Designing the Future with Digital Twins

Digital Twin of a Heavy Lift Vessel

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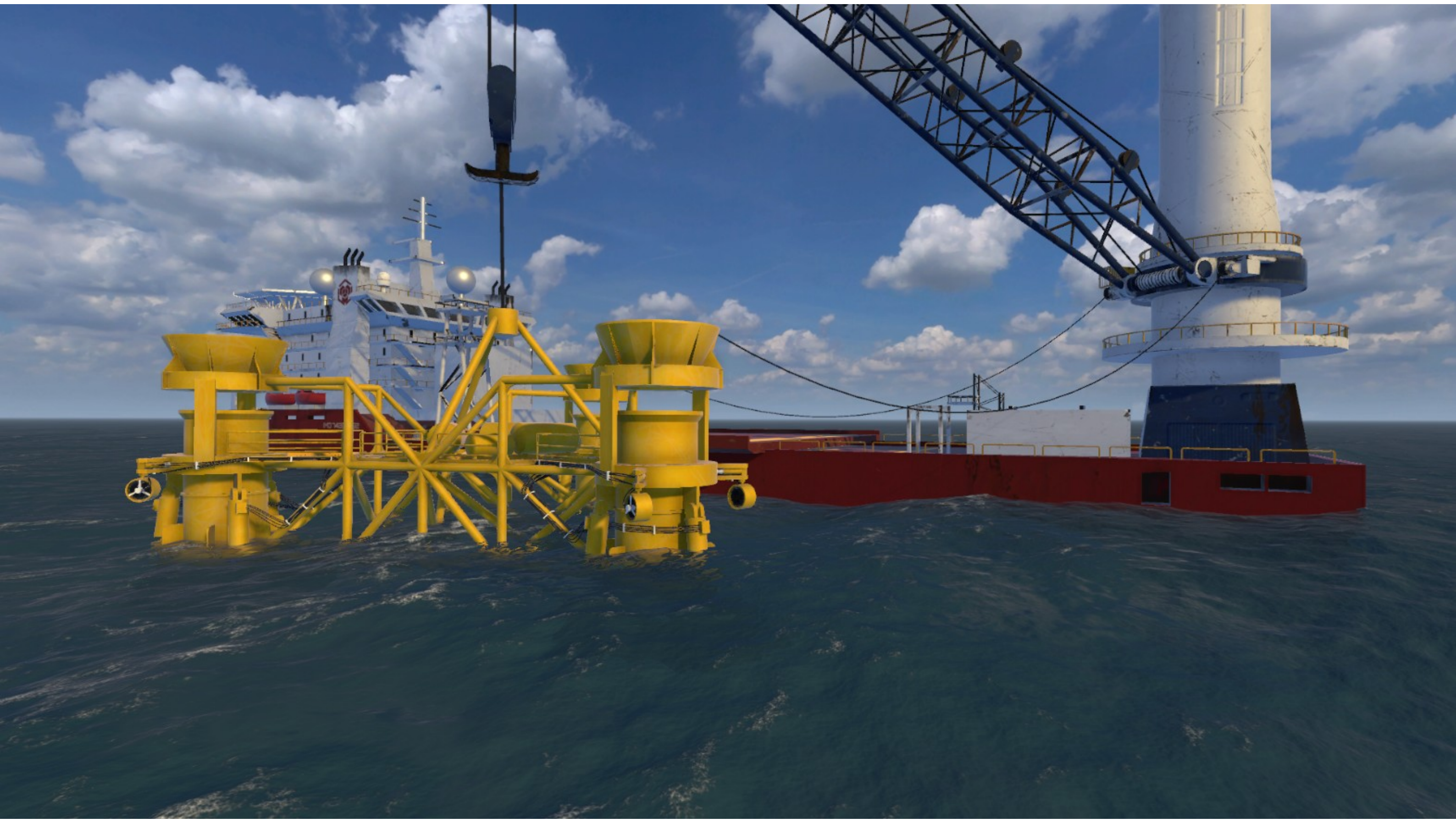

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1. Introduction

At Controllab we create digital twins: high-fidelity simulation models that predict exactly how new machines will behave in the real world. This technical paper provides a detailed description of the development process and application of a heavy lift vessel digital twin.

