layer over these communication protocols can be used to interact with and visualize the running simulations. The clients can choose to either pull updates from the server at their own pace, or subscribe to the updates at a defined frequency. In the latter case, the server will try to accommodate the desired updating speed of the clients, but logically cannot send updates more frequently than the frequency of the simulation itself.

Chapter 4

4 Case Study: Virtual Crane Prototyping Simulator

This chapter presents the whole VP system through a common type of marine crane: the knuckle boom crane (KBC). Section 4.1 describes the crane designer tool for mechanical design, including the workspace editor and the mechanical editor. Section 4.2 describes model development of physics and dynamic systems. Section 4.3 presents simulations based on the proposed VP framework, co-simulations results and visualizations, etc.

As shown in Fig. 4.1, the KBC is a 3-DoF offshore crane (Morten K Bak and Hansen, 2013a). It consists of three links that resemble the finger knuckles: the base sitting on the pedestal, the main boom, and the outer jib. The actuators of the KBC include the slew motor, the main cylinders and the outer cylinders for manipulation, and the winch for lifting. The power systems of these actuators are usually hydraulic because of the high ratio of effort output and the system robustness for operations in rough conditions. Nowadays, hybrid power systems (i.e., electro-hydraulic) are increasingly adopted for motion control of cranes to improve the overall system efficiency to save energy. The responding characteristics of the hydraulic components play a crucial role in the system performance (Morten K Bak and Hansen, 2013b).

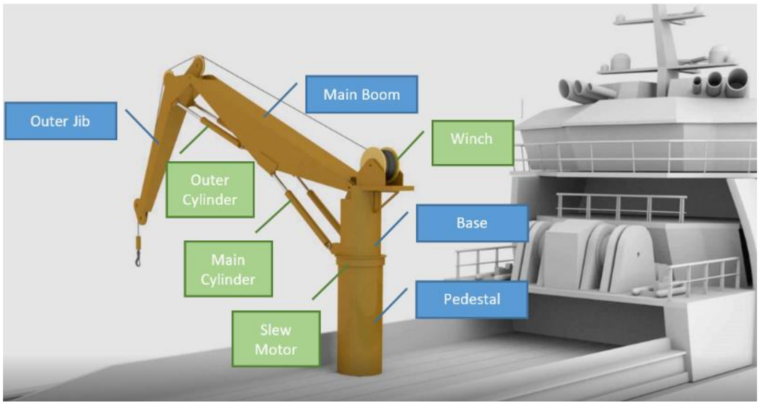


Fig. 4.1 The knuckle boom crane systems

4.1 Mechanical Design - The Crane Designer Tool

4.1.1 The Workspace Editor

The first step of designing a new type of crane is to specify the DoF, link dimensions, and joint types. Given these initial approximates, the workspace of the crane can be calculated and visualized in a 2D plane or 3D space constrained by the end effector positions of the crane that are determined by the crane links and joint limits, as illustrated in Fig. 4.2. These positions are obtained through an iteration process of moving each joint in which each corresponding joint is re-positioned from its lower to upper limit sequentially, and the end effector position is computed at each iteration step. At each step, the coordinate of the end effector is computed and saved as a vertex. All vertices form a mesh are added to the Three.js scene to visualize the crane workspace in the WE editor.

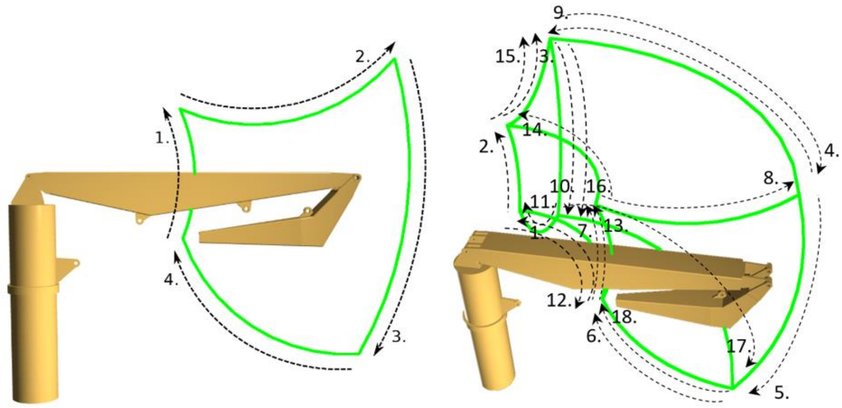


Fig. 4.2 Generating the workspace in a 2D plane or 3D space

The load capability is determined by the power systems, assuming the strength of the structure is always satisfied. An iteration process of permuting runs through all the possible joint configurations. For each permutation, the maximum payload is computed considering the maximum torque of each joint. At last, the smallest value is accepted as the maximum lifting capacity of the crane. The lifting capabilities at different positions are illustrated in a 2D load chart, which splits the entire workspace into areas that indicate the lifting capacity. Each area is assigned a color representing the maximum payload scale that the crane can hoist in that area, as shown in Fig. 4.3. Varying the joint torque limitations changes the lifting capabilities of the crane, and the load chart is re-computed and re-rendered accordingly. The user can modify the link lengths and joint limits by clicking and dragging in the workspace editor directly. This alters the shape of the workspace and the colors of the load chart in real time.

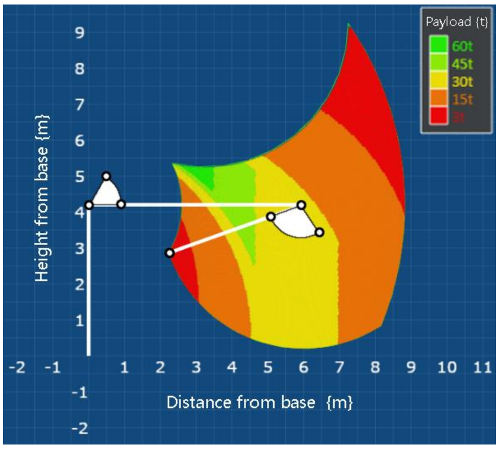
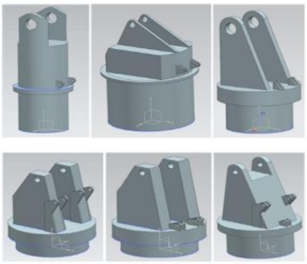
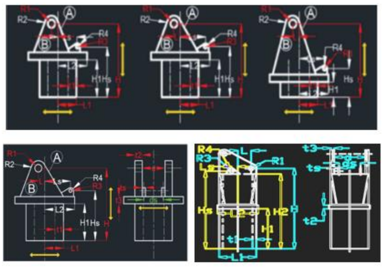
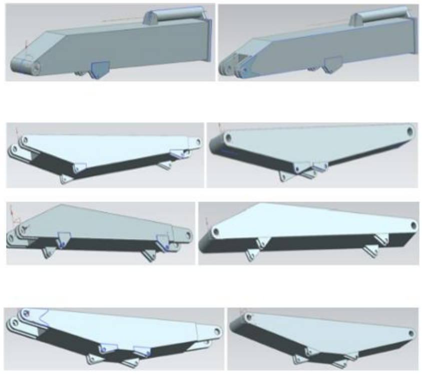
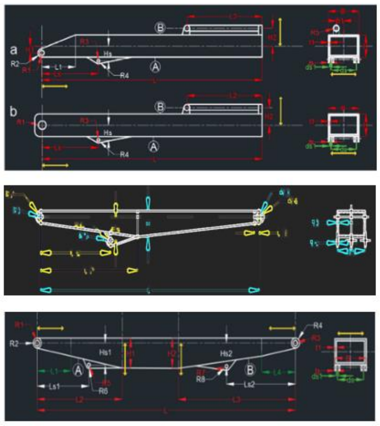
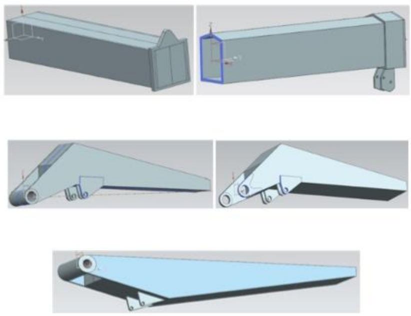
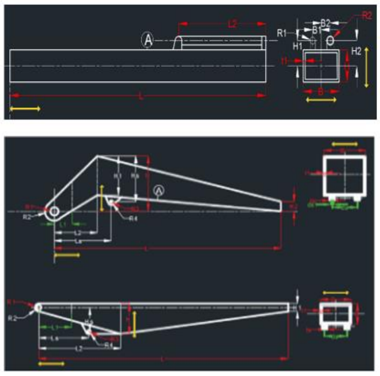
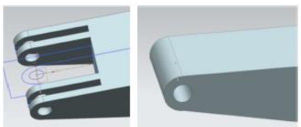
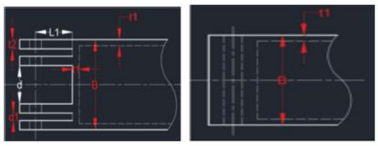


Fig. 4.3 The load chart generated and visulized in the workspace editor

4.1.2 The Mechanical Editor

The mechanical editor is a JavasScript web application, using the Three.js library for 3D visualization. As shown in Tab 4.1, a parametric component library is developed containing a variety of basic components such as links, joints, cylinder attachments, etc. These components in the library are 3D mesh models composed of vertices and faces. The user can manipulate a set of parameters to control the arrangement of the vertices, thereby modifying the shape of each component parametrically. For example, the KBC is decomposed into three links, as shown in Fig. 4.4. Thus, in the designer tool, each link is regarded as a basic unit for both editing and exporting. A link unit consists of several components such as the main body, and the joint connecting parts, etc. Through selecting and assembling the components from the library, the designer can easily create a parametric link. And then different types of cranes can be built by varying the permutations and combinations of different links and joints.

Tab 4.1 Crane mechanical component library

Base		
Boom		
Jib		
Joint		

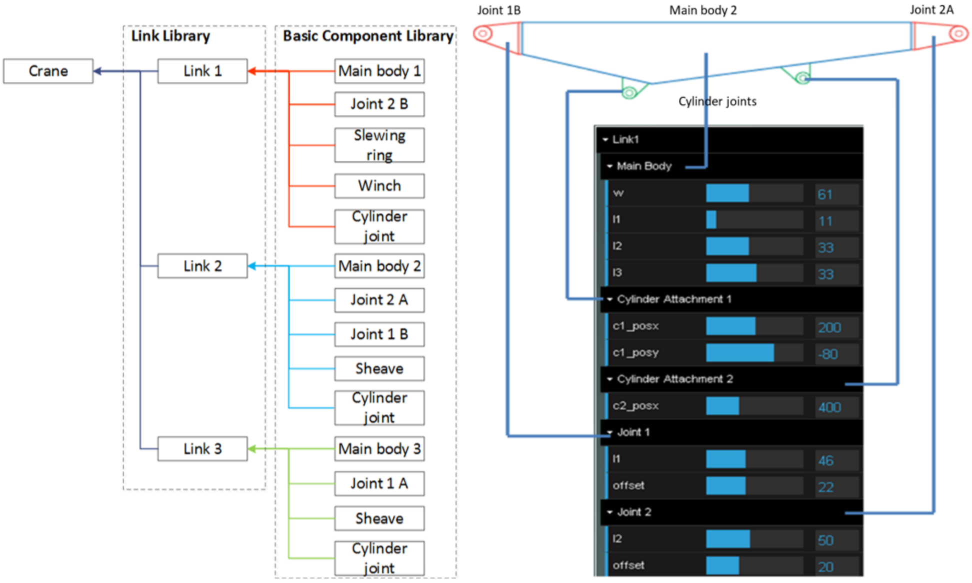


Fig. 4.4 The crane boom decomposed for design

The 3D model is exposed to the users in the mechanical editor along with the workspace editor in the browser, as shown in Fig. 4.5. The main parameters of each link, such as the length, width, and actuator position, can be changed directly in the editors. By manipulating these parameters, the corresponding 3D model will be modified and re-rendered in real time.

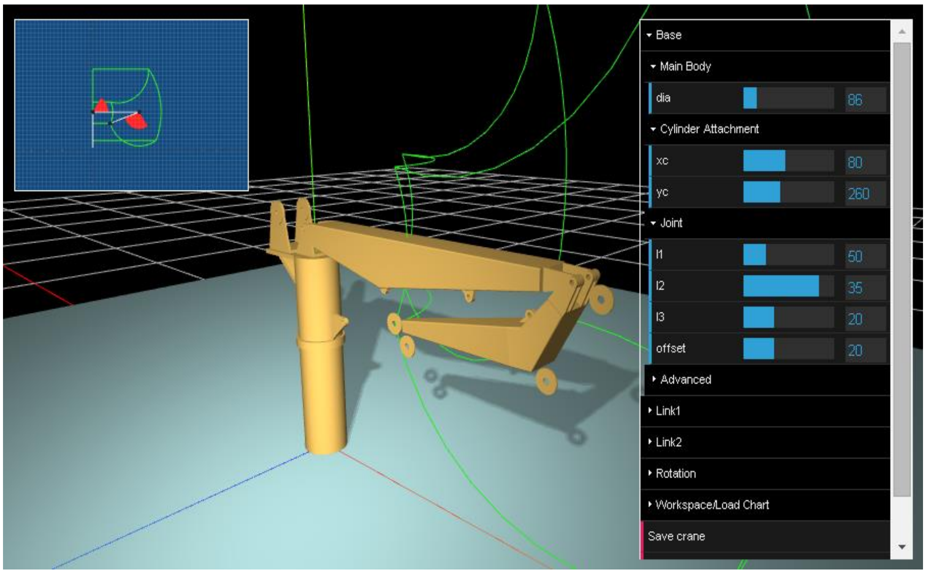


Fig. 4.5 The knuckle boom crane as rendered by the crane designer

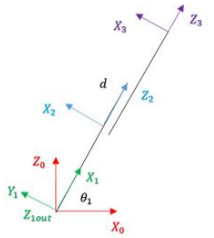
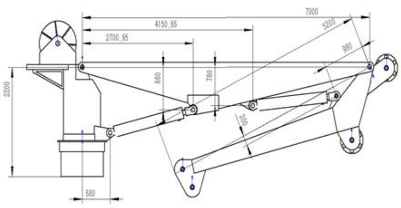
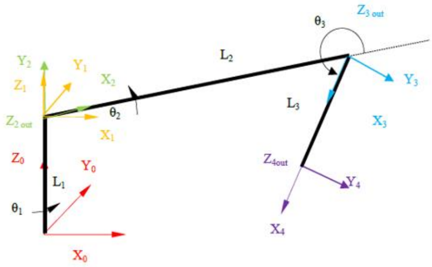
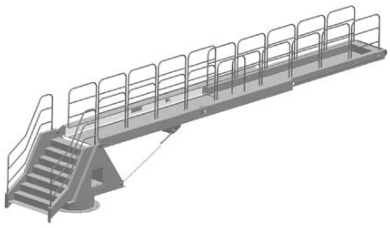
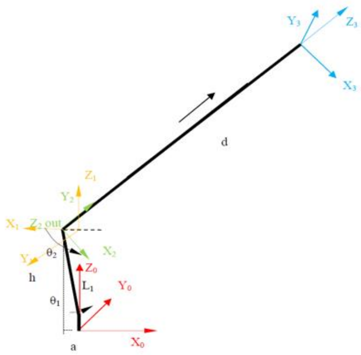
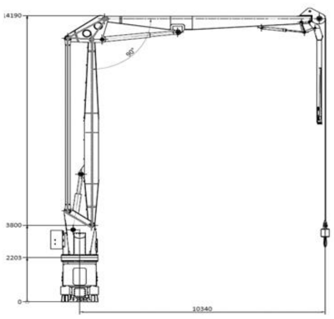
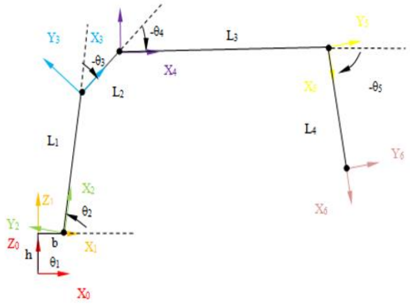
4.2 Model Development of Dynamic Systems

4.2.1 Physics and Multi-body Dynamics

The 3D Mechanics Editor used in Paper I is a 3D dynamic modeling toolbox of 20-sim, which provides a library of basic objects, constraints, and sensors, etc. 3D representations of an object can also be imported for visualization and animation and the physics properties can be assigned manually (Chu *et al.*, 2015). The 3D Mechanics Editor generates a model with physics and dynamics of the objects, which can be connected directly to other BG models, compiled and simulated in 20-sim. The drawback of the approach is that the stiffness of the constraints affects the simulation performance in terms of accuracy and efficiency, particularly for strongly-coupled systems. Special care needs to be taken to assign proper compliance of the kinematic constraints.

The appended Paper II presents an alternative method using the Lagrange's equations in the Hamilton form to describe the multi-body dynamics of the crane (Chu and Æsøy, 2015). Using this approach avoids the breaking-up of strongly-coupled system with high stiffness constraints. However, since the whole system is regarded as one and described using one equation set, this approach is less flexible for design and less efficient for modeling. Considering this issue, it is possible to provide a library of multi-body dynamics models for different types of cranes and to add the mesh models for collision detection, as shown in Tab 4.2. Vorhölter et al. developed a universal crane model for ship design, specifically, heavy lifting vessels (Vorhölter, Christiansen and Hatecke, 2014). Special focus was given to keep a common user interface for ship designer and operation engineer independently of any type and different functionalities of cranes. To solve the equations of motion of the multi-body dynamic system, the D'Alembert's principle was applied, which also eliminates the constraint forces as using the Lagrange-Hamilton approach.

Tab 4.2 Kinematic illustration of different types of cranes

Crane Type	Crane Structure illustration	Kinematic diagram
A-Frame (RP-type)		
Knuckle Boom Crane (RRR-type)		
Telescope Crane / Gangway (RRP-type)		
Dual Drag Link Crane (RRRR-type)		

In the VP crane simulator, the physics engine AgX© handles the physics and multi-body dynamics of the crane. It uses a Java wrapper for interfacing with other sub-models. The products from the crane designer tool are exported after the evaluation of the workspace and load capacity according to the design requirements. A .ZIP-file packs the mesh models and physics properties into a single data collection. The data is saved as a .JSON-formatted object, which enables the developers or other advanced users to read and interpret the data for other design and simulation practices. The .JSON-formatted files also provide the designer with data that third-party simulators and modeling editors can parse.

4.2.2 Hydraulic Power Systems

A simplified hydraulic diagram of the KBC power system is shown in Fig. 4.6. Modeling of the hydraulic system for co-simulation with other sub-models can be done using any FMI supported software tools other than BG and 20-sim. Most importantly, the models need to allow for easy modification and must be modularized for model reuse and classified according to their complexity levels for different simulation purposes.

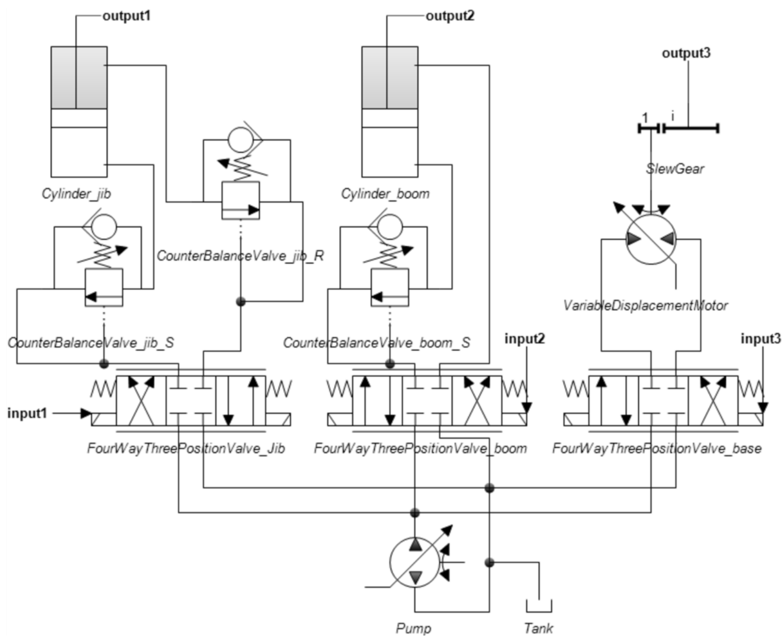


Fig. 4.6 Simplified hydraulic diagram of the KBC

For co-simulation, the complete hydraulic system of the KBC is divided into three sub-systems: the slew motor of the base, and the cylinders of the main boom and the outer jib. The FMU exportation is defined at the sub-system level instead of the component level or complete system level. This makes both model development and integration using FMU co-simulation easier. The BG model implementations in 20-sim are described in (Chu, Æsøy, *et al.*, 2014), see also (Chu, Hatledal, Æsøy, *et al.*, 2017) and Appendix B, as shown as in Fig. 4.7. The input control signal is the gain of the relative spool displacement of the direction valve. The output is the velocity of the cylinder piston or angular velocity of the motor.

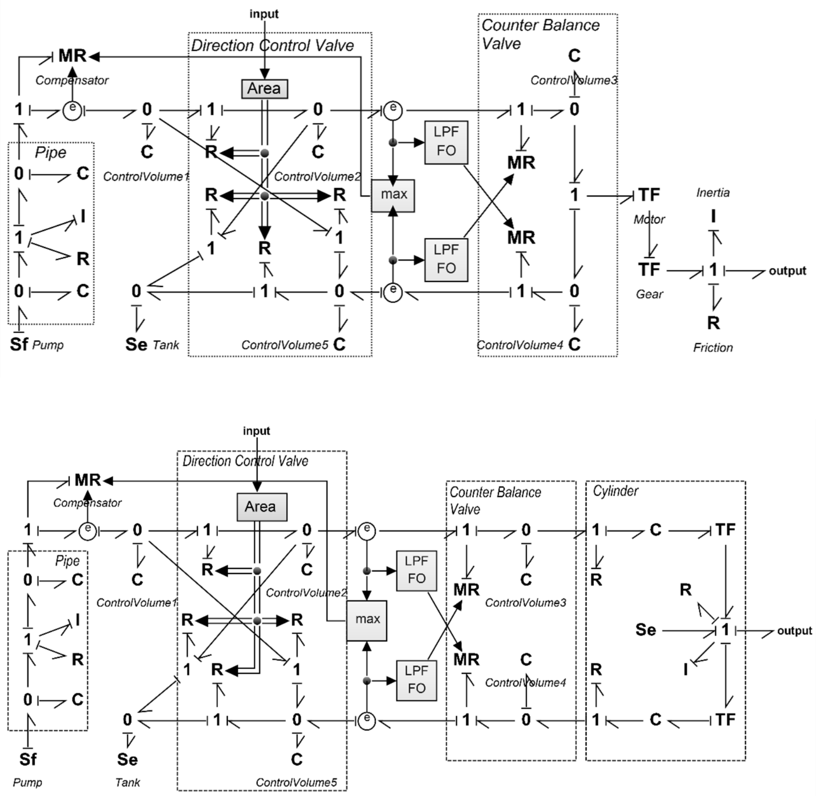
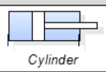
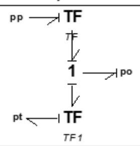
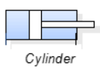
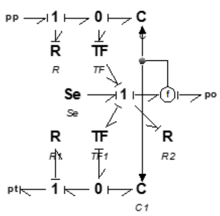


Fig. 4.7 BG implementations of the hydraulic motor and cylinder model

For users who lack the requisite knowledge in BG modeling, a component library allowing for efficient and flexible model development is provided. The component-based models are represented using iconic diagrams, and BG representations show the variants of model implementation with different complexities. For example, Tab 4.3 shows the component model of hydraulic cylinders. The double-acting cylinder contains two different implementations. The simplified model only describes the power transformation from hydraulic pressure to mechanical force through the piston-rod mechanism; while the extended model also considered the flow restrictions of cylinder ports, the compressibility of the fluid in the chambers, friction loss, and end stoppers. The reason for this classification is that the behaviors such as the flow restrictions and the fluid compressibility are nonlinear, which are identified as stiff elements for computation. Excluding these stiff elements in modeling of a component is recommended but not always possible or even desired. In such cases, the stiffness of these constraints must be determined based on the specific applications. A tutorial is appended describing the component model development of the hydraulic systems using the BG method and model implementation in 20-sim.

Tab 4.3 Model implementations of the component model of the hydraulic cylinder

Model Implementation	**Model Representation**	**Interface**		**Model Behavior**
	Icon Diagram / Bond Graph	Input & Output Causality	Parameters & Variables	Variables {unit}
Double-Acting - Simplified		pp, pt, po	Diameter d	$A = \frac{\pi \cdot d^2}{4}$ $F = A \cdot P$
		pressure in, force out		Force {kN}
Double-Acting - Extended		pp, pt, po	Density ρ Inlet Diameter d_i Discharge Coefficient cd Bulk Modulus β Initial Pressure P_0 Piston Diameter d_{pstn} Rod Diameter d_{rod} Friction Factor f Dead Volume V_0 Initial Displacement x_0 Stroke s Bumper Stiffness k Bumper Damping Factor c	$A = \frac{\pi \cdot d^2}{4}$ $\dot{V} = cd \cdot A \cdot \sqrt{\frac{2 \cdot \lvert P \rvert}{\rho}} \cdot sgn(P)$ $V = x \cdot A \subseteq [V_0, (x_0 + s) \cdot A]$ $P = \frac{\beta}{V} \int \Delta\dot{V} \cdot dt$ $F = A \cdot P$ $F_f = f \cdot v$ $F_b = \begin{cases} -k \cdot (\delta - x) - c \cdot v, x < \delta \\ 0, \delta < x < \delta + s \\ -k \cdot (x - s - \delta) - c \cdot v, x > \delta + s \end{cases}$
		flow in, force out		Pressure Loss {bar} Pressure {bar} Force {kN} Friction Force {kN}

4.2.3 Operational Control Algorithms

As mentioned in the introduction, ship motions and the pendulum load cause many problems for accurate positioning during offshore crane operations. Traditional heave compensation solutions using the winch are relatively straightforward from the control point of view; however, the response of the winch power system and the lifting wire fatigue raise many problems (Takagawa, 2010). Previous work presents an effective heave compensation approach using the crane body based on the inverse kinematics control algorithm (Chu, Sanfilippo, *et al.*, 2014). The proposed inverse control algorithm for heave compensated operations can be implemented regardless of the structure of the crane, making it more efficient for the operators to position the load.

The kinematic diagram of the KBC is depicted in Fig. 4.8 based on the D-H method. The forward transformation matrix gives the position and orientation of the end tip of the crane.

$$ {}^{0}_{4}T = \begin{bmatrix} {}^{\mathbf{0}}_{4}\boldsymbol{R} & {}^{\mathbf{0}}_{4}\boldsymbol{P} \\ \mathbf{0} & \mathbf{1} \end{bmatrix} = \begin{bmatrix} c1c23 & -c1c23 & s1 & c1(L2c2 + L3c23) \\ -s1c23 & -s1s23 & -c1 & s1(L2c2 + L3c23) \\ s23 & c23 & 0 & L_1 + L_2s2 + L_3c23 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

Where $ci = \cos(\theta_i)$, $si = \sin(\theta_i)$, $cij = \cos(\theta_i + \theta_i)$, $sij = \sin(\theta_i + \theta_i)$ $(i, j = 1{,}2{,}3)$.

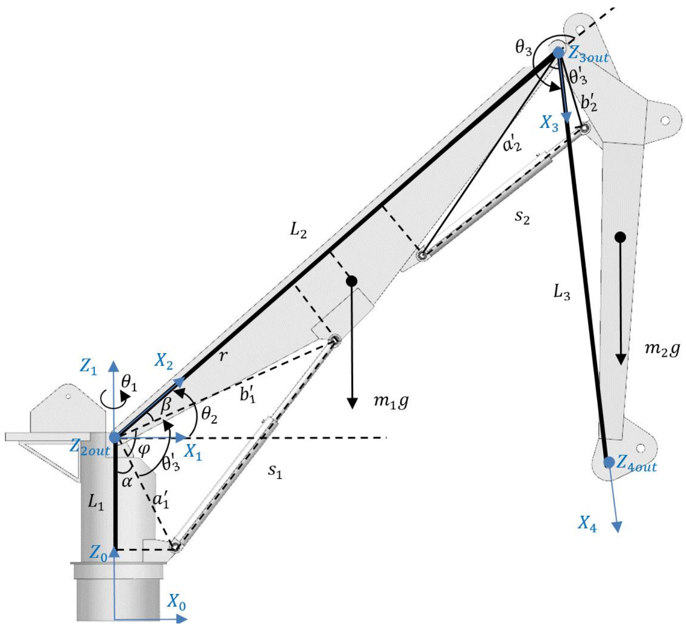


Fig. 4.8 Kinematic diagram of the knuckle boom crane

Calculating the time derivative of the position vector ${}^{0}_{4}\boldsymbol{P}$ yields the Jacobian matrix, which relates the joint angular velocities to the linear velocities of the crane end tip.

$$ {}^{0}_{4}J = \begin{bmatrix} -s1(L2c2 + L3c23) & -c1(L2c2 + L3c23) & -L3c1s23 \\ c1(L2c2 + L3c23) & -s1(L2s2 + L3s23) & -L3s1s23 \\ 0 & L2c2 + L3c23 & L3c23 \end{bmatrix} \tag{2} $$

Given the crane tip velocity, the required joint angular velocities can be calculated, as written by Eq. 3. Theoretically, active compensation can be achieved by feeding the reverse movements to keep the crane tip stabilized, as shown in Fig. 4.9.

$$ \dot{\theta} = J(\theta)^{-1} \begin{bmatrix} -v_{roll\_h} \\ 0 \\ -v_{heave} - v_{roll\_v} \end{bmatrix} \tag{3} $$

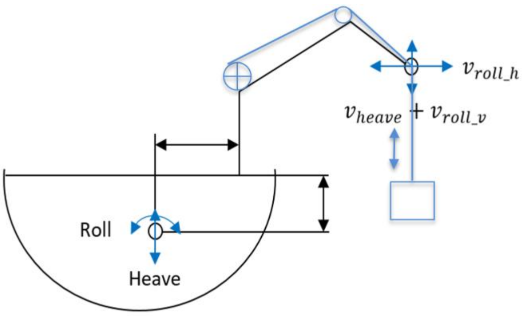


Fig. 4.9 Active heave and roll compensation

The inverse control algorithms and compensation functions are implemented directly in Java and exposed over RMI, similar to the hydraulic FMUs, allowing them (which might be CPU intensive) to run as a separate process or on a different host. Cranes implemented in the operation simulator can be controlled in a variety of different ways, for example by direct joint-by-joint control, inverse control, or compensation using the crane or the winch.

4.3 Coupling of Simulations and Visualizations

Given the dynamic models of the sub-systems of the KBC described in Section 4.2, the crane operation simulator can be set up based on the proposed VP framework. As shown in Fig. 4.10, the VP simulator for the KBC includes the ship with the hydrodynamic model from the physics engine AgX©, the hydraulic power systems of the crane implemented in 20-sim and handled as co-simulation FMUs, and the physics and dynamics of the crane handled by AgX© based on the models from the crane designer. The control algorithms are implemented in the simulation manager directly, but could also be handled as separate FMUs. The integration layer has access to all the dynamic engines and solvers. Both the physics engine and various models implemented as FMUs can be included and intertwined in the simulation so that they interact with each other. For example, the output velocity from a hydraulic FMU is used as the input to the multi-body model of the crane, while the acting force from the crane is sent back to the hydraulic FMU.

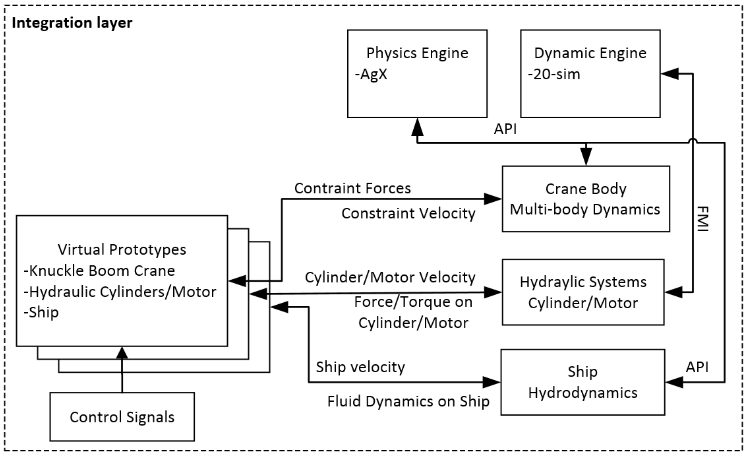
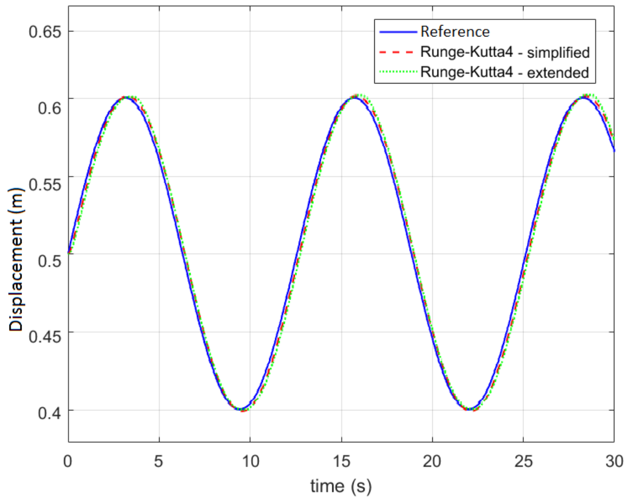


Fig. 4.10 Model integration of the crane operation simulator

The overall simulation accuracy and stability needs to be treated carefully, when stiff systems, such as the hydraulic cylinders and the attached crane body via constraints, are modelled separately and integrated through co-simulation with different servers. The weighting between simulation accuracy and stability must be examined purposefully. As a result, the time steps for co-simulation, data exchange and communication for visualization vary from case to case. For example, the real-time performance of the simulation must be ensured during operational training applications. In this case, the modeling and simulation of dynamic systems could be simplified, or must be simplified when many objects are included in the simulation. For analytical simulations, detailed modeling of the dynamics must reflect the interested properties and behaviors of the physical systems, while simulation efficiency in the time domain becomes less crucial. The following section will provide comparison of the results based on different model implementations and case studies of using FMI co-simulation.

4.3.1 Simulation Results and Co-simulation Performances

Based on the cylinder models with different complexities in Section 4.2.2, Fig. 4.11 shows the displacement of the cylinder piston given a regular sine wave movement. Velocity PID-control is applied and the reference of the movements is the set point signal to the controller.



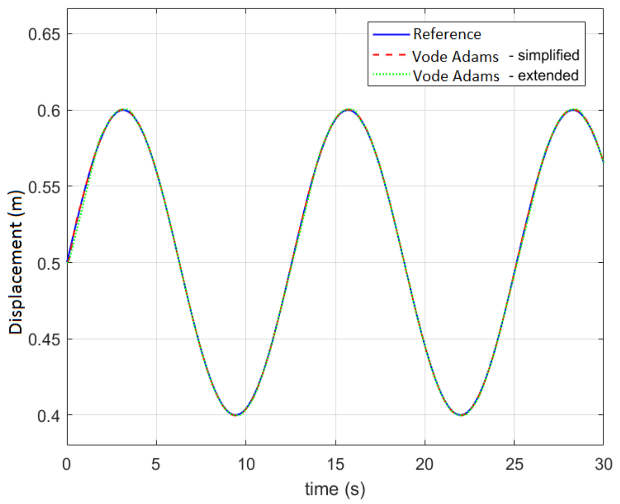


Fig. 4.11 Displacement of the cylinder piston

As shown in Tab 4.4, the root-mean-square error (RMSE) of the piston displacement validates both the simplified model and the extended model in reflecting the behavior the cylinder movement. However, the real-time factor (RTF) suggests that the extended model might fail in real-time simulation. Using a variable time-step (e.g., Vode Adams) solver shortens the simulation time as compared with using a fixed time-step (e.g., Runge-Kutta4) solver. It can be expected that an integrated model would fail in real-time simulation with either simplified or extended behavior models of the components. Depending on the situation, one could conclude that the simplified model implementation shows equally valid results of the behavior of the cylinder movement. The simplified model implementation contains fewer parameters and state variables for modeling and computations, which leads to the decrease in model complexity and simulation time. For concept design and operation training applications using simulations, it might be sufficient to use simplified models where the real-time feature is essential rather than the responding characteristics of every component of the dynamic systems.