In industries like steel and marine, equipment has become so complex that critical issues often only surface during commissioning. This leads to delays, unexpected costs, and operational risk. We remove this risk with our digital twins. For every new piece of equipment, you can simulate performance in advance, identify and resolve major issues early, and dramatically reduce costly surprises.

Controllab specialises in digital twins for heavy machinery. We have experience with cranes, pile grippers, dredgers, pipe-laying spreads, and more. We use digital twins to carry out design studies, test control software and develop training simulators.

Figure 1: Heavy lift vessel with crane and template.

As all of our commercial projects are carried out under an NDA, we cannot disclose many details publicly. This is why we asked two interns, Ruben Peters and Harold de Jong, to develop a digital twin using open-source information. Working under the guidance of our senior engineers, the interns created a digital twin of a heavy lift vessel with a pre-piling template as load. The aim was to produce a digital twin that can be operated as a training simulators and show the lifting and placement of the template.

This paper describes the development process of the digital twin. First, we will outline the general building process, followed by a detailed description of the modelling of the crane vessel and a template. Finally, we will present the simulation results.

2. Building Process

2.1. Digital Twin

At Controllab, a digital twin is defined as a simulation model that illustrates the dynamics of machinery, including their motions, accuracy, forces and power usage. The simulation results are displayed as 3D visualisations, plots, and graphical user interfaces (GUIs). These simulation models can be used for various purposes:

- Design assessment: Simulate a machine that has not yet been built and test its capabilities.
- Operations: Test whether the machine can carry out its task safely and efficiently.
- HIL simulation: Couple the digital twin to a PLC to test the control software.
- Training simulation: Train operators how to use the machine.

At the core of our models lies our proprietary physics engine, 20-sim, which is the gold standard for real-time simulation of heavy machines. Industry leaders such as DEME, Allseas, Van Oord, and Boskalis rely on it to get their operations right. With 20-sim you can model and simulate multi-domain physics models (mechanics, hydraulics, electronics). It is an excellent package for the real-time simulation of large, complex machines.

20-sim models can be exported as a DLL for use with Unity. Unity is a widely used 3D development engine for creating interactive 2D/3D applications. We use Unity to display a machine in 3D and to create the graphical user interfaces (GUI) for operating them. During a simulation we can use 20-sim's plotting capabilities to analyse important variables such as the vessel motion, power usage and load positions.

2.2. Development process

Definitions

We use a standardised process to develop digital twins, starting with defining the main objects and associated reference frames of the digital twin. The figure below gives an overview of the crane vessel.