Tab 4.4 Simulation performance - efficiency and accuracy

Model Implementation	RTF*	RMSE
Runge-Kutta4 - simplified	0.73	2.38e-3
Runge-Kutta4 - extended	2.36	3.30e-3
Vode Adams - simplified	0.0003	2.73e-3
Vode Adams - extended	0.067	3.8e-3

**The RTF is defined as the natural time divided by the simulation time.*

Using co-simulation, it is possible to break the strongly-coupled system and handle them separately. The testing model for co-simulation stability is divided into two parts: the hydraulic cylinder and the crane boom with the constraint. Firstly, two FMUs are compiled and exported from the BG model in 20-sim, and implemented in the VP framework. Secondly, the FMU with the crane boom is replaced by a model built and handled by the physics engine AgX©. The deviation of the displacement using co-simulation is shown in Fig. 4.12. The reference is the result of using the extended model and the integration method is Vode Adams. The RTF and RMSE of the result suggests that the simulation times can be reduced using co-simulation, as shown in Tab 4.5.

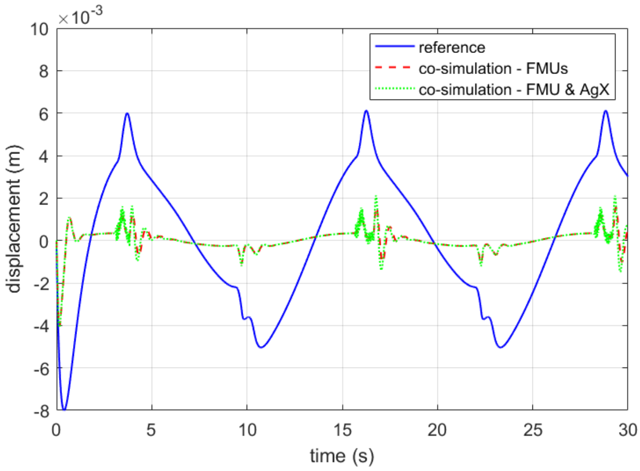


Fig. 4.12 Displacement deviation of the cylinder piston using co-simulation

Tab 4.5 Co-simulation performance - efficiency and accuracy

Model Implementation	RTF*	RMSE
Runge-Kutta4 - FMUs by 20-sim	0.19	0.52e-3
Runge-Kutta4 - FMU by 20-sim &AgX	0.17	0.55e-3
Vode Adams - FMUs by 20-sim	0.03	0.61e-3
Vode Adams - FMU by 20-sim &AgX	0.05	0.62e-3

The time-steps of co-simulations can be increased within the range of providing valid results in order to achieve the shortest simulation time. The requirement for real-time for operations imposes an intractable challenge to the micro-steps, which determine the simulation accuracy and efficiency. Meanwhile, the convergence of the co-simulation process depends on the macro-step size of the simulation. In other words, divergence and poor accuracy can be minimized by setting the macro-steps relatively small, but doing so also increases the computation time. With respect to numerical stability, implicit coupling schemes usually entails better behaviors than explicit methods, especially for models with derivative causalities and algebraic loops. However, even implicit methods may fail or require small macro-step sizes in order to produce reliable results. Enhanced stability behavior can be achieved by extending the coupling conditions, taking into account the derivatives and integrals of the constitutive equations (Schweizer *et al.*, 2015).

4.3.2 Manual Manipulation via Joystick

Given a random input signal from a joystick to the direction valve of the cylinder, the behaviors of the hydraulic cylinder and the crane in the proposed VP system are presented as shown in Fig. 4.13. When the gain is positive, the speed of the piston is positive and the displacement of the piston increases, which means in effect that the cylinder is being extended. When the gain is negative, the speed of the piston is negative and the displacement decreases, which means in effect that the cylinder is being retracted.

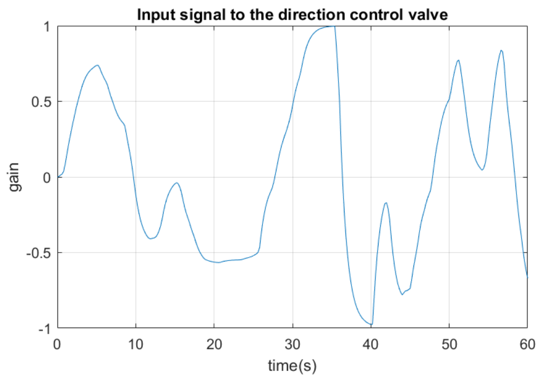


Fig. 4.13 Control signal to the direction control valve from the joystick

Fig. 4.14 shows the behaviors of the cylinder piston. The reference speed and displacement are from the hydraulic FMUs, and the actual speed and displacement pulled from the rigid body model handled by the physics engine AgX©. The stroke of the piston is defined at1.4m plus 0.01m deflection of the bumpers. As a result, the displacement of the piston stops increasing at about 8s and 35s even as the gain and speed are still in a positive direction. The pressures at the two chambers of the hydraulic cylinder reflect this. When the cylinder piston is researched to the bumpers, the pressure at the piston side of the cylinder increases to the maximum pressure, while the pressure at the payload side drops to 0 (return line pressure to the drain tank).

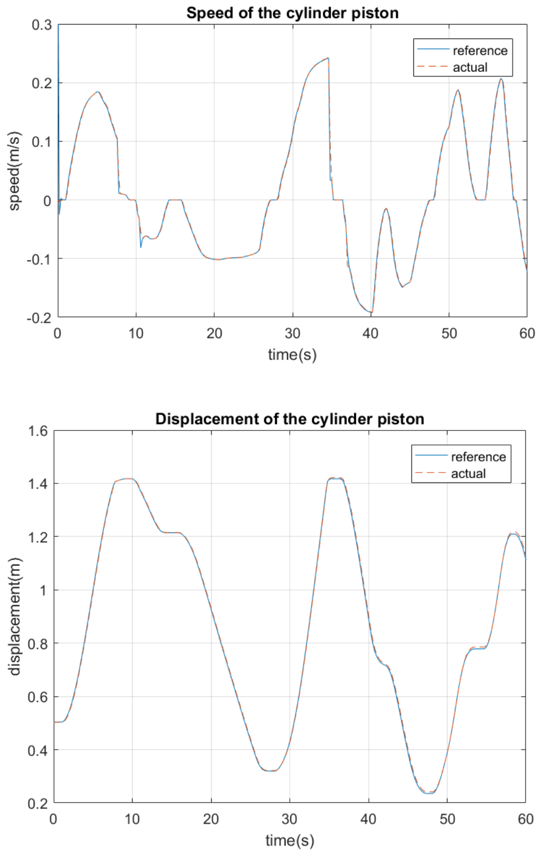


Fig. 4.14 Speed and displacement of the cylinder piston during manual manipulations

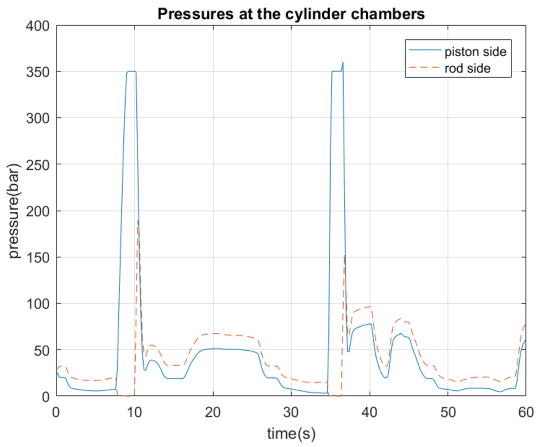


Fig. 4.15 Pressure at the main cylinder during manual manipulations

4.3.3 Active Heave Compensation

The proposed control algorithm for maritime crane operations is based inverse kinematic control of multi-body systems. This improves the work efficiency in accurate positioning of the crane under heave compensation and anti-sway operations. Fig. 4.16 shows the displacement of the crane tip under active heave compensation (AHC) mode given a regular sine wave representing the heave motion. The control signal is the inverse of the heave motion as the reference displacement of the crane tip. The actual displacement represents the global displacement of the crane tip during AHC. Activated from 12s, over 95 percent of the heave motion was eliminated.

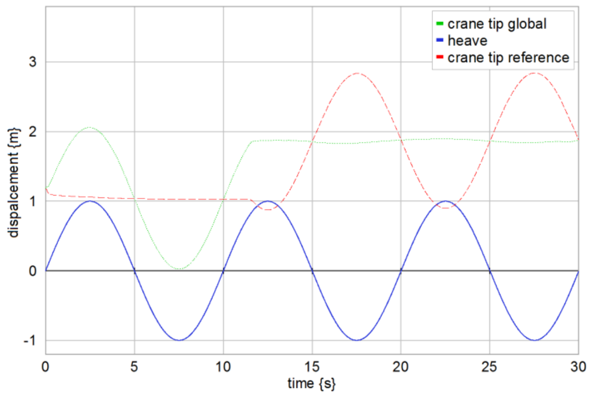


Fig. 4.16 Displacement of the crane tip during active heave compensation

The effectiveness of the AHC algorithm depends on the performances of the hydraulic power systems as well as the structural properties of the crane. External disturbances, such as the payload sway and the wind effects, were not included in the test. Analyzing the behavioral characteristics of the hydraulic system helps to improve the understanding of the behaviors of the components during AHC operations, which is why it's important to have high fidelity models for operations. For example, Fig. 4.17 shows the volumetric flow rate of the cylinder piston side chamber. This can also help to reduce system redundancy in oversizing the power systems and actuators, hence enhanced overall system efficiency. The references of the results are from the integrated model done in 20-sim. The co-simulation results using the FMUs showed noticeable deviations. Several matters cause these differences in the results, including different model setups in 20-sim and the VP crane simulator, the macro-steps of co-simulation and the different solvers of the FMUs handled by 20-sim and the physics engine AgX©.

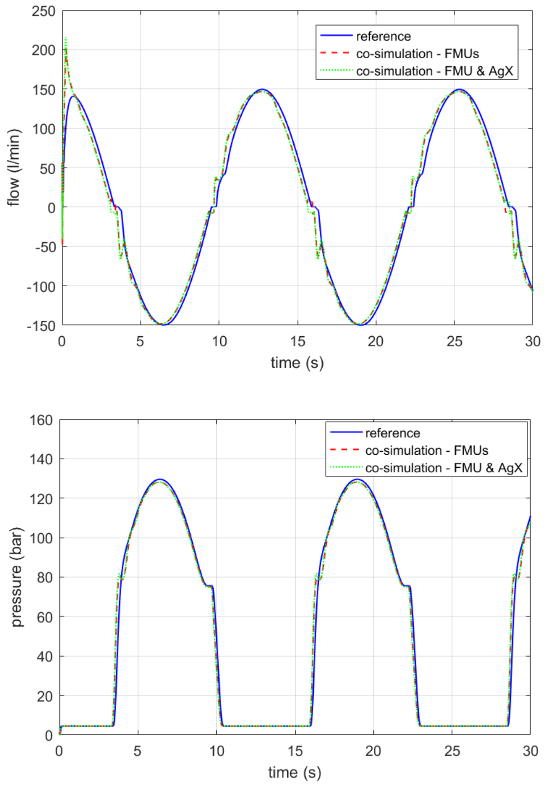


Fig. 4.17 Flow rate and pressure at the cylinder piston side chamber

4.3.4 2D/3D Visualizations

Data generated by the VP simulators is made accessible to the user in real time. More specifically, a collection of available plots of simulation variables is presented to the user through the browser or other tools for display. For example, complete time-series can also be downloaded as comma separated files (.csv) to be read in Matlab®. In order to interact with the simulation and virtual prototypes, a set of HTML5 webpages has been implemented in order to handle user input, display 2D plots, 3D visuals, and other types of data according to user requirements. The plotting library, CanvasJS, has been used to simplify the creation of 2D plots, and Fig. 4.18 shows a webpage displaying real-time plotting results from a running simulation. Plotting works by having the client poll for updates, which contains the most current data at the time of the poll, at a regular interval. Caching is done internally by the client in order to save bandwidth, and to let the view determine the number of data points to be displayed.

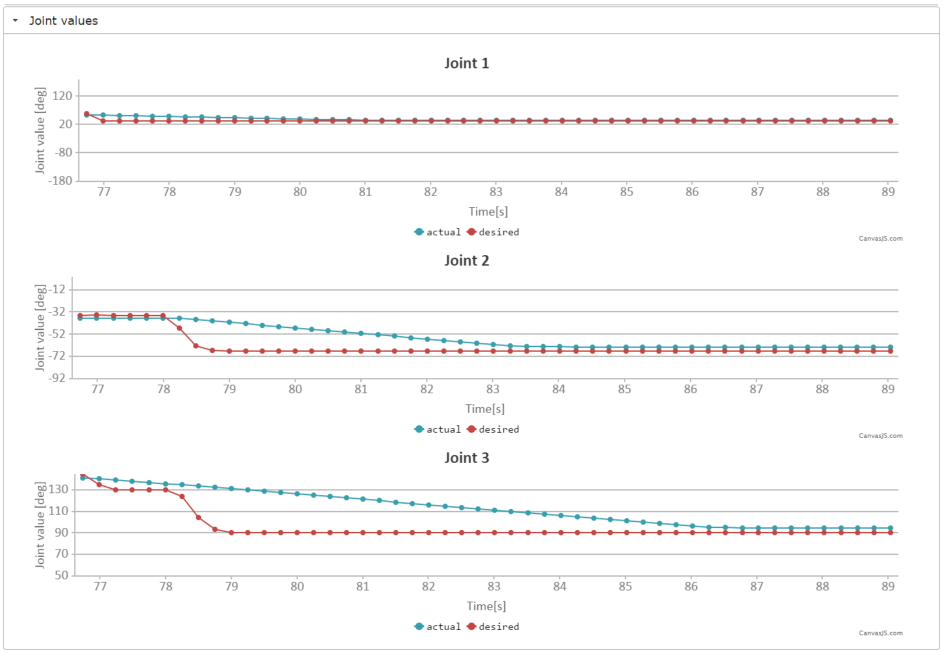


Fig. 4.18 2D views in the web-browser

In order to show the modularity of the VP framework for visualization, rendering of 3D visuals is created using the Java game engine jMonkeyEngine3. This implementation supports both the use of TCP/IP and WebSockets to communicate with the simulation server. Fig. 4.19 shows the same scene using OpenGL and in the web-browser using WebGL respectively. Changes to the simulation models done in either of the implementations are propagated to all connected clients, and their views are updated accordingly.

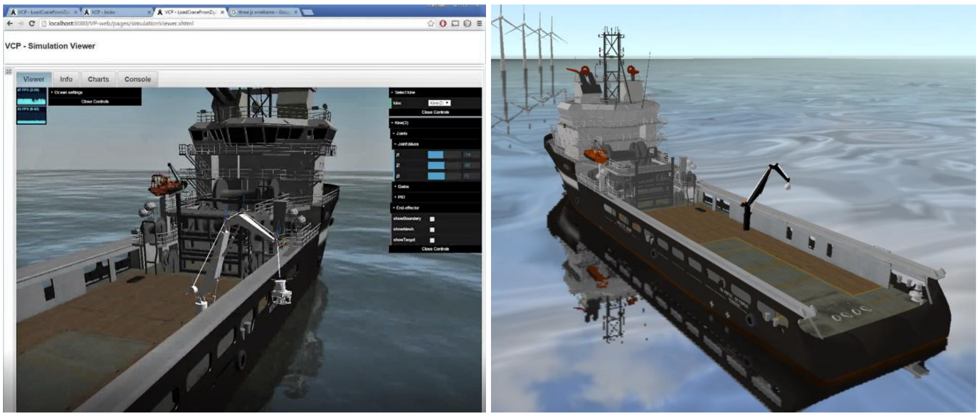


Fig. 4.19 3D scene rendered in OpenGL and WebGL simultaneously

The approach of making the simulation accessible over the network provides more flexibility, allowing multiple users to interact with the same simulation on different computers. In other words it allows users to control and visualize the simulation in their preferred tools. However, carries a considerable communication overhead. For large scale simulation scenarios with many visual objects, the amount of data needed to render the simulation with a pleasing frame rate can be overwhelming for the internet connection and the client's processing ability to handle. In such cases the VP framework can be used as a library, where the data is accessed through regular API calls that do not have communication overhead. Simulation data, such as the plotting data, which does not require such a high update frequency can still be accessed through the network.

Chapter 5

5 Conclusions

Chapters 1-4 discussed the advantages and challenges VP poses for complex multi-domain system design and operations. Modern engineering design is characterized by high customization, high complexity, high price, low production volume, and short development time. Over the last few decades, leading industries such as aerospace, automobile, and shipbuilding design have increasingly employed VP techniques for product and system design. Marine crane operation simulators currently in existence almost exclusively serve training purposes. Most focus on virtual reality regarding human interaction and 3D visualization. Integrating physics and dynamics in the operation simulators is challenging, as it requires handling large scale complex scenarios in real-time.

Since 2010, the FMI standard is increasingly recognized and adopted for interfacing of heterogeneous simulation models of the multi-domain physical systems, where modeling and simulation is usually favored by several different software tools. The proposed software structure of the VP framework is based on the application of the FMI co-simulation standard. VP for marine crane system design include mechanical design, kinematics, multi-body dynamics, hydraulic power systems, and operational control algorithms. The implementation of the KBC simulator validates the effectiveness of the VP system for design and operations.

5.1 Summary of Contributions

The VP system supports the current marine operation system design significantly, allowing for combined collaborations between customers, designers, engineers, operators, etc. Simulations with high-fidelity dynamic models improve the work efficiency of product development, system testing and analysis, and safety of operations. The main novelty of the proposed VP system is that it’s open and flexible for modeling, simulation and visualization. Knowledge within different domains can be reused and efficiently facilitated by the FMI standard, which most of the available software tools support. Integrating effective and efficient physics and dynamic models enhances the operation simulator based on the VP framework. The original contributions of the research work include the followings:

- **Proposed and developed an open, flexible and efficient framework for VP of complex multi-domain dynamic systems.**

- **Introduced a generic approach to model development to support multi-objective simulations based on the proposed VP framework.**
- **Enhanced the crane operation simulator with physics and dynamics including mechanics, kinematics, multi-body dynamics, hydraulics, and hydrodynamics, etc.**

5.2 Summary of Pubilications

Paper I, a pre-feasibility study, presents an integrated model of the crane system. The work exposed the challenges in modeling and simulation of such complex multi-domain systems. To handle the simulation in real-time with all the sub-models running at the same time by the same server is nearly impossible, which means it is useless for operations. There are two potential ways to address this: by simplifying the computational-wise stiff models to make the simulation more efficient, or decomposing the whole model of the entire system in order to handle them separately. However, model simplification would compromise model fidelity in reflecting the physical behaviors of the system, while decomposing the model would create problems with the interfacing of the sub-models, in particular when handled by different software tools.

Paper II presents an alternative approach to describe the multi-body dynamics of the crane, which is implemented using the same modeling method as for the hydraulic systems. This solves part of the problem presented in Paper I, where the strongly coupled links via high stiffness constraints are replaced by describing the crane as a whole mechanism with one equation set. This approach, however, offers less flexibility for modeling and model integration.

Paper III introduces an effective approach to simulate and visualize the mechanical design using WebGL. According to the design specifications, the crane designer tool computes and visualizes the workspace and load chart directly in the web browser. The lightweight tool for design space exploration is helpful, in particular, at the early stage of new product development process. Defined by a set of parameters and variables, the products from the designer tool of the crane body parts can be used later in the VP operation simulator.

Paper IV introduces the VP framework based on the FMI co-simulation standard. The paper describes the software architecture of the VP framework and the implementation of the crane simulator. The FMI standard offers a shared format for interfacing and is currently supported by most of the available software tools for modeling and simulation. With this common standard available, model development and handling can be performed separately with different domain-specific tools. Integration of the sub-models only needs to take care of the data for interaction at a proper frequency depending on the case. In other words, modeling and simulation computational-wise stiff systems can be represented in different complexity levels and handled at their own time-steps. The paper focuses on the potentials and flexibilities of the proposed VP framework for multi-domain dynamic system.

Paper V presents a multi-objective component-based model development approach based on the OOM method. The model architecture is defined in layers to facilitate model modularization and interfacing for the proposed VP framework. Determined by the purpose of simulation, model implementations with different complexity levels considering computation efficiency and accuracy are provided. A component model library of the hydraulic systems is developed using the BG method and implemented in a commercial software tool 20-sim which supports the FMI co-simulation. Appendix B provides further description of the details of the component models and model implementations.

5.3 Outline of Future Work

Several avenues remain to make the current implementation of the proposed VP system more generic and robust. The future work for research includes:

- To improve and standardize a more generic and efficient software architecture of the VP system regarding the flexibility of rendering different simulation scenarios, which will also enlarge the application scope from marine crane systems. Interaction systems such as the dynamics of the ship and onboard machinery also have significant influence on crane design and operations. Hatecke presented simulations of the ship motions in time domain, where the hydrostatic and hydrodynamic forces are separately treated in frequency domain and efficiently computed (Hatecke, 2016). To reduce the computation effort, the instantons hydrostatic forces are interpolated from a look-up table. The linear radiation forces are computed by a state-space system, where a new time domain identification method has been developed. Recently, Rokseth *et al.* presented modeling of an offshore vessel in crane operations with a focus on strong rigid body connections (Rokseth, Skjong and Pedersen, 2017).
- To establish open, flexible and tool-independent component model libraries for different simulation purposes, including the mechanical parts, hydraulic power systems, and control algorithms and compensation functions. In this way, building a scene in the VP

simulator becomes more efficient, especially for the users who lack knowledge of dynamic systems.

- The model fidelity of physics and dynamics of the system needs to be backed up by experimental data on physical prototypes or testing on real systems. Recent work on simulation of the hydro-thermodynamics of AHC accumulator has showed convincing results compared to the obtained field test data (Chu, Æsøy, *et al.*, 2016).
- To document the benchmarking for model simplification and simulation performance, specifically the simulation accuracy and stability of using co-simulations based on the FMI standard. For stiff systems, the stability of the simulation is crucial when tightly-coupled parts are separated. The crane operation simulator contains many objects in the scenario where the micro and macro time-steps are critical to obtain reasonable results during real-time simulations. Master algorithms need to be introduced when necessary in order to improve the simulation efficiency and accuracy (Mengist *et al.*, 2015; Sadjina *et al.*, 2017). Advanced Co-simulation Open System Architecture is an on-going project that will address the questions this dissertation leaves unanswered (Krammer, Marko and Benedikt, 2016). It is dedicated to real-time system co-simulation to develop both a non-proprietary advanced co-simulation interface for real-time systems integration and an according integration methodology which shall be a substantial contribution to the international standardization, e.g., the FMI.

References

Aarseth, J., Lien, A. H., Bunes, O., Chu, Y., Æsøy, V., Marine, R.-R. and Helge, A. (2014) 'A Hardware-In-The-Loop Simulator For Offshore Machinery Control System Testing.', in *Proceedings of 2014 28th European Conference on Modeling & Simulation (ECMS)*. Brescia, Italy, pp. 57–63.

van Albada, S. B., van Albada, G. D., Hildre, H. P. and Zhang, H. (2013) 'A Novel Approach To Anti-Sway Control For Marine Shipboard Cranes', in *Proceedings of 2013 27th European Conference on Modeling & Simulation (ECMS)*. Alesund, Norway, pp. 249–256.

Amálio, N., Payne, R., Cavalcanti, A. and Woodcock, J. (2016) 'Checking SysML Models for Co-simulation BT - Formal Methods and Software Engineering', in Ogata, K., Lawford, M., and Liu, S. (eds) *Proceedings of 18th International Conference on Formal Engineering Methods, ICFEM*. Tokyo, Japan: Springer International Publishing, pp. 450–465.

Amditis, A., Karaseitanidis, I. and Mantzouranis, I. (2008) 'Virtual Reality Research in Europe: Towards Structuring the European Research Area BT - Product Engineering: Tools and Methods Based on Virtual Reality', in Talaba, D. and Amditis, A. (eds). Dordrecht: Springer Netherlands, pp. 3–20.

Bak, M. K. (2014) *Model Based Design of Electro-Hydraulic Motion Control Systems for Offshore Pipe Handling Equipment, Doctoral dissertation for the degree of Philosophiae Doctor (Ph.D.)*. Univercity of Agder, Kristiansand, Norway.

Bak, M. K. and Hansen, M. R. (2013a) 'Analysis of offshore knuckle boom crane-part one: modeling and parameter identification', *Modeling, Identification and Control*. Norsk Forening for Automatisering (NFA), 34(4), pp. 157–174.

Bak, M. K. and Hansen, M. R. (2013b) 'Analysis of offshore knuckle boom crane-part two: Motion control', *Modeling, Identification and Control*. Norsk Forening for Automatisering (NFA), 34(4), pp. 175–181.

Bak, M. K. and Hansen, M. R. (2013) 'Model based design optimization of operational reliability in offshore boom cranes', *International Journal of Fluid Power*, 14(3), pp. 53–65. doi: 10.1080/14399776.2013.10801413.

Bennett, G. R. (1997) 'The application of virtual prototyping in the development of complex aerospace products', *Aircraft Engineering and Aerospace Technology*. Emerald, 69(1), pp. 19–25.

Bertsch, C. and Schulmeister, E. A. U. (2014) 'The Functional Mockup Interface-seen from an industrial perspective', *10 th International Modelica Conference, Lund, Sweden*, pp. 27–33.

Blochwitz, T., Otter, M., Akesson, J., Arnold, M., Clauss, C., Elmqvist, H., Friedrich, M., Junghanns, A., Mauss, J. and Neumerkel, D. (2012) ‘Functional mockup interface 2.0: The standard for tool independent exchange of simulation models’, in *Proceedings of the 9th International MODELICA Conference*. Munich, Germany, pp. 173–184.

Bordegoni, M. and Rizzi, C. (2011) *Innovation in Product Design - From CAD to Virtual Prototyping*. 1st edn. Edited by M. Bordegoni and C. Rizzi. London, UK: Springer-Verlag London.

Borutzky, W. (1999) ‘Bond graph modeling from an object oriented modeling point of view’, *Simulation Practice and Theory*, 7(5–6), pp. 439–461.

Broenink, J. F. (1997) ‘Bond-graph modeling in modelica ™’, in *Proceedings of 9th European simulation symposium*. Passau, Germany, pp. 19–22.

Broenink, J. F. (1999) ‘Object-oriented modeling with bond graphs and Modelica’, in *International Conference on Bond Graph Modeling and Simulation, part of the WMC ’99, the Western MultiConference*. San Francisco, CA, pp. 163–168.

Budde, R., Kautz, K.Kuhlenkamp, K., Zlighoven, H. (1992) *Prototyping: An Approach to Evolutionary System Development.* 1st edn. Springer-Verlag Berlin Heidelberg.

Cellier, F. and Nebot, À. (2005) ‘The Modelica Bond Graph Library’, in *Proceedings of th 4th International Modelica Conference*. Harburg, Germany, pp. 57–65.

Chatterjee, A., Mahapatra, A., Roy, S. S. and Mukherjee, N. P. (2005) ‘Virtual prototyping in mechanical product development - A review’, in *12th National Conference on Machines and Mechanisms, NaCoMM 2005*. Guwahati, India, pp. 405–410.

Chin, C. S. (2012) ‘Dynamic positioning simulation, thrust optimization design and control of a drill ship under disturbances and faulty thruster’, *SIMULATION*. SAGE Publications, 88(11), pp. 1338–1349.

Choi, S. H. and Cheung, H. H. (2008) ‘A versatile virtual prototyping system for rapid product development’, *Computers in Industry*, 59(5), pp. 477–488.

Christou, M. and Konstantinidou, M. A. (2012) *Safety of offshore oil and gas operations: Lessons from past accident analysis*. Luxembourg.

Chu, Y. and Æsøy, V. (2015) ‘A Multi-Body Dynamic Model Based on Bond Graph for Maritime Hydraulic Crane Operations’, in *Proceedings of ASME International Conference on Offshore Mechanics and Arctic Engineering (OMAE).* St. John’s, Newfoundland, Canada, p. V001T01A010.

Chu, Y., Æsøy, V., Bunes, Ø. and Pedersen, E. (2016) ‘Modeling and simulation of the accumulator during active heave compensation operations’, in *Proceedings of ASME International Conference on Offshore Mechanics and Arctic Engineering (OMAE)*. Busan, South Korea, p. V001T01A007.

Chu, Y., Æsøy, V., Ehlers, S. and Zhang, H. (2015) 'Integrated multi-domain system modelling and simulation for offshore crane operations', *Journal of Ship Technology Research*, 62(1), pp. 36–46.

Chu, Y., Æsøy, V., Zhang, H. and Bunes, O. (2014) 'Modelling And Simulation Of An Offshore Hydraulic Crane', in *Proceedings of 2014 28th European Conference on Modeling & Simulation (ECMS)*. Brescia, Italy, pp. 87–93.

Chu, Y., Deng, Y., Pedersen, B. S. and Zhang, H. (2016) 'Parameterization and Visualization of Marine Crane Concept Design', in *Proceedings of ASME International Conference on Offshore Mechanics and Arctic Engineering (OMAE)*. Busan, South Korea, p. V007T06A095.

Chu, Y., Hatledal, L. I., Æsøy, V., Ehlers, S. and Zhang, H. (2017) 'An Object-Oriented Modeling Approach to Virtual Prototyping of Marine Operation Systems Based on FMI Co-simulation', *Journal of Offshore Mechanics and Arctic Engineering*. ASME.

Chu, Y., Hatledal, L. I., Sanfilippo, F., Æsøy, V., Zhang, H. and Schaathun, H. G. (2015) 'Virtual prototyping system for maritime crane design and operation based on functional mock-up interface', in *Proceedings of MTS/IEEE OCEANS 2015*. Genova, Italy, pp. 1–4.

Chu, Y., Hatledal, L. I., Zhang, H., Æsøy, V. and Ehlers, S. (2017) 'Virtual Prototyping for Maritime Crane Design and Operations', *Journal of Marine Science and Technology*.

Chu, Y., Sanfilippo, F., Asoy, V. and Zhang, H. (2014) 'An effective heave compensation and anti-sway control approach for offshore hydraulic crane operations', in *Proceedings of IEEE 2014 International Conference on Mechatronics and Automation (ICMA)*. Tianjin,China, pp. 1282–1287.

Chu, Y., Zhang, H. and Wang, W. (2016) 'Enhancement of Virtual Simulator for Marine Crane Operations via Haptic Device with Force Feedback', in *Proceedings of EuroHaptics 2016 10th International Conference, Lecture notes in computer science: Haptics: Perception, Devices, Control, and Applications*. London, UK: Springer International Publishing, pp. 327–337.

Drenth, E., Törmänen, M., Johansson, K., Andersson, B.-A., Andersson, D., Torstensson, I. and Åkesson, J. (2014) 'Consistent Simulation Environment with FMI based Tool Chain', in *Proceedings of the 10 th International Modelica Conference*. Lund, Sweden, pp. 1277–1283.

Erdelyi, H., Prescott, W., Donders, S. and Anthonis, J. (2012) 'FMI implementation in LMS Virtual. Lab Motion and application to a vehicle dynamics case', in *Proceedings of the 9th International MODELICA Conference*. Munich; Germany: Linköping University Electronic Press, pp. 759–764.

Estefan, J. A. (2008) 'Survey of Model-Based Systems Engineering (MBSE) Methodologies', *Jet Propulsion*, 25, pp. 1–70.

Friedenthal, S., Moore, A. and Steiner, R. (2011) *A practical guide to SysML: The systems modeling language*. 3rd edn. Elsevier.

Ha, S., Kim, L., Park, S., Jun, C. and Rho, H. (2009) 'Virtual prototyping enhanced by a haptic interface', *CIRP Annals - Manufacturing Technology*, 58(1), pp. 135–138.

Halse, K. H., Æsøy, V., Ponkratov, D., Chu, Y., Xu, J. and Pedersen, E. (2014) 'Lifting Operations for Subsea Installations Using Small Construction Vessels and Active Heave Compensation Systems: A Simulation Approach', in *Proceedings of ASME. International Conference on Offshore Mechanics and Arctic Engineering*. San Francisco, California, USA, p. V01AT01A019.

Hameed, I. A., Bye, R. T., Osen, O. L., Pedersen, B. S. and Schaathun, H. G. (2016) 'Intelligent computer-automated crane design using an online crane prototyping tool', in *Proceedings of 30th European Conference on Modelling and Simulation, ECMS 2016*. Regensburg, Germany, pp. 564–573.

Hatecke, H. (2016) *Dynamic Stability of Heavy Lift Vessels During Loss of Tandem Load, Doctoral dissertation for the degree of Philosophiae Doctor (Ph.D.)*. Hamburg University of Technology.

Hatecke, H., Krüger, S., Christiansen, J. and Vorhölter, H. (2014) 'A Fast Sea-Keeping Simulation Method for Heavy-Lift Operations Based on Multi-Body System Dynamics', in *Proceedings of ASME. International Conference on Offshore Mechanics and Arctic Engineering*. San Francisco, California, USA, p. V01AT01A032.

Hatledal, L., Sanfilippo, F., Chu, Y. and Zhang, H. (2015) 'A Voxel-based Numerical Method for Computing and Visualising the Workspace of Offshore Cranes', in *Proceedings of ASME International Conference on Ocean, Offshore and Arctic Engineering*. St. John's, Newfoundland, Canada, p. V001T01A012.

Henningsson, M., Åkesson, J., Tummescheit, H., Neema, H., Gohl, J., Lattmann, Z., Sztipanovits, J., Karsai, G., Neema, S. and Bapty, T. (2014) 'An FMI-Based Tool for Robust Design of Dynamical Systems', in *10th International Modelica Conference*. Lund, Sweden, pp. 35–42.

Henriksen, J., Bak, M. K. and Hansen, M. R. (2011) 'A Method for Finite Element Based Modeling of Flexible Components in Time Domain Simulation of Knuckle Boom Crane', in *Proceedings of The 24th International Congress on Condition Monitoring and Diagnostics Engineering Management*. Stavanger, Norway, pp. 215–1224.

Holt, J. and Perry, S. (2013) *SysML for systems engineering: A Model-Based Approach*. 2nd edn, *Professional applications of computing series*. 2nd edn. The Institution of Engineering and Technology.

Jensen, J. C., Chang, D. H. and Lee, E. A. (2011) 'A model-based design methodology for cyber-physical systems', in *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th*

International. Istanbul, Turkey, pp. 1666–1671.

Kongsberg (2017) *Maritime Simulation*. Available at: https://www.kongsberg.com/en/kongsberg-digital/ (Accessed: 8 August 2017).

Krammer, M., Marko, N. and Benedikt, M. (2016) ‘Interfacing real-time systems for advanced co-simulation - The ACOSAR approach’, in *CEUR Workshop Proceedings*, pp. 32–39.

Ku, N., Ha, S. and Roh, M.-I. (2014) ‘Crane Modeling and Simulation in Offshore Structure Building Industry’, *International Journal of Computer Theory and Engineering*, 6(3), pp. 278–284.

Kübler, R. and Schiehlen, W. (2000) ‘Two Methods of Simulator Coupling’, *Mathematical and Computer Modelling of Dynamical Systems*, 6(2), pp. 93–113.

Küchler, S., Mahl, T., Neupert, J., Schneider, K. and Sawodny, O. (2011) ‘Active control for an offshore crane using prediction of the vessels motion’, *IEEE/ASME Transactions on Mechatronics*, 16(2), pp. 297–309.

Lau, H. Y. K., Mak, K. L. and Lu, M. T. H. (2003) ‘A virtual design platform for interactive product design and visualization’, *Journal of Materials Processing Technology*, 139(1–3 SPEC), pp. 402–407.

Lee, K.-Y., Cha, J.-H. and Park, K.-P. (2010) ‘Dynamic Response of a Floating Crane in Waves by Considering the Nonlinear Effect of Hydrostatic Force’, *Ship Technology Research*. Taylor & Francis, 57(1), pp. 64–73.

Li, P. and Wang, C. (2009) ‘Design and implementation of visual simulation system for shipborne crane control’, *2009 Chinese Control and Decision Conference*. Guilin, China, pp. 5482–5486.

Mengist, A., Asghar, A., Pop, A., Fritzson, P., Braun, W., Siemers, A. and Fritzson, D. (2015) ‘An Open-Source Graphical Composite Modeling Editor and Simulation Tool Based on FMI and TLM Co-Simulation’, in *11th International Modelica Conference*. Versailles, France: Linköping University Electronic Press, pp. 181–188.

Modelica Association (2000) *ModelicaTM - A Unified Object-Oriented Language for Physical Systems Modeling: Language Specification*.

Neema, H., Gohl, J., Lattmann, Z., Sztipanovits, J., Karsai, G., Neema, S., Bapty, T., Batteh, J., Tummescheit, H. and Sureshkumar, C. (2014) ‘Model-Based Integration Platform for FMI Co-Simulation and Heterogeneous Simulations of Cyber-Physical Systems’, in *Proceedings of the 10th International Modelica Conference*. Lund, Sweden, pp. 235–245.

Object Management Group (2011) *UML Profile For MARTE, version 1.1*.

OSC (2017) *Offshore Simulation Center*. Available at: http://osc.no/ (Accessed: 8 August 2017).

Pahl, G., Beitz, W., Feldhusen, J. and Grote, K.-H. (2007) *Engineering Design - A Systematic Approach*. 3rd edn. London, UK: Springer-Verlag London.

Parker, G., Graziano, M., Leban, F., Green, J. and Bird, J. D. (2007) 'Reducing Crane Payload Swing Using A Rider Block Tagline Control System', in *OCEANS 2007 - Europe*. Aberdeen, Scotland, United Kingdom, pp. 1–5.