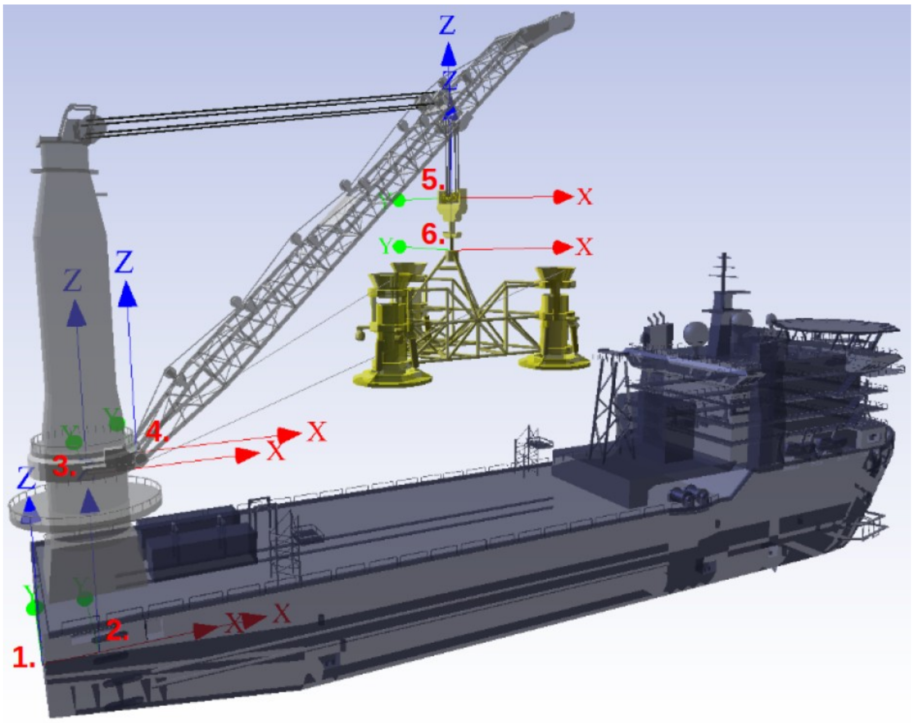


Figure 2: Definition of reference frames.

Parameters that cannot be extracted from the data (CAD files) are manually written in comma-separated values (CSV) file. Names and definitions are described in a Basis of Design document.

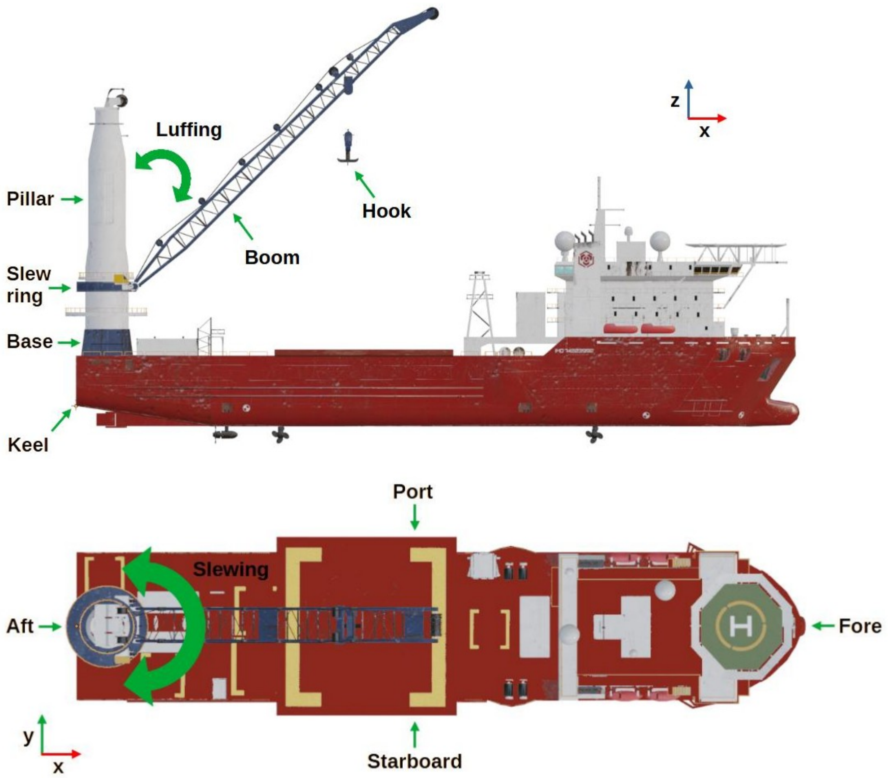


Figure 3: Naming conventions for the crane vessel.

Blender Toolbox

Blender is a free, open-source 3D computer graphics software suite. We have developed a Blender toolbox that enables us to import CAD and graphics files into Blender and allocate joints and rigid bodies to the various parts of the CAD file. We purchased a 3D model of a crane vessel online, imported it into Blender, and removed all unwanted assets. Using the toolbox, we exported both the vessel and crane models to 20-sim.