Prats, M., Pérez, J., Fernández, J. J. and Sanz, P. J. (2012) 'An open source tool for simulation and supervision of underwater intervention missions', in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. Vilamoura-Algarve, Portugal, pp. 2577–2582.

Pulecchi, T., Casella, F. and Lovera, M. (2010) 'Object-oriented modelling for spacecraft dynamics: Tools and applications', *Simulation Modelling Practice and Theory*, 18(1), pp. 63–86.

Ramos, A. L., Ferreira, J. V. and Barceló, J. (2012) 'Model-based systems engineering: An emerging approach for modern systems', *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews*, 42(1), pp. 101–111.

Red, B. and Green, B. (2011) 'Model-View-Controller', *Structure*, (Mvc), pp. 125–143.

Rokseth, B., Skjong, S. and Pedersen, E. (2017) 'Modeling of Generic Offshore Vessel in Crane Operations With Focus on Strong Rigid Body Connections', *IEEE Journal of Oceanic Engineering*, 42(4), pp. 846–868.

Sadjina, S., Kyllingstad, L. T., Skjong, S. and Pedersen, E. (2017) 'Energy conservation and power bonds in co-simulations: non-iterative adaptive step size control and error estimation', *Engineering with Computers*, 33(3), pp. 607–620.

Schweizer, B., Li, P., Lu, D. and Meyer, T. (2015) 'Stabilized implicit co-simulation methods: solver coupling based on constitutive laws', *Archive of Applied Mechanics*, 85(11), pp. 1559–1594.

Skaare, B. and Egeland, O. (2006) 'Parallel force/position crane control in marine operations', *IEEE Journal of Oceanic Engineering*. IEEE, 31(3), pp. 599–613.

Skjong, S. and Pedersen, E. (2016) 'Model-based control designs for offshore hydraulic winch systems', *Ocean Engineering*, 121, pp. 224–238.

Slomka, F., Kollmann, S., Moser, S. and Kempf, K. (2011) 'A multidisciplinary design methodology for cyber-physical systems', in *Workshop Proceedings of Fourth International Workshop on Model Based Architecting and Construction of Embedded Systems*. Wellington, New Zealand, pp. 23–37.

Suh, N. P. (1990) *The principles of design*. Oxford University Press.

Takagawa, S. (2010) 'A new concept design of heave compensation system for longer life of cables', in

OCEANS'10 IEEE Sydney, OCEANSSYD 2010. Sydney, Australia, pp. 1–5.

Terashima, K., Ito, R., Noda, Y., Masui, Y. and Iwasa, T. (2010) 'Innovative integrated simulator for agile control design on shipboard crane considering ship and load sway', in *2010 IEEE International Conference on Control Applications*, pp. 1293–1300.

Thekkedan, M. Das, Chin, C. S. and Woo, W. L. (2015) 'Virtual reality simulation of fuzzy-logic control during underwater dynamic positioning', *Journal of Marine Science and Application*, 14(1), pp. 14–24.

Viel, A. (2014) 'Implementing stabilized co-simulation of strongly coupled systems using the Functional Mock-up Interface 2.0', in *Proceedings of the 10th International Modelica Conference*. Lund; Sweden: Linköping University Electronic Press; Linköpings universitet, pp. 213–223.

Völter, M., Stahl, T., Bettin, J., Haase, A. and Helsen, S. (2013) *Model-driven software development: technology, engineering, management*. John Wiley & Sons.

Vorhölter, H., Christiansen, J. and Hatecke, H. (2014) 'Universal Crane Model for the Ship Design System E4', in *Proceedings of ASME International Conference on Ocean, Offshore and Arctic Engineering*. San Francisco, California, USA, p. V01AT01A036.

Vorhölter, H., Hatecke, H. and Feder, D. (2015) 'Design Study of Floating Crane Vessels for Lifting Operations in the Offshore Wind Industry', *International Marine Design Conference*, 2, pp. 273–285.

Vortex (2017) *Vortex port equipment simulators*. Available at: https://www.cm-labs.com/ (Accessed: 8 August 2017).

Wang, G. (2002) 'Definition and Review of Virtual Prototyping', *Journal of Computing and Information Science in Engineering*, 2(3), pp. 232–237.

References

Appendix A A Tutorial for Component Model Development

Component-based multi-objective model development based on the Object-Oriented Modeling approach

A physical system can be decomposed into several components. A component can be represented by a set of state variables describing its physics and dynamic behaviors. Depending on the selection of states for modeling, the component model representing a component, (i.e., an object by the definition of OOM), may have several alternative implementations. These implementations for one component model share the same *simulation* interfaces, which are the inputs and outputs to other interactive component models. The representations and *user* interfaces which are defined as a selection of the properties for the user, can be different, whether they are dimensional parameters for modeling, simulation initials or state variables for plotting and visualization.

Model Implementations

- Model simplification must reflect the basic behavior of the component at least, and include the properties that affect the characteristics of the sub-system and system. Other interested properties for certain simulation purposes can be included.
- State variables are a selection of variables describes the behaviors of the component depending on the model simplification.
- Causality, preferred input and output, defines the interactive relations of the component model to its adherent component models.
- Integration methods matter for the simulation performance. Specifically for stiff systems, implicit multi-step such as BDF, MBDF and variable time step methods such as Vode Adams are better than explicit fixed-step methods like Euler, Runge-Kutta, etc.
- Simulation time step (macro step for co-simulation) and computation time step (micro step for computation) needs to be treated cautiously, when e.g., computational-stiff sub-models are included, or strongly-coupled systems are separated for modelling and integrated via co-simulation.

Graphical Representations

- Using iconic diagram for the component model representing the different alternatives of the model implementations
- Using bond graphs for the model implementations representing the behaviors of the component

Interfaces

- Using general naming for the interfaces, e.g., *p* indicating port, *pi* as the input port and *po* as the output port
- In the case of multiple input and output ports, use descriptive names instead of numbers to make it clearer for connecting other sub-models

- Use descriptive names for the *dimensioning* parameters and *state* variables to support model modifications for design exploration and data exchange for plotting and visualization
- Within one component, "local globals" are globally assigned to all the lower level sub-models and elements of the component model; "global globals" can be used, but can be defined as "local globals" as well in case of missing of the assignment of values in an integrated model. These variables can be, e.g., density, surrounding temperature, atmosphere pressure, etc.

Behavior Model

- Define the variables according to the causality
- Use engineering units when defining parameters and variables, and convert to IS units when implementing the constitutive equations
- Avoid having nonlinear expressions in simplified model implementations

Model Libraries

To support system model development, component model libraries are developed in various domains, e.g. hydraulics, mechanical, electrical, and thermal, etc.

Installation

Copy the library folders to the installation folder of the program C:\Program Files (x86)\20-sim 4.6\Models\Library. Restart the program, the libraries will be included in the library tree of the editor window, as shown in Fig. 1.

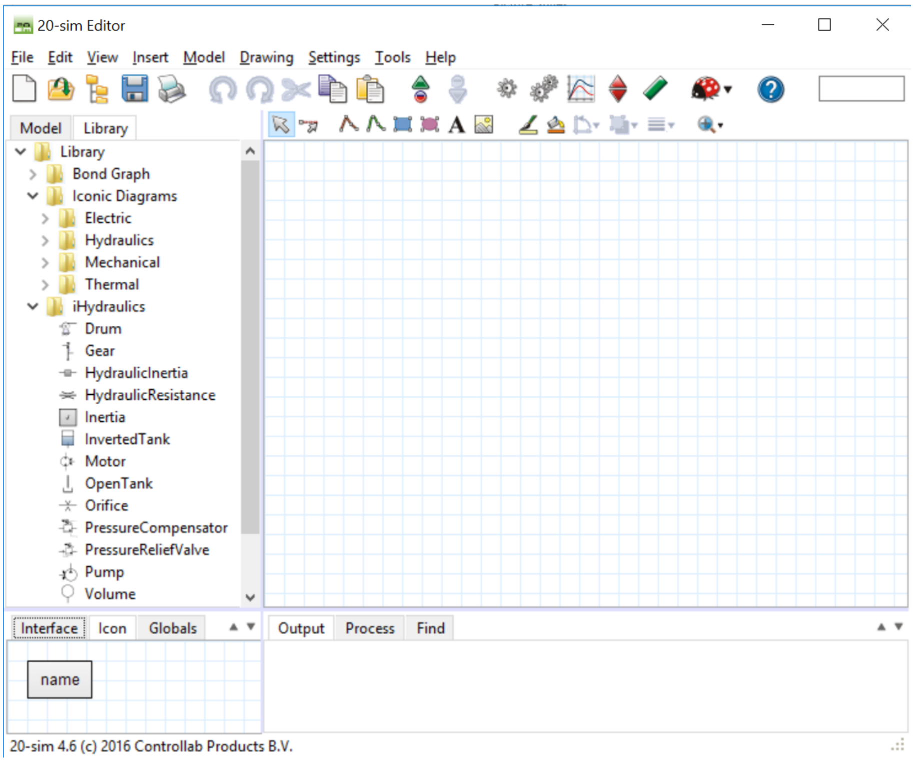
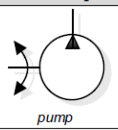
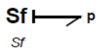
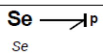
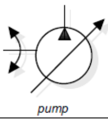
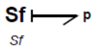
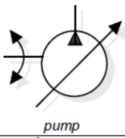
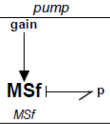


Fig. 1 Customized component model libraries in the editor

The main components of the hydraulic systems based on the KBC include the followings:

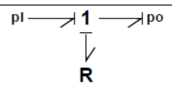
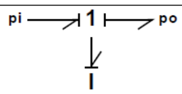
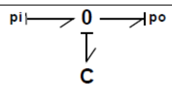
1.1. Hydraulic Pump

Hydraulic pump delivers flow to the system providing pressure.

Model Implementation	**Model Representation**	**Interface**		**Model Behavior**
	Icon Diagram / Bond Graph	Input & Output / Causality	Parameters & Variables	Variables {unit}
Constant Flow Source		p	Displacement ξ {m^3/rev} Speed rpm {rev/min}	$\dot{V} = \frac{\xi \cdot rpm}{60}$
		Flow Out		Flow rate $\dot{V}$ {l/min}
Constant Effort Source		p	Set Pressure P_{set} {bar}	$P = P_{set}$
		Pressure Out		Pressure P {bar}
Pressure Proportional Flow Source		p	Set Pressure P_{set} {bar} Output Pressure P {bar} Pressure Deviation for full flow ΔP {bar} Displacement ξ {m^3/rev} Speed rpm {rev/min}	$\dot{V} = \begin{cases} \frac{P_{set} - P}{\Delta P} \cdot \frac{\xi \cdot rpm}{60}, & P < P_{set} \\ 0, & P \geq P_{set} \end{cases}$
		Flow Out		Flow rate $\dot{V}$ {l/min}
Variable Flow Source		p	Gain k Displacement ξ {m^3/rev} Speed rpm {rev/min}	$\dot{V} = k * \frac{\xi \cdot rpm}{60}$
		Flow Out		Flow rate $\dot{V}$ {l/min}

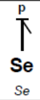
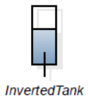
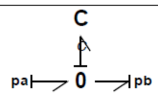
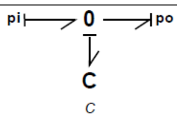
1.2. Fluid Dynamics

Fluid in the pipeline may cause stability problems to the system. Dynamics of fluid flow in the pipeline between the components consists of the properties such as inertia effect, friction loss, and fluid compressibility.

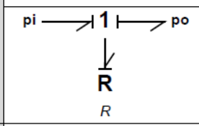
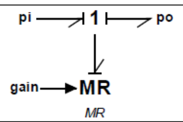
Model Implementation	**Model Representation**	**Interface**		**Model Behavior**
	Icon Diagram	Input & Output	Parameters & Variables	Variables {unit}
	Bond Graph	Causality		
Resistance[1]	 HydraulicResistance	pi, po	Diameter d Length l Density ρ Viscosity μ Roughness r	$A = \frac{\pi \cdot d^2}{4}$ $\Delta P = f \cdot \frac{1}{2} \cdot \frac{L}{d} \cdot \rho \cdot (\frac{\dot{V}}{A})^2$
	 R	flow in, pressure out		Pressure loss ΔP {bar}
Inertia	 FluidInertia	pi, po	Density ρ Viscosity μ Diameter d Length l Roughness r	$A = \frac{\pi \cdot d^2}{4}$ $\int \Delta P \cdot dt = \frac{\rho \cdot l}{A} \cdot \dot{V}$
	 I	pressure in, flow out		Flow $\dot{V}$ {l/min}
Compressibility[2]	 FluidCompressibility	pi, po	Diameter d Length l Bulk Modulus β Initial Pressure P_0	$A = \frac{\pi \cdot d^2}{4}$ $P = \frac{\beta}{A \cdot l} \int \Delta\dot{V} \cdot dt$
	 C	flow in, pressure out		Pressure P {bar}

[1]*Fluid flow friction factor f is dependent on the flow pattern in the pipeline, which can be obtained by calculating the Reynold's number.*
[2]*Bulk Modulus is assumed as constant.*

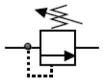
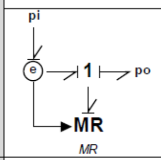
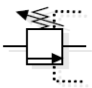
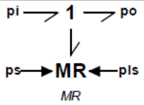
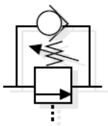
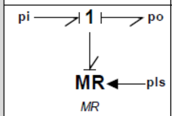
1.3. Volume

Model Implementation	**Model Representation**	**Interface**		**Model Behavior**
	Icon Diagram / Bond Graph	Input & Output / Causality	Parameters & Variables	Variables {unit}
Open tank		p	Set Pressure P_{set}	$P = P_{set}$
		pressure out		Pressure {bar}
Incompressible fluid		pi, po	Density ρ Diameter d Initial Height h_0	$P = \rho \cdot g \cdot h = \rho \cdot g \cdot \frac{\int \dot{V}\, dt}{A}$
		flow in, pressure out		Pressure {bar}
Control volume		pi, po	Bulk Modulus β Initial Pressure P_0 Control Volume V	$P = \frac{\beta}{V} \int \Delta\dot{V} \cdot dt$
		flow in, pressure out		Pressure {bar}

1.4. Flow Restriction

Model Implementation	Model Representation	Interface		Model Behavior
	Icon Diagram / Bond Graph	Input & Output / Causality	Parameters & Variables	Variables {unit}
Orifice (fixed opening)		pi, po	Density ρ Discharge Coefficient cd Diameter d	$A = \frac{\pi \cdot d^2}{4}$ $\dot{V} = cd \cdot A \sqrt{\frac{2 \cdot \lvert P \rvert}{\rho}} \cdot sgn(P)$
		pressure in, flow out		Flow $\dot{V}$ {l/min}
Orifice (variable opening)		pr, pi, po	Gain k Density ρ Discharge Coefficient cd Diameter d	$\dot{V} = k * cd \cdot A \sqrt{\frac{2 \cdot \lvert P \rvert}{\rho}} \cdot sgn(P)$
		pressure in, flow out		Flow $\dot{V}$ {l/min}

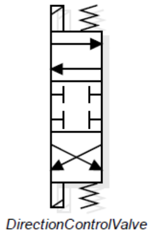
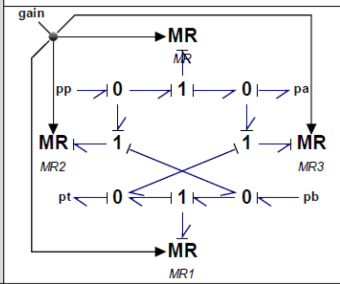
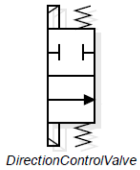
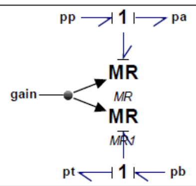
1.5. Pressure Control Valve

Model Implementation	**Model Representation**: Icon Diagram / Bond Graph	**Interface**: Input & Output Causality	**Interface**: Parameters & Variables	**Model Behavior**: Variables {unit}
Pressure Relieve Valve	 PressureReliefValve	pi, po	Open Pressure ΔP_{open} Diameter d Density ρ Discharge Coefficient cd	$A=\frac{\pi\cdot d^2}{4}$ $\dot{V}=\begin{cases} cd\cdot A\sqrt{\frac{2\cdot\lvert P\rvert}{\rho}}\cdot sgn(P), \Delta P>\Delta P_{open} \\ 0, \Delta P<\Delta P_{open}\end{cases}$
		pressure in, flow out		Flow rate $\dot{V}$ {l/min}
Pressure Compensator[1]	 PressureCompensator	pi, po, ps, pls	Density ρ Compensator Pressure ΔP_{set} Flowdp5 $\dot{V}_{dp5}$ Discharge Coefficient cd	$k=\frac{\Delta P_{set}-\Delta P}{\Delta P_{set}}$ $\dot{V}=\begin{cases} k\cdot cd\cdot A\sqrt{\frac{2\cdot\lvert P\rvert}{\rho}}\cdot sgn(P), \Delta P<\Delta P_{set} \\ 0, \Delta P\geq\Delta P_{set}\end{cases}$
		pressure in, flow out		Flow $\dot{V}$ {l/min}
Counter balance valve[2]	 CounterBalanceValve	pls, pa, pb	Density ρ Flowdp5 $\dot{V}_{max}$ Open Pressure P_{open} Cracking Pressure P_{max} Discharge Coefficient cd	$k=-\frac{P_{ls}-P_{open}}{P_{max}-P_{open}}$ $\dot{V}=\begin{cases} cd\cdot A\cdot\sqrt{\frac{2\cdot\lvert P\rvert}{\rho}}\cdot sgn(P), P>0 \\ k\cdot cd\cdot A\cdot\sqrt{\frac{2\cdot\lvert P\rvert}{\rho}}\cdot sgn(P), P<0\ \&\ P_{ls}>P_{opn}\end{cases}$
		pressure in, flow out		Flow $\dot{V}$ {l/min}

[1]*The opening area of the valve is calculated from the flow-pressure drop characteristic chart given by the valve vender.*

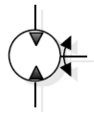
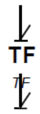
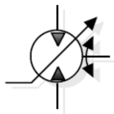
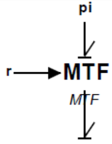
[2]*The opening of the valve is controlled by the load sensing pressure when the cylinder is subject to negative load, which means the speed and external force are in the same direction.*

1.6. Direction Control Valve

Model Implementation	**Model Representation** – Icon Diagram / Bond Graph	**Interface** – Input & Output / Causality	**Interface** – Parameters & Variables	**Model Behavior** – Variables {unit}
4-way-3-position[1]		pp, pa, pb, pt	Density ρ Dead band δx Area A Discharge Coefficient cd	$\dot{V} = \frac{x-\delta x}{1-\delta x} \cdot cd \cdot A \cdot \sqrt{\frac{2 \cdot \lvert P \rvert}{\rho}} \cdot sgn(P)$
		pressure in, flow out		Flow $\dot{V}$ {l/min}
2-way-2-position[2]		pp, pa, pb, pt	Gain k Density ρ Area A Discharge Coefficient cd	$\dot{V} = cd \cdot A \cdot \sqrt{\frac{2 \cdot \lvert P \rvert}{\rho}} \cdot sgn(P)$
		pressure in, flow out		Flow $\dot{V}$ {l/min}

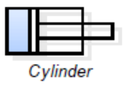
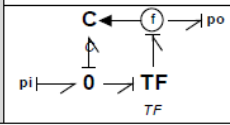
[1]*The opening areas of the ports are controlled by the relative spool positon x from the valve controller. Use if- then-else or switch-case logic in the coding.*
[2]*2-way-2-position valve is an on-off valve.*

1.7. Motor

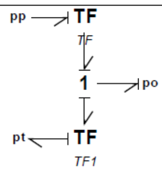
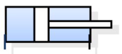
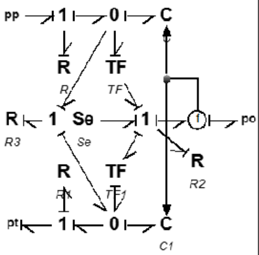
Model Implementation	**Model Representation**	**Interface**		**Model Behavior**
	Icon Diagram	Input & Output	Parameters & Variables	Variables {unit}
	Bond Graph	Causality		
Fixed Displacement Motor		pi, po	Displacement ξ {m^3/rev}	$T = \frac{\xi}{2 \cdot \pi} \cdot P$ $\dot{V} = \frac{\xi}{2 \cdot \pi} \cdot \omega$
		pressure in , flow out		Torque T {kN} Flow $\dot{V}$ {l/min}
Variable Displacement Motor[1]		pi, po	Gain k Displacement ξ {m^3/rev}	$T = \frac{r \cdot \xi}{2 \cdot \pi} \cdot P$ $\dot{V} = \frac{r \cdot \xi}{2 \cdot \pi} \cdot \omega$
		pressure in, flow out		Torque T {kN} Flow $\dot{V}$ {l/min}

[1]*The variable motor displacement is controlled by the output gain of the motor controller r.*

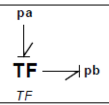
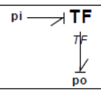
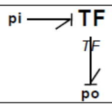
1.8. Single-Acting Cylinder

Model Implementation	Model Representation	Interface		Model Behavior
	Icon Diagram / Bond Graph	Input & Output / Causality	Parameters & Variables	Variables {unit}
Single-Acting		pi, po	Bulk Modulus β Initial Pressure P_0 Diameter d Initial Displacement x_0 Dead Volume V_0 Stroke s	$A = \frac{\pi \cdot d^2}{4}$ $V = x \cdot A \subseteq [V_0, (x_0 + s) \cdot A]$ $P = \frac{\beta}{V} \int \Delta\dot{V} \cdot dt$ $F = A \cdot P$
		flow in, force out		Pressure {bar} Force {kN}

1.9. Double-Acting Cylinder

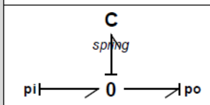
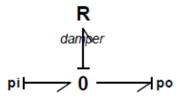
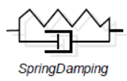
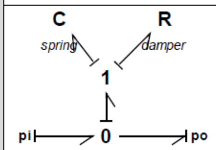
Model Implementation	**Model Representation**	**Interface**		**Model Behavior**
	Icon Diagram / Bond Graph	Input & Output / Causality	Parameters & Variables	Variables {unit}
Double-Acting - Simplified		pp, pt, po	Diameter d	$A = \frac{\pi \cdot d^2}{4}$ $F = A \cdot P$
		pressure in, force out		Force {kN}
Double-Acting - Extended		pp, pt, po	Density ρ Inlet Diameter d_i Discharge Coefficient cd Bulk Modulus β Initial Pressure P_0 Piston Diameter d_{pstn} Rod Diameter d_{rod} Friction Factor f Dead Volume V_0 Initial Displacement x_0 Stroke s Bumper Stiffness k Bumper Damping Factor c	$A = \frac{\pi \cdot d^2}{4}$ $\dot{V} = cd \cdot A \cdot \sqrt{\frac{2 \cdot \lvert P \rvert}{\rho}} \cdot sgn(P)$ $V = x \cdot A \subseteq [V_0, (x_0 + s) \cdot A]$ $P = \frac{\beta}{V} \int \Delta\dot{V} \cdot dt$ $F = A \cdot P$ $F_f = f \cdot v$ $F_b = \begin{cases} -k \cdot (\delta - x) - c \cdot v, x < \delta \\ 0, \delta < x < \delta + s \\ -k \cdot (x - s - \delta) - c \cdot v, x > \delta + s \end{cases}$
		flow in, force out		Pressure Loss {bar} Leakage Loss {l/min} Pressure {bar} Force {kN} Friction Force {kN}

1.10. Transmission

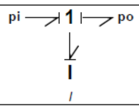
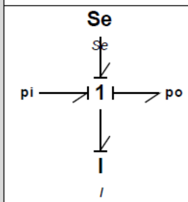
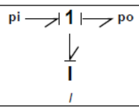
Model Implementation	Model Representation: Icon Diagram / Bond Graph	Interface: Input & Output / Causality	Interface: Parameters & Variables	Model Behavior: Variables {unit}
Gear	 Gear	pi, po	Gear Ratio i	$T_o = T_i / i$ $\omega_o = \omega_i \cdot i$
		torque in, torque out		Torque T_o {kNm} Speed ω_o {rpm}
Winch drum	 Drum	pi, po	Drum Radius r	$F_o = T_i / r$ $v_o = \omega_i \cdot r$
		torque in, force out		Force T_o {kNm} Speed v_o {m/s}
Winch with wire[1]	 Drum	pi, po	Wire Length L_{max} Initial Wire Length L_0 Wire Diameter d Drum Radius r Drum Width b	$F_o = T_i / \sqrt{r^2 + \frac{k \cdot d^2}{\pi \cdot b} \cdot L}$ $v_o = \omega_i \cdot \sqrt{r^2 + \frac{k \cdot d^2}{\pi \cdot b} \cdot L}$
		torque in, force out		Force F_o {kNm} Speed v_o {m/s}

[1] *The winch radius with wire is calculated by winch drum radius plus the wire on the winch drum with a packing factor k.*

1.11. Spring-Damper

Model Implementation	**Model Representation**	**Interface**		**Model Behavior**
	Icon Diagram / Bond Graph	Input & Output / Causality	Parameters & Variables	Variables {unit}
Spring		pi, po	Spring Stiffness k	$F_k = k \cdot \int v\,dt$
		velocity in, force out		Spring Force F_k {kN}
Damper		pi, po	Damping Factor c	$F_c = c \cdot v$
		velocity in, force out		Damping Force F_c {kN}
Spring-Damper		pi, po	Spring Stiffness k Damping Factor c	$F_k = k \cdot \int v\,dt$ $F_c = c \cdot v$
		velocity in, forces out		Spring Force F_k {kN} Damping Force F_c {kN}

1.12. Mass/Inertia

Model Implementation	Model Representation: Icon Diagram / Bond Graph	Interface: Input & Output / Causality	Interface: Parameters & Variables	Model Behavior: Variables {unit}
Mass-horizontal		pi, po	Mass m	$v = \frac{\int F\,dt}{m}$
		force in, velocity out		Velocity v {m/s}
Mass-vertical		pi, po	Mass m	$F_g = m \cdot g$ $v = \frac{\int F\,dt}{m}$
		force in, velocity out		Gravity force F_g {kN} Velocity v {m/s}
Inertia-rotational		pi, po	Inertia i	$\omega = \frac{\int F\,dt}{i}$
		torque in, angular velocity out		Angular velocity ω {deg/s}

Appendix B Publications

I. Chu, Y., Æsøy, V., Ehlers, S. and Zhang, H., 2015. Integrated multi-domain system modelling and simulation for offshore crane operations. Ship Technology Research, 62(1), pp.36-46.

II. Chu, Y. and Æsøy, V., 2015. A Multi-Body Dynamic Model Based on Bond Graph for Maritime Hydraulic Crane Operations. In ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering, St. John's, Newfoundland, Canada, p. V001T01A010.

III. Chu, Y., Deng, Y., Pedersen, B.S. and Zhang, H., 2016. Parameterization and Visualization of Marine Crane Concept Design. In ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering, Busan, South Korea, p. V007T06A095.

IV. Chu, Y., Hatledal. L. I., Æsøy, V., Ehlers, S. and Zhang, H., 2015. Virtual prototyping for marine crane design and operations, Journal of Marine Science and Technology, first online Nov. 2017.

VI. Chu, Y., Hatledal. L. I., Æsøy, V., Ehlers, S. and Zhang, H., 2015. An Object-Oriented Modeling Approach to Virtual Prototyping of Marine Operation Systems Based on on Functional Mock-up Interface Co-simulation, Journal of Offshore Mechanics and Arctic Engineering, 140(2), first online Nov, 2017.

Paper 1: Chu, Yingguang; Æsøy, Vilmar; Ehlers, Sören; Zhang, Houxiang. Integrated multi-domain system modelling and simulation for offshore crane operations. Ship Technology Research 2015 ;Volum 62.(1) s. 36-46. DOI: http://doi.org/10.1179/0937725515Z.0000000004

Paper 2: Chu, Yingguang; Æsøy, Vilmar. A multi-body dynamic model based on bond graph for maritime hydraulic crane operations. I: ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering. ASME Press 2015. s. V001T01A010. DOI: http://doi.org/10.1115/OMAE2015-41616

Paper 3: Chu, Yingguang; Pedersen, Birger Skogeng; Zhang, Houxiang. Parameterization and Visualization of Marine Crane Concept Design. I: ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering - Volume 7: Ocean Engineering. ASME Press 2016. s. V007T06A095. DOI: http://doi.org/10.1115/OMAE2016-54448

Is not included due to copyright

Paper 4: Chu, Yingguang; Hatledal, Lars Ivar; Zhang, Houxiang; Æsøy, Vilmar; Ehlers, Sören. Virtual prototyping for maritime crane design and operations. Journal of Marine Science and Technology 2017 s. 1-13. DOI: http://doi.org/10.1007/s00773-017-0509-z

Is not included due to copyright

Paper 5: Chu, Yingguang; Hatledal, Lars Ivar; Æsøy, Vilmar; Ehlers, Sören; Zhang, Houxiang. An Object-Oriented Modeling Approach to Virtual Prototyping of Marine Operation Systems Based on Functional Mock-Up Interface Co-Simulation. Journal of Offshore Mechanics and Arctic Engineering 2018 ;Volum 140.(2) s. DOI: http://doi.org/10.1115/1.4038346

Previous PhD theses published at the Departement of Marine Technology (earlier: Faculty of Marine Technology) NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Report No.	**Author**	**Title**
	Kavlie, Dag	Optimization of Plane Elastic Grillages, 1967
	Hansen, Hans R.	Man-Machine Communication and Data-Storage Methods in Ship Structural Design, 1971
	Gisvold, Kaare M.	A Method for non-linear mixed -integer programming and its Application to Design Problems, 1971
	Lund, Sverre	Tanker Frame Optimalization by means of SUMT-Transformation and Behaviour Models, 1971
	Vinje, Tor	On Vibration of Spherical Shells Interacting with Fluid, 1972
	Lorentz, Jan D.	Tank Arrangement for Crude Oil Carriers in Accordance with the new Anti-Pollution Regulations, 1975
	Carlsen, Carl A.	Computer-Aided Design of Tanker Structures, 1975
	Larsen, Carl M.	Static and Dynamic Analysis of Offshore Pipelines during Installation, 1976
UR-79-01	Brigt Hatlestad, MK	The finite element method used in a fatigue evaluation of fixed offshore platforms. (Dr.Ing. Thesis)
UR-79-02	Erik Pettersen, MK	Analysis and design of cellular structures. (Dr.Ing. Thesis)
UR-79-03	Sverre Valsgård, MK	Finite difference and finite element methods applied to nonlinear analysis of plated structures. (Dr.Ing. Thesis)
UR-79-04	Nils T. Nordsve, MK	Finite element collapse analysis of structural members considering imperfections and stresses due to fabrication. (Dr.Ing. Thesis)
UR-79-05	Ivar J. Fylling, MK	Analysis of towline forces in ocean towing systems. (Dr.Ing. Thesis)
UR-80-06	Nils Sandsmark, MM	Analysis of Stationary and Transient Heat Conduction by the Use of the Finite Element Method. (Dr.Ing. Thesis)
UR-80-09	Sverre Haver, MK	Analysis of uncertainties related to the stochastic modeling of ocean waves. (Dr.Ing. Thesis)
UR-81-15	Odland, Jonas	On the Strength of welded Ring stiffened cylindrical Shells primarily subjected to axial Compression
UR-82-17	Engesvik, Knut	Analysis of Uncertainties in the fatigue Capacity of

		Welded Joints
UR-82-18	Rye, Henrik	Ocean wave groups
UR-83-30	Eide, Oddvar Inge	On Cumulative Fatigue Damage in Steel Welded Joints
UR-83-33	Mo, Olav	Stochastic Time Domain Analysis of Slender Offshore Structures
UR-83-34	Amdahl, Jørgen	Energy absorption in Ship-platform impacts
UR-84-37	Mørch, Morten	Motions and mooring forces of semi submersibles as determined by full-scale measurements and theoretical analysis
UR-84-38	Soares, C. Guedes	Probabilistic models for load effects in ship structures
UR-84-39	Aarsnes, Jan V.	Current forces on ships
UR-84-40	Czujko, Jerzy	Collapse Analysis of Plates subjected to Biaxial Compression and Lateral Load
UR-85-46	Alf G. Engseth, MK	Finite element collapse analysis of tubular steel offshore structures. (Dr.Ing. Thesis)
UR-86-47	Dengody Sheshappa, MP	A Computer Design Model for Optimizing Fishing Vessel Designs Based on Techno-Economic Analysis. (Dr.Ing. Thesis)
UR-86-48	Vidar Aanesland, MH	A Theoretical and Numerical Study of Ship Wave Resistance. (Dr.Ing. Thesis)
UR-86-49	Heinz-Joachim Wessel, MK	Fracture Mechanics Analysis of Crack Growth in Plate Girders. (Dr.Ing. Thesis)
UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)
UR-86-51	Walter Lian, MH	A Numerical Study of Two-Dimensional Separated Flow Past Bluff Bodies at Moderate KC-Numbers. (Dr.Ing. Thesis)
UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)
UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)
UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)
UR-86-55	Sigurd Falch, MH	A Numerical Study of Slamming of Two-Dimensional Bodies. (Dr.Ing. Thesis)
UR-87-56	Arne Braathen, MH	Application of a Vortex Tracking Method to the Prediction of Roll Damping of a Two-Dimension Floating Body. (Dr.Ing. Thesis)

UR-87-57	Bernt Leira, MK	Gaussian Vector Processes for Reliability Analysis involving Wave-Induced Load Effects. (Dr.Ing. Thesis)
UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
MTA-88-59	Bernt Arild Bremdal, MP	An Investigation of Marine Installation Processes – A Knowledge - Based Planning Approach. (Dr.Ing. Thesis)
MTA-88-60	Xu Jun, MK	Non-linear Dynamic Analysis of Space-framed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
MTA-89-63	Chang Li, MH	Force Coefficients of Spheres and Cubes in Oscillatory Flow with and without Current. (Dr.Ing. Thesis
MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
MTA-89-65	Arild Jæger, MH	Seakeeping, Dynamic Stability and Performance of a Wedge Shaped Planing Hull. (Dr.Ing. Thesis)
MTA-89-66	Chan Siu Hung, MM	The dynamic characteristics of tilting-pad bearings
MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
MTA-89-68	Jiao Guoyang, MK	Reliability Analysis of Crack Growth under Random Loading, considering Model Updating. (Dr.Ing. Thesis)
MTA-89-69	Arnt Olufsen, MK	Uncertainty and Reliability Analysis of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-70	Wu Yu-Lin, MR	System Reliability Analyses of Offshore Structures using improved Truss and Beam Models. (Dr.Ing. Thesis)
MTA-90-71	Jan Roger Hoff, MH	Three-dimensional Green function of a vessel with forward speed in waves. (Dr.Ing. Thesis)
MTA-90-72	Rong Zhao, MH	Slow-Drift Motions of a Moored Two-Dimensional Body in Irregular Waves. (Dr.Ing. Thesis)
MTA-90-73	Atle Minsaas, MP	Economical Risk Analysis. (Dr.Ing. Thesis)
MTA-90-74	Knut-Aril Farnes, MK	Long-term Statistics of Response in Non-linear Marine Structures. (Dr.Ing. Thesis)
MTA-90-75	Torbjørn Sotberg, MK	Application of Reliability Methods for Safety Assessment of Submarine Pipelines. (Dr.Ing.