20-sim

With 20-sim, you can develop 3D dynamic models consisting of rigid bodies connected by joints. These joints can be coupled to 1D sensors and actuators. Control systems read the sensors and steer the actuators. You can custom-make 3D models, import them from the Blender toolbox, or select them from libraries. Blender models are typically of vessels, loads and linkages, such as cranes. Cables and blocks are 3D models that usually come from a library.

20-sim comes with a large set of libraries for electric, hydraulic and mechanical components. Special libraries like the offshore library and the control library also have been used for the crane vessel.

20-sim offshore library
vessel models with buoyancy, wave forces
loads with buoyancy, wave forces, splash zone passage
waves, current and wind
anchors cables and mooring lines
propellers and thrusters
hoist cables, hoist blocks, tag lines, rigging
winches (layers, spooling, brakes, clutches)
sensors (MRU,GNSS,inclinometer, load cell)
electric and hydraulic drive trains

All of these component models can be imported in 20-sim drawing editor and connected to create the final assembly model. The assembly model can be compiled and simulated. If the simulation shows good results, you can export the simulation model as a DLL to Unity.

Real-Time

The assembly model must run in real time. Each simulation step must be executed at the same speed as physical wall-clock time. This ensures that every millisecond in the model corresponds to a millisecond in reality, making the 3D animation in Unity realistic.

The assembly models are usually quite large. Therefore, special precautions are taken to ensure that mode calculations are performed extremely quickly. This begins with the library components, for which considerable effort has gone into creating stable, high-fidelity models that require minimal calculations. Computationally intensive algorithms, such as contact detection, have been optimised to the highest degree and use parallel execution wherever possible. Finally, significant effort has gone into making 20-sim extremely fast at calculations.

Physics Builder

The 20-sim building process can be automated using the Physics Builder (PB). The Physics Builder reads a recipe (description of the models and connections) and creates the complete 20-sim model automatically. Parameters are then read from a CSV-file and imported into the model.

Once a simulation model has reached maturity, our engineers create a PB recipe in 20-sim. This describes all the components of a model, where they are located (in a library, generated in Blender or stored under GIT) and how they are interconnected. From then on, they only work with the recipe, generating the 20-sim model automatically using the Physics Builder. Changes can only be made at library model level, where tests can be run to verify correct behaviour. This way of working prevents errors from entering the model and corrupting the simulation.

Unity

When completed, the 20-sim model is exported to Unity as a DLL. It acts as a physics engine, simulating the motion of the vessel, crane boom, load, and other components. In Unity, these motions are coupled to the 3D shapes representing the vessel, crane boom, etc. These shapes can be created in Blender, Maya and other tools. 3D assets such as waves, clouds, the sun and the seabed are added to complete the scenery and improve the 3D visualisation of the crane vessel.