		Thesis)
MTA-90-76	Zeuthen, Steffen, MP	SEAMAID. A computational model of the design process in a constraint-based logic programming environment. An example from the offshore domain. (Dr.Ing. Thesis)
MTA-91-77	Haagensen, Sven, MM	Fuel Dependant Cyclic Variability in a Spark Ignition Engine - An Optical Approach. (Dr.Ing. Thesis)
MTA-91-78	Løland, Geir, MH	Current forces on and flow through fish farms. (Dr.Ing. Thesis)
MTA-91-79	Hoen, Christopher, MK	System Identification of Structures Excited by Stochastic Load Processes. (Dr.Ing. Thesis)
MTA-91-80	Haugen, Stein, MK	Probabilistic Evaluation of Frequency of Collision between Ships and Offshore Platforms. (Dr.Ing. Thesis)
MTA-91-81	Sødahl, Nils, MK	Methods for Design and Analysis of Flexible Risers. (Dr.Ing. Thesis)
MTA-91-82	Ormberg, Harald, MK	Non-linear Response Analysis of Floating Fish Farm Systems. (Dr.Ing. Thesis)
MTA-91-83	Marley, Mark J., MK	Time Variant Reliability under Fatigue Degradation. (Dr.Ing. Thesis)
MTA-91-84	Krokstad, Jørgen R., MH	Second-order Loads in Multidirectional Seas. (Dr.Ing. Thesis)
MTA-91-85	Molteberg, Gunnar A., MM	The Application of System Identification Techniques to Performance Monitoring of Four Stroke Turbocharged Diesel Engines. (Dr.Ing. Thesis)
MTA-92-86	Mørch, Hans Jørgen Bjelke, MH	Aspects of Hydrofoil Design: with Emphasis on Hydrofoil Interaction in Calm Water. (Dr.Ing. Thesis)
MTA-92-87	Chan Siu Hung, MM	Nonlinear Analysis of Rotordynamic Instabilities in Highspeed Turbomachinery. (Dr.Ing. Thesis)
MTA-92-88	Bessason, Bjarni, MK	Assessment of Earthquake Loading and Response of Seismically Isolated Bridges. (Dr.Ing. Thesis)
MTA-92-89	Langli, Geir, MP	Improving Operational Safety through exploitation of Design Knowledge - an investigation of offshore platform safety. (Dr.Ing. Thesis)
MTA-92-90	Sævik, Svein, MK	On Stresses and Fatigue in Flexible Pipes. (Dr.Ing. Thesis)
MTA-92-91	Ask, Tor Ø., MM	Ignition and Flame Growth in Lean Gas-Air Mixtures. An Experimental Study with a Schlieren System. (Dr.Ing. Thesis)
MTA-86-92	Hessen, Gunnar, MK	Fracture Mechanics Analysis of Stiffened Tubular Members. (Dr.Ing. Thesis)

MTA-93-93	Steinebach, Christian, MM	Knowledge Based Systems for Diagnosis of Rotating Machinery. (Dr.Ing. Thesis)
MTA-93-94	Dalane, Jan Inge, MK	System Reliability in Design and Maintenance of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-93-95	Steen, Sverre, MH	Cobblestone Effect on SES. (Dr.Ing. Thesis)
MTA-93-96	Karunakaran, Daniel, MK	Nonlinear Dynamic Response and Reliability Analysis of Drag-dominated Offshore Platforms. (Dr.Ing. Thesis)
MTA-93-97	Hagen, Arnulf, MP	The Framework of a Design Process Language. (Dr.Ing. Thesis)
MTA-93-98	Nordrik, Rune, MM	Investigation of Spark Ignition and Autoignition in Methane and Air Using Computational Fluid Dynamics and Chemical Reaction Kinetics. A Numerical Study of Ignition Processes in Internal Combustion Engines. (Dr.Ing. Thesis)
MTA-94-99	Passano, Elizabeth, MK	Efficient Analysis of Nonlinear Slender Marine Structures. (Dr.Ing. Thesis)
MTA-94-100	Kvålsvold, Jan, MH	Hydroelastic Modelling of Wetdeck Slamming on Multihull Vessels. (Dr.Ing. Thesis)
MTA-94-102	Bech, Sidsel M., MK	Experimental and Numerical Determination of Stiffness and Strength of GRP/PVC Sandwich Structures. (Dr.Ing. Thesis)
MTA-95-103	Paulsen, Hallvard, MM	A Study of Transient Jet and Spray using a Schlieren Method and Digital Image Processing. (Dr.Ing. Thesis)
MTA-95-104	Hovde, Geir Olav, MK	Fatigue and Overload Reliability of Offshore Structural Systems, Considering the Effect of Inspection and Repair. (Dr.Ing. Thesis)
MTA-95-105	Wang, Xiaozhi, MK	Reliability Analysis of Production Ships with Emphasis on Load Combination and Ultimate Strength. (Dr.Ing. Thesis)
MTA-95-106	Ulstein, Tore, MH	Nonlinear Effects of a Flexible Stern Seal Bag on Cobblestone Oscillations of an SES. (Dr.Ing. Thesis)
MTA-95-107	Solaas, Frøydis, MH	Analytical and Numerical Studies of Sloshing in Tanks. (Dr.Ing. Thesis)
MTA-95-108	Hellan, Øyvind, MK	Nonlinear Pushover and Cyclic Analyses in Ultimate Limit State Design and Reassessment of Tubular Steel Offshore Structures. (Dr.Ing. Thesis)
MTA-95-109	Hermundstad, Ole A., MK	Theoretical and Experimental Hydroelastic Analysis of High Speed Vessels. (Dr.Ing. Thesis)
MTA-96-110	Bratland, Anne K., MH	Wave-Current Interaction Effects on Large-Volume Bodies in Water of Finite Depth. (Dr.Ing. Thesis)
MTA-96-111	Herfjord, Kjell, MH	A Study of Two-dimensional Separated Flow by a Combination of the Finite Element Method and

		Navier-Stokes Equations. (Dr.Ing. Thesis)
MTA-96-112	Æsøy, Vilmar, MM	Hot Surface Assisted Compression Ignition in a Direct Injection Natural Gas Engine. (Dr.Ing. Thesis)
MTA-96-113	Eknes, Monika L., MK	Escalation Scenarios Initiated by Gas Explosions on Offshore Installations. (Dr.Ing. Thesis)
MTA-96-114	Erikstad, Stein O., MP	A Decision Support Model for Preliminary Ship Design. (Dr.Ing. Thesis)
MTA-96-115	Pedersen, Egil, MH	A Nautical Study of Towed Marine Seismic Streamer Cable Configurations. (Dr.Ing. Thesis)
MTA-97-116	Moksnes, Paul O., MM	Modelling Two-Phase Thermo-Fluid Systems Using Bond Graphs. (Dr.Ing. Thesis)
MTA-97-117	Halse, Karl H., MK	On Vortex Shedding and Prediction of Vortex-Induced Vibrations of Circular Cylinders. (Dr.Ing. Thesis)
MTA-97-118	Igland, Ragnar T., MK	Reliability Analysis of Pipelines during Laying, considering Ultimate Strength under Combined Loads. (Dr.Ing. Thesis)
MTA-97-119	Pedersen, Hans-P., MP	Levendefiskteknologi for fiskefartøy. (Dr.Ing. Thesis)
MTA-98-120	Vikestad, Kyrre, MK	Multi-Frequency Response of a Cylinder Subjected to Vortex Shedding and Support Motions. (Dr.Ing. Thesis)
MTA-98-121	Azadi, Mohammad R. E., MK	Analysis of Static and Dynamic Pile-Soil-Jacket Behaviour. (Dr.Ing. Thesis)
MTA-98-122	Ulltang, Terje, MP	A Communication Model for Product Information. (Dr.Ing. Thesis)
MTA-98-123	Torbergsen, Erik, MM	Impeller/Diffuser Interaction Forces in Centrifugal Pumps. (Dr.Ing. Thesis)
MTA-98-124	Hansen, Edmond, MH	A Discrete Element Model to Study Marginal Ice Zone Dynamics and the Behaviour of Vessels Moored in Broken Ice. (Dr.Ing. Thesis)
MTA-98-125	Videiro, Paulo M., MK	Reliability Based Design of Marine Structures. (Dr.Ing. Thesis)
MTA-99-126	Mainçon, Philippe, MK	Fatigue Reliability of Long Welds Application to Titanium Risers. (Dr.Ing. Thesis)
MTA-99-127	Haugen, Elin M., MH	Hydroelastic Analysis of Slamming on Stiffened Plates with Application to Catamaran Wetdecks. (Dr.Ing. Thesis)
MTA-99-128	Langhelle, Nina K., MK	Experimental Validation and Calibration of Nonlinear Finite Element Models for Use in Design of Aluminium Structures Exposed to Fire. (Dr.Ing. Thesis)
MTA-99-	Berstad, Are J., MK	Calculation of Fatigue Damage in Ship Structures.

129		(Dr.Ing. Thesis)
MTA-99-130	Andersen, Trond M., MM	Short Term Maintenance Planning. (Dr.Ing. Thesis)
MTA-99-131	Tveiten, Bård Wathne, MK	Fatigue Assessment of Welded Aluminium Ship Details. (Dr.Ing. Thesis)
MTA-99-132	Søreide, Fredrik, MP	Applications of underwater technology in deep water archaeology. Principles and practice. (Dr.Ing. Thesis)
MTA-99-133	Tønnessen, Rune, MH	A Finite Element Method Applied to Unsteady Viscous Flow Around 2D Blunt Bodies With Sharp Corners. (Dr.Ing. Thesis)
MTA-99-134	Elvekrok, Dag R., MP	Engineering Integration in Field Development Projects in the Norwegian Oil and Gas Industry. The Supplier Management of Norne. (Dr.Ing. Thesis)
MTA-99-135	Fagerholt, Kjetil, MP	Optimeringsbaserte Metoder for Ruteplanlegging innen skipsfart. (Dr.Ing. Thesis)
MTA-99-136	Bysveen, Marie, MM	Visualization in Two Directions on a Dynamic Combustion Rig for Studies of Fuel Quality. (Dr.Ing. Thesis)
MTA-2000-137	Storteig, Eskild, MM	Dynamic characteristics and leakage performance of liquid annular seals in centrifugal pumps. (Dr.Ing. Thesis)
MTA-2000-138	Sagli, Gro, MK	Model uncertainty and simplified estimates of long term extremes of hull girder loads in ships. (Dr.Ing. Thesis)
MTA-2000-139	Tronstad, Harald, MK	Nonlinear analysis and design of cable net structures like fishing gear based on the finite element method. (Dr.Ing. Thesis)
MTA-2000-140	Kroneberg, André, MP	Innovation in shipping by using scenarios. (Dr.Ing. Thesis)
MTA-2000-141	Haslum, Herbjørn Alf, MH	Simplified methods applied to nonlinear motion of spar platforms. (Dr.Ing. Thesis)
MTA-2001-142	Samdal, Ole Johan, MM	Modelling of Degradation Mechanisms and Stressor Interaction on Static Mechanical Equipment Residual Lifetime. (Dr.Ing. Thesis)
MTA-2001-143	Baarholm, Rolf Jarle, MH	Theoretical and experimental studies of wave impact underneath decks of offshore platforms. (Dr.Ing. Thesis)
MTA-2001-144	Wang, Lihua, MK	Probabilistic Analysis of Nonlinear Wave-induced Loads on Ships. (Dr.Ing. Thesis)
MTA-2001-145	Kristensen, Odd H. Holt, MK	Ultimate Capacity of Aluminium Plates under Multiple Loads, Considering HAZ Properties. (Dr.Ing. Thesis)
MTA-2001-146	Greco, Marilena, MH	A Two-Dimensional Study of Green-Water

		Loading. (Dr.Ing. Thesis)
MTA-2001-147	Heggelund, Svein E., MK	Calculation of Global Design Loads and Load Effects in Large High Speed Catamarans. (Dr.Ing. Thesis)
MTA-2001-148	Babalola, Olusegun T., MK	Fatigue Strength of Titanium Risers – Defect Sensitivity. (Dr.Ing. Thesis)
MTA-2001-149	Mohammed, Abuu K., MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
MTA-2002-150	Holmedal, Lars E., MH	Wave-current interactions in the vicinity of the sea bed. (Dr.Ing. Thesis)
MTA-2002-151	Rognebakke, Olav F., MH	Sloshing in rectangular tanks and interaction with ship motions. (Dr.Ing. Thesis)
MTA-2002-152	Lader, Pål Furset, MH	Geometry and Kinematics of Breaking Waves. (Dr.Ing. Thesis)
MTA-2002-153	Yang, Qinzheng, MH	Wash and wave resistance of ships in finite water depth. (Dr.Ing. Thesis)
MTA-2002-154	Melhus, Øyvin, MM	Utilization of VOC in Diesel Engines. Ignition and combustion of VOC released by crude oil tankers. (Dr.Ing. Thesis)
MTA-2002-155	Ronæss, Marit, MH	Wave Induced Motions of Two Ships Advancing on Parallel Course. (Dr.Ing. Thesis)
MTA-2002-156	Økland, Ole D., MK	Numerical and experimental investigation of whipping in twin hull vessels exposed to severe wet deck slamming. (Dr.Ing. Thesis)
MTA-2002-157	Ge, Chunhua, MK	Global Hydroelastic Response of Catamarans due to Wet Deck Slamming. (Dr.Ing. Thesis)
MTA-2002-158	Byklum, Eirik, MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
IMT-2003-1	Chen, Haibo, MK	Probabilistic Evaluation of FPSO-Tanker Collision in Tandem Offloading Operation. (Dr.Ing. Thesis)
IMT-2003-2	Skaugset, Kjetil Bjørn, MK	On the Suppression of Vortex Induced Vibrations of Circular Cylinders by Radial Water Jets. (Dr.Ing. Thesis)
IMT-2003-3	Chezhian, Muthu	Three-Dimensional Analysis of Slamming. (Dr.Ing. Thesis)
IMT-2003-4	Buhaug, Øyvind	Deposit Formation on Cylinder Liner Surfaces in Medium Speed Engines. (Dr.Ing. Thesis)
IMT-2003-5	Tregde, Vidar	Aspects of Ship Design: Optimization of Aft Hull with Inverse Geometry Design. (Dr.Ing. Thesis)
IMT-	Wist, Hanne Therese	Statistical Properties of Successive Ocean Wave

2003-6		Parameters. (Dr.Ing. Thesis)
IMT-2004-7	Ransau, Samuel	Numerical Methods for Flows with Evolving Interfaces. (Dr.Ing. Thesis)
IMT-2004-8	Soma, Torkel	Blue-Chip or Sub-Standard. A data interrogation approach of identity safety characteristics of shipping organization. (Dr.Ing. Thesis)
IMT-2004-9	Ersdal, Svein	An experimental study of hydrodynamic forces on cylinders and cables in near axial flow. (Dr.Ing. Thesis)
IMT-2005-10	Brodtkorb, Per Andreas	The Probability of Occurrence of Dangerous Wave Situations at Sea. (Dr.Ing. Thesis)
IMT-2005-11	Yttervik, Rune	Ocean current variability in relation to offshore engineering. (Dr.Ing. Thesis)
IMT-2005-12	Fredheim, Arne	Current Forces on Net-Structures. (Dr.Ing. Thesis)
IMT-2005-13	Heggernes, Kjetil	Flow around marine structures. (Dr.Ing. Thesis
IMT-2005-14	Fouques, Sebastien	Lagrangian Modelling of Ocean Surface Waves and Synthetic Aperture Radar Wave Measurements. (Dr.Ing. Thesis)
IMT-2006-15	Holm, Håvard	Numerical calculation of viscous free surface flow around marine structures. (Dr.Ing. Thesis)
IMT-2006-16	Bjørheim, Lars G.	Failure Assessment of Long Through Thickness Fatigue Cracks in Ship Hulls. (Dr.Ing. Thesis)
IMT-2006-17	Hansson, Lisbeth	Safety Management for Prevention of Occupational Accidents. (Dr.Ing. Thesis)
IMT-2006-18	Zhu, Xinying	Application of the CIP Method to Strongly Nonlinear Wave-Body Interaction Problems. (Dr.Ing. Thesis)
IMT-2006-19	Reite, Karl Johan	Modelling and Control of Trawl Systems. (Dr.Ing. Thesis)
IMT-2006-20	Smogeli, Øyvind Notland	Control of Marine Propellers. From Normal to Extreme Conditions. (Dr.Ing. Thesis)
IMT-2007-21	Storhaug, Gaute	Experimental Investigation of Wave Induced Vibrations and Their Effect on the Fatigue Loading of Ships. (Dr.Ing. Thesis)
IMT-2007-22	Sun, Hui	A Boundary Element Method Applied to Strongly Nonlinear Wave-Body Interaction Problems. (PhD Thesis, CeSOS)
IMT-2007-23	Rustad, Anne Marthine	Modelling and Control of Top Tensioned Risers. (PhD Thesis, CeSOS)
IMT-2007-24	Johansen, Vegar	Modelling flexible slender system for real-time simulations and control applications
IMT-2007-25	Wroldsen, Anders Sunde	Modelling and control of tensegrity structures.

		(PhD Thesis, CeSOS)
IMT-2007-26	Aronsen, Kristoffer Høye	An experimental investigation of in-line and combined inline and cross flow vortex induced vibrations. (Dr. avhandling, IMT)
IMT-2007-27	Gao, Zhen	Stochastic Response Analysis of Mooring Systems with Emphasis on Frequency-domain Analysis of Fatigue due to Wide-band Response Processes (PhD Thesis, CeSOS)
IMT-2007-28	Thorstensen, Tom Anders	Lifetime Profit Modelling of Ageing Systems Utilizing Information about Technical Condition. (Dr.ing. thesis, IMT)
IMT-2008-29	Refsnes, Jon Erling Gorset	Nonlinear Model-Based Control of Slender Body AUVs (PhD Thesis, IMT)
IMT-2008-30	Berntsen, Per Ivar B.	Structural Reliability Based Position Mooring. (PhD-Thesis, IMT)
IMT-2008-31	Ye, Naiquan	Fatigue Assessment of Aluminium Welded Box-stiffener Joints in Ships (Dr.ing. thesis, IMT)
IMT-2008-32	Radan, Damir	Integrated Control of Marine Electrical Power Systems. (PhD-Thesis, IMT)
IMT-2008-33	Thomassen, Paul	Methods for Dynamic Response Analysis and Fatigue Life Estimation of Floating Fish Cages. (Dr.ing. thesis, IMT)
IMT-2008-34	Pákozdi, Csaba	A Smoothed Particle Hydrodynamics Study of Two-dimensional Nonlinear Sloshing in Rectangular Tanks. (Dr.ing.thesis, IMT/ CeSOS)
IMT-2007-35	Grytøyr, Guttorm	A Higher-Order Boundary Element Method and Applications to Marine Hydrodynamics. (Dr.ing.thesis, IMT)
IMT-2008-36	Drummen, Ingo	Experimental and Numerical Investigation of Nonlinear Wave-Induced Load Effects in Containerships considering Hydroelasticity. (PhD thesis, CeSOS)
IMT-2008-37	Skejic, Renato	Maneuvering and Seakeeping of a Singel Ship and of Two Ships in Interaction. (PhD-Thesis, CeSOS)
IMT-2008-38	Harlem, Alf	An Age-Based Replacement Model for Repairable Systems with Attention to High-Speed Marine Diesel Engines. (PhD-Thesis, IMT)
IMT-2008-39	Alsos, Hagbart S.	Ship Grounding. Analysis of Ductile Fracture, Bottom Damage and Hull Girder Response. (PhD-thesis, IMT)
IMT-2008-40	Graczyk, Mateusz	Experimental Investigation of Sloshing Loading and Load Effects in Membrane LNG Tanks Subjected to Random Excitation. (PhD-thesis, CeSOS)
IMT-2008-41	Taghipour, Reza	Efficient Prediction of Dynamic Response for Flexible amd Multi-body Marine Structures. (PhD-

		thesis, CeSOS)
IMT-2008-42	Ruth, Eivind	Propulsion control and thrust allocation on marine vessels. (PhD thesis, CeSOS)
IMT-2008-43	Nystad, Bent Helge	Technical Condition Indexes and Remaining Useful Life of Aggregated Systems. PhD thesis, IMT
IMT-2008-44	Soni, Prashant Kumar	Hydrodynamic Coefficients for Vortex Induced Vibrations of Flexible Beams, PhD thesis, CeSOS
IMT-2009-45	Amlashi, Hadi K.K.	Ultimate Strength and Reliability-based Design of Ship Hulls with Emphasis on Combined Global and Local Loads. PhD Thesis, IMT
IMT-2009-46	Pedersen, Tom Arne	Bond Graph Modelling of Marine Power Systems. PhD Thesis, IMT
IMT-2009-47	Kristiansen, Trygve	Two-Dimensional Numerical and Experimental Studies of Piston-Mode Resonance. PhD-Thesis, CeSOS
IMT-2009-48	Ong, Muk Chen	Applications of a Standard High Reynolds Number Model and a Stochastic Scour Prediction Model for Marine Structures. PhD-thesis, IMT
IMT-2009-49	Hong, Lin	Simplified Analysis and Design of Ships subjected to Collision and Grounding. PhD-thesis, IMT
IMT-2009-50	Koushan, Kamran	Vortex Induced Vibrations of Free Span Pipelines, PhD thesis, IMT
IMT-2009-51	Korsvik, Jarl Eirik	Heuristic Methods for Ship Routing and Scheduling. PhD-thesis, IMT
IMT-2009-52	Lee, Jihoon	Experimental Investigation and Numerical in Analyzing the Ocean Current Displacement of Longlines. Ph.d.-Thesis, IMT.
IMT-2009-53	Vestbøstad, Tone Gran	A Numerical Study of Wave-in-Deck Impact usin a Two-Dimensional Constrained Interpolation Profile Method, Ph.d.thesis, CeSOS.
IMT-2009-54	Bruun, Kristine	Bond Graph Modelling of Fuel Cells for Marine Power Plants. Ph.d.-thesis, IMT
IMT 2009-55	Holstad, Anders	Numerical Investigation of Turbulence in a Sekwed Three-Dimensional Channel Flow, Ph.d.-thesis, IMT.
IMT 2009-56	Ayala-Uraga, Efren	Reliability-Based Assessment of Deteriorating Ship-shaped Offshore Structures, Ph.d.-thesis, IMT
IMT 2009-57	Kong, Xiangjun	A Numerical Study of a Damaged Ship in Beam Sea Waves. Ph.d.-thesis, IMT/CeSOS.
IMT 2010-58	Kristiansen, David	Wave Induced Effects on Floaters of Aquaculture Plants, Ph.d.-thesis, CeSOS.

IMT 2010-59	Ludvigsen, Martin	An ROV-Toolbox for Optical and Acoustic Scientific Seabed Investigation. Ph.d.-thesis IMT.
IMT 2010-60	Hals, Jørgen	Modelling and Phase Control of Wave-Energy Converters. Ph.d.thesis, CeSOS.
IMT 2010- 61	Shu, Zhi	Uncertainty Assessment of Wave Loads and Ultimate Strength of Tankers and Bulk Carriers in a Reliability Framework. Ph.d. Thesis, IMT/ CeSOS
IMT 2010-62	Shao, Yanlin	Numerical Potential-Flow Studies on Weakly-Nonlinear Wave-Body Interactions with/without Small Forward Speed, Ph.d.thesis,CeSOS.
IMT 2010-63	Califano, Andrea	Dynamic Loads on Marine Propellers due to Intermittent Ventilation. Ph.d.thesis, IMT.
IMT 2010-64	El Khoury, George	Numerical Simulations of Massively Separated Turbulent Flows, Ph.d.-thesis, IMT
IMT 2010-65	Seim, Knut Sponheim	Mixing Process in Dense Overflows with Emphasis on the Faroe Bank Channel Overflow. Ph.d.thesis, IMT
IMT 2010-66	Jia, Huirong	Structural Analysis of Intect and Damaged Ships in a Collission Risk Analysis Perspective. Ph.d.thesis CeSoS.
IMT 2010-67	Jiao, Linlin	Wave-Induced Effects on a Pontoon-type Very Large Floating Structures (VLFS). Ph.D.-thesis, CeSOS.
IMT 2010-68	Abrahamsen, Bjørn Christian	Sloshing Induced Tank Roof with Entrapped Air Pocket. Ph.d.thesis, CeSOS.
IMT 2011-69	Karimirad, Madjid	Stochastic Dynamic Response Analysis of Spar-Type Wind Turbines with Catenary or Taut Mooring Systems. Ph.d.-thesis, CeSOS.
IMT - 2011-70	Erlend Meland	Condition Monitoring of Safety Critical Valves. Ph.d.-thesis, IMT.
IMT – 2011-71	Yang, Limin	Stochastic Dynamic System Analysis of Wave Energy Converter with Hydraulic Power Take-Off, with Particular Reference to Wear Damage Analysis, Ph.d. Thesis, CeSOS.
IMT – 2011-72	Visscher, Jan	Application of Particla Image Velocimetry on Turbulent Marine Flows, Ph.d.Thesis, IMT.
IMT – 2011-73	Su, Biao	Numerical Predictions of Global and Local Ice Loads on Ships. Ph.d.Thesis, CeSOS.
IMT – 2011-74	Liu, Zhenhui	Analytical and Numerical Analysis of Iceberg Collision with Ship Structures. Ph.d.Thesis, IMT.
IMT – 2011-75	Aarsæther, Karl Gunnar	Modeling and Analysis of Ship Traffic by Observation and Numerical Simulation. Ph.d.Thesis, IMT.

Imt – 2011-76	Wu, Jie	Hydrodynamic Force Identification from Stochastic Vortex Induced Vibration Experiments with Slender Beams. Ph.d.Thesis, IMT.
Imt – 2011-77	Amini, Hamid	Azimuth Propulsors in Off-design Conditions. Ph.d.Thesis, IMT.
IMT – 2011-78	Nguyen, Tan-Hoi	Toward a System of Real-Time Prediction and Monitoring of Bottom Damage Conditions During Ship Grounding. Ph.d.thesis, IMT.
IMT- 2011-79	Tavakoli, Mohammad T.	Assessment of Oil Spill in Ship Collision and Grounding, Ph.d.thesis, IMT.
IMT- 2011-80	Guo, Bingjie	Numerical and Experimental Investigation of Added Resistance in Waves. Ph.d.Thesis, IMT.
IMT- 2011-81	Chen, Qiaofeng	Ultimate Strength of Aluminium Panels, considering HAZ Effects, IMT
IMT- 2012-82	Kota, Ravikiran S.	Wave Loads on Decks of Offshore Structures in Random Seas, CeSOS.
IMT- 2012-83	Sten, Ronny	Dynamic Simulation of Deep Water Drilling Risers with Heave Compensating System, IMT.
IMT- 2012-84	Berle, Øyvind	Risk and resilience in global maritime supply chains, IMT.
IMT- 2012-85	Fang, Shaoji	Fault Tolerant Position Mooring Control Based on Structural Reliability, CeSOS.
IMT- 2012-86	You, Jikun	Numerical studies on wave forces and moored ship motions in intermediate and shallow water, CeSOS.
IMT- 2012-87	Xiang ,Xu	Maneuvering of two interacting ships in waves, CeSOS
IMT- 2012-88	Dong, Wenbin	Time-domain fatigue response and reliability analysis of offshore wind turbines with emphasis on welded tubular joints and gear components, CeSOS
IMT- 2012-89	Zhu, Suji	Investigation of Wave-Induced Nonlinear Load Effects in Open Ships considering Hull Girder Vibrations in Bending and Torsion, CeSOS
IMT- 2012-90	Zhou, Li	Numerical and Experimental Investigation of Station-keeping in Level Ice, CeSOS
IMT- 2012-91	Ushakov, Sergey	Particulate matter emission characteristics from diesel enignes operating on conventional and alternative marine fuels, IMT
IMT- 2013-1	Yin, Decao	Experimental and Numerical Analysis of Combined In-line and Cross-flow Vortex Induced Vibrations, CeSOS

IMT-2013-2	Kurniawan, Adi	Modelling and geometry optimisation of wave energy converters, CeSOS
IMT-2013-3	Al Ryati, Nabil	Technical condition indexes doe auxiliary marine diesel engines, IMT
IMT-2013-4	Firoozkoohi, Reza	Experimental, numerical and analytical investigation of the effect of screens on sloshing, CeSOS
IMT-2013-5	Ommani, Babak	Potential-Flow Predictions of a Semi-Displacement Vessel Including Applications to Calm Water Broaching, CeSOS
IMT-2013-6	Xing, Yihan	Modelling and analysis of the gearbox in a floating spar-type wind turbine, CeSOS
IMT-7-2013	Balland, Océane	Optimization models for reducing air emissions from ships, IMT
IMT-8-2013	Yang, Dan	Transitional wake flow behind an inclined flat plate-----Computation and analysis, IMT
IMT-9-2013	Abdillah, Suyuthi	Prediction of Extreme Loads and Fatigue Damage for a Ship Hull due to Ice Action, IMT
IMT-10-2013	Ramìrez, Pedro Agustìn Pèrez	Ageing management and life extension of technical systems- Concepts and methods applied to oil and gas facilities, IMT
IMT-11-2013	Chuang, Zhenju	Experimental and Numerical Investigation of Speed Loss due to Seakeeping and Maneuvering. IMT
IMT-12-2013	Etemaddar, Mahmoud	Load and Response Analysis of Wind Turbines under Atmospheric Icing and Controller System Faults with Emphasis on Spar Type Floating Wind Turbines, IMT
IMT-13-2013	Lindstad, Haakon	Strategies and measures for reducing maritime CO2 emissons, IMT
IMT-14-2013	Haris, Sabril	Damage interaction analysis of ship collisions, IMT
IMT-15-2013	Shainee, Mohamed	Conceptual Design, Numerical and Experimental Investigation of a SPM Cage Concept for Offshore Mariculture, IMT
IMT-16-2013	Gansel, Lars	Flow past porous cylinders and effects of biofouling and fish behavior on the flow in and around Atlantic salmon net cages, IMT
IMT-17-2013	Gaspar, Henrique	Handling Aspects of Complexity in Conceptual Ship Design, IMT
IMT-18-2013	Thys, Maxime	Theoretical and Experimental Investigation of a Free Running Fishing Vessel at Small Frequency of Encounter, CeSOS
IMT-19-2013	Aglen, Ida	VIV in Free Spanning Pipelines, CeSOS

IMT-1-2014	Song, An	Theoretical and experimental studies of wave diffraction and radiation loads on a horizontally submerged perforated plate, CeSOS
IMT-2-2014	Rogne, Øyvind Ygre	Numerical and Experimental Investigation of a Hinged 5-body Wave Energy Converter, CeSOS
IMT-3-2014	Dai, Lijuan	Safe and efficient operation and maintenance of offshore wind farms ,IMT
IMT-4-2014	Bachynski, Erin Elizabeth	Design and Dynamic Analysis of Tension Leg Platform Wind Turbines, CeSOS
IMT-5-2014	Wang, Jingbo	Water Entry of Freefall Wedged – Wedge motions and Cavity Dynamics, CeSOS
IMT-6-2014	Kim, Ekaterina	Experimental and numerical studies related to the coupled behavior of ice mass and steel structures during accidental collisions, IMT
IMT-7-2014	Tan, Xiang	Numerical investigation of ship's continuous- mode icebreaking in leverl ice, CeSOS
IMT-8-2014	Muliawan, Made Jaya	Design and Analysis of Combined Floating Wave and Wind Power Facilities, with Emphasis on Extreme Load Effects of the Mooring System, CeSOS
IMT-9-2014	Jiang, Zhiyu	Long-term response analysis of wind turbines with an emphasis on fault and shutdown conditions, IMT
IMT-10-2014	Dukan, Fredrik	ROV Motion Control Systems, IMT
IMT-11-2014	Grimsmo, Nils I.	Dynamic simulations of hydraulic cylinder for heave compensation of deep water drilling risers, IMT
IMT-12-2014	Kvittem, Marit I.	Modelling and response analysis for fatigue design of a semisubmersible wind turbine, CeSOS
IMT-13-2014	Akhtar, Juned	The Effects of Human Fatigue on Risk at Sea, IMT
IMT-14-2014	Syahroni, Nur	Fatigue Assessment of Welded Joints Taking into Account Effects of Residual Stress, IMT
IMT-1-2015	Bøckmann, Eirik	Wave Propulsion of ships, IMT
IMT-2-2015	Wang, Kai	Modelling and dynamic analysis of a semi-submersible floating vertical axis wind turbine, CeSOS
IMT-3-2015	Fredriksen, Arnt Gunvald	A numerical and experimental study of a two-dimensional body with moonpool in waves and current, CeSOS
IMT-4-2015	Jose Patricio Gallardo Canabes	Numerical studies of viscous flow around bluff bodies, IMT

IMT-5-2015	Vegard Longva	Formulation and application of finite element techniques for slender marine structures subjected to contact interactions, IMT
IMT-6-2015	Jacobus De Vaal	Aerodynamic modelling of floating wind turbines, CeSOS
IMT-7-2015	Fachri Nasution	Fatigue Performance of Copper Power Conductors, IMT
IMT-8-2015	Oleh I Karpa	Development of bivariate extreme value distributions for applications in marine technology,CeSOS
IMT-9-2015	Daniel de Almeida Fernandes	An output feedback motion control system for ROVs, AMOS
IMT-10-2015	Bo Zhao	Particle Filter for Fault Diagnosis: Application to Dynamic Positioning Vessel and Underwater Robotics, CeSOS
IMT-11-2015	Wenting Zhu	Impact of emission allocation in maritime transportation, IMT
IMT-12-2015	Amir Rasekhi Nejad	Dynamic Analysis and Design of Gearboxes in Offshore Wind Turbines in a Structural Reliability Perspective, CeSOS
IMT-13-2015	Arturo Jesùs Ortega Malca	Dynamic Response of Flexibles Risers due to Unsteady Slug Flow, CeSOS
IMT-14-2015	Dagfinn Husjord	Guidance and decision-support system for safe navigation of ships operating in close proximity, IMT
IMT-15-2015	Anirban Bhattacharyya	Ducted Propellers: Behaviour in Waves and Scale Effects, IMT
IMT-16-2015	Qin Zhang	Image Processing for Ice Parameter Identification in Ice Management, IMT
IMT-1-2016	Vincentius Rumawas	Human Factors in Ship Design and Operation: An Experiential Learning, IMT
IMT-2-2016	Martin Storheim	Structural response in ship-platform and ship-ice collisions, IMT
IMT-3-2016	Mia Abrahamsen Prsic	Numerical Simulations of the Flow around single and Tandem Circular Cylinders Close to a Plane Wall, IMT
IMT-4-2016	Tufan Arslan	Large-eddy simulations of cross-flow around ship sections, IMT

IMT-5-2016	Pierre Yves-Henry	Parametrisation of aquatic vegetation in hydraulic and coastal research,IMT
IMT-6-2016	Lin Li	Dynamic Analysis of the Instalation of Monopiles for Offshore Wind Turbines, CeSOS
IMT-7-2016	Øivind Kåre Kjerstad	Dynamic Positioning of Marine Vessels in Ice, IMT
IMT-8-2016	Xiaopeng Wu	Numerical Analysis of Anchor Handling and Fish Trawling Operations in a Safety Perspective, CeSOS
IMT-9-2016	Zhengshun Cheng	Integrated Dynamic Analysis of Floating Vertical Axis Wind Turbines, CeSOS
IMT-10-2016	Ling Wan	Experimental and Numerical Study of a Combined Offshore Wind and Wave Energy Converter Concept
IMT-11-2016	Wei Chai	Stochastic dynamic analysis and reliability evaluation of the roll motion for ships in random seas, CeSOS
IMT-12-2016	Øyvind Selnes Patricksson	Decision support for conceptual ship design with focus on a changing life cycle and future uncertainty, IMT
IMT-13-2016	Mats Jørgen Thorsen	Time domain analysis of vortex-induced vibrations, IMT
IMT-14-2016	Edgar McGuinness	Safety in the Norwegian Fishing Fleet – Analysis and measures for improvement, IMT
IMT-15-2016	Sepideh Jafarzadeh	Energy effiency and emission abatement in the fishing fleet, IMT
IMT-16-2016	Wilson Ivan Guachamin Acero	Assessment of marine operations for offshore wind turbine installation with emphasis on response-based operational limits, IMT
IMT-17-2016	Mauro Candeloro	Tools and Methods for Autonomous Operations on Seabed and Water Coumn using Underwater Vehicles, IMT
IMT-18-2016	Valentin Chabaud	Real-Time Hybrid Model Testing of Floating Wind Tubines, IMT
IMT-1-2017	Mohammad Saud Afzal	Three-dimensional streaming in a sea bed boundary layer
IMT-2-2017	Peng Li	A Theoretical and Experimental Study of Wave-induced Hydroelastic Response of a Circular Floating Collar
IMT-3-2017	Martin Bergström	A simulation-based design method for arctic maritime transport systems

IMT-4-2017	Bhushan Taskar	The effect of waves on marine propellers and propulsion
IMT-5-2017	Mohsen Bardestani	A two-dimensional numerical and experimental study of a floater with net and sinker tube in waves and current
IMT-6-2017	Fatemeh Hoseini Dadmarzi	Direct Numerical Simualtion of turbulent wakes behind different plate configurations
IMT-7-2017	Michel R. Miyazaki	Modeling and control of hybrid marine power plants
IMT-8-2017	Giri Rajasekhar Gunnu	Safety and effiency enhancement of anchor handling operations with particular emphasis on the stability of anchor handling vessels
IMT-9-2017	Kevin Koosup Yum	Transient Performance and Emissions of a Turbocharged Diesel Engine for Marine Power Plants
IMT-10-2017	Zhaolong Yu	Hydrodynamic and structural aspects of ship collisions
IMT-11-2017	Martin Hassel	Risk Analysis and Modelling of Allisions between Passing Vessels and Offshore Installations
IMT-12-2017	Astrid H. Brodtkorb	Hybrid Control of Marine Vessels – Dynamic Positioning in Varying Conditions
IMT-13-2017	Kjersti Bruserud	Simultaneous stochastic model of waves and current for prediction of structural design loads
IMT-14-2017	Finn-Idar Grøtta Giske	Long-Term Extreme Response Analysis of Marine Structures Using Inverse Reliability Methods
IMT-15-2017	Stian Skjong	Modeling and Simulation of Maritime Systems and Operations for Virtual Prototyping using co-Simulations
IMT-1-2018	Yingguang Chu	Virtual Prototyping for Marine Crane Design and Operations