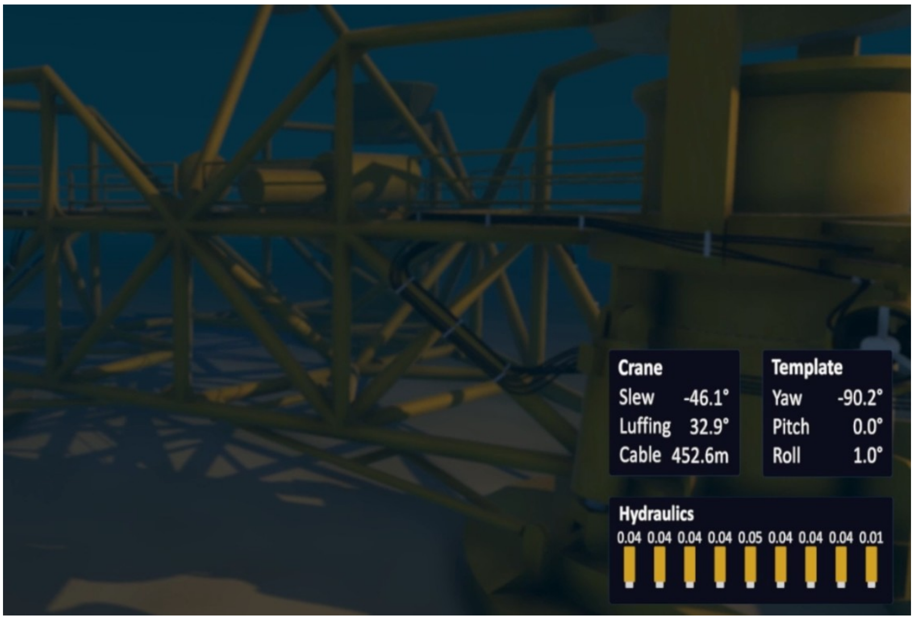


Figure 4: 3D visualization of the template and and 2D visualization of the HMI.

Unity can also be used to create 2D sceneries. We use this to develop the human-machine interface (HMI). The HMI enables the operator to start the simulation and operate the various controls (ballasting, DP, crane and template motion) during the simulation.

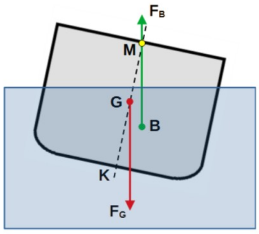
3. Modelling

3.1. Vessel

A 3D model of the crane vessel was purchased online. This model only shows the shape of the vessel and the crane, and does not contain any additional information. The following dimensions were chosen based on commercial heavy lift vessels such as the Giant 7 and the Sapura 3000.

Vessel Geometry

length:	163 m
breadth:	33.3 m
draugth:	8,85 m
displacement:	37603 mT
GM:	11,3 m



In the Blender toolbox, the vessel's hull can be divided into segments. These can then be exported to a vessel model. This model consists of a rigid body to which the segments are attached. Based on its individual geometry, each segment calculates the hydrodynamic forces acting on it. These forces are buoyancy, which varies with local wave height, and drag force, which varies with local water speed. Combined with the rigid body (centre of mass and inertia), this creates a vessel model with a moving centre of buoyancy and metacentric height, as shown in the above figure.

3.2. Ballasting

In a real vessel, there may be up to 100 ballast tanks of various shapes, sizes and locations. In the crane vessel model, eight ballast tanks, each with a capacity of 4,000 m³, were used, arranged evenly in terms of size and spacing.

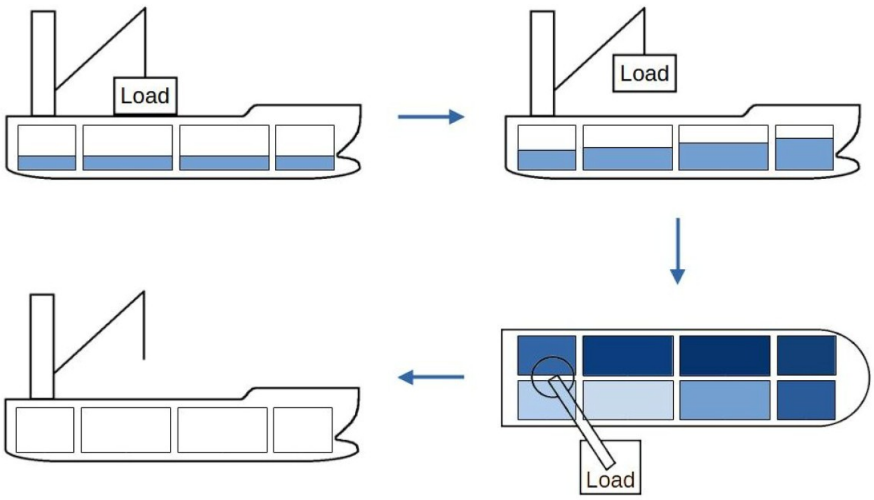


Figure 5: Distribution of the ballast tanks.

To evenly distribute the loads on the vessel when the crane is lifting a heavy load, the water level in each ballast tank must be individually controlled. A controller was designed that uses the least squares method to calculate the desired water level in each ballast tank. The control system is shown in the figure below and compares the actual roll and pitch angles with the desired roll and pitch angle. The difference between the two will result in pump rates to transfer water between the ballast tanks.

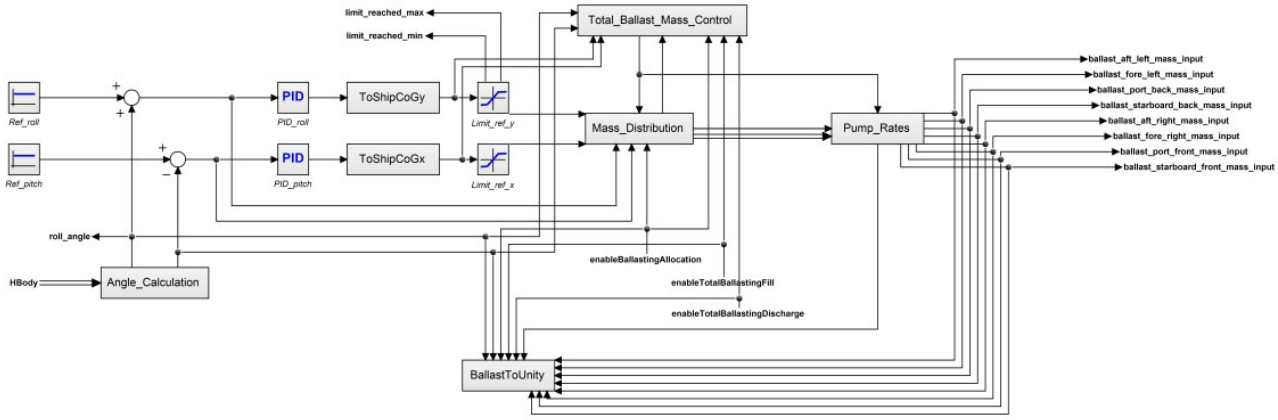


Figure 6: Ballasting control system in 20-sim.

3.3. Dynamic Positioning

A Dynamic Positioning (DP) system is a computer-controlled system that automatically maintains a vessel's position and heading to a desired value. It uses the vessel's own thrusters to counteract environmental forces such as wind, waves, and currents. Four thrusters keep the crane vessel at a fixed position. The control system is shown in the figure below. It compares the desired location and orientation of the vessel and compares these with its actual location and orientation. The difference between the two is used as an input for PI controllers. The controller output is sent to a DP controller block which calculates the required thrust and thrust angles for the four thrusters.

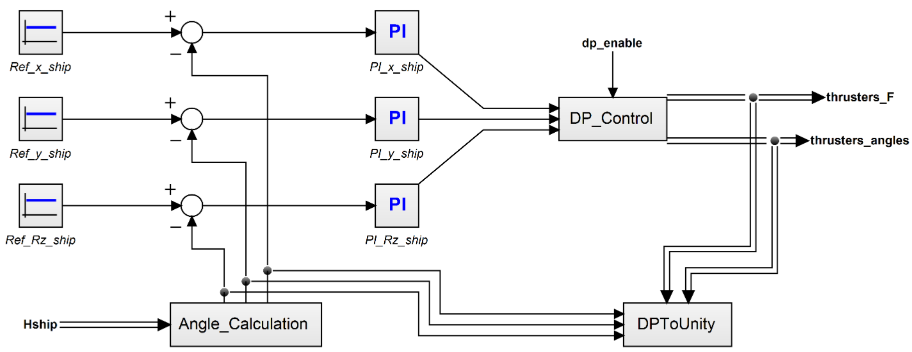


Figure 7: DP control system in 20-sim.

3.4. Crane

After importing the crane into the Blender toolbox, reference frames were attached to the base, luffing platform, boom and hoist blocks. Then the crane model was exported to 20-sim. In 20-sim the cables were attached. The boom lift consists of two sets of cables with 8 falls. The main hoist consists of two sets of cables with 6 falls. The tugger lines are single. The resulting crane model in 20-sim is shown in the next figure.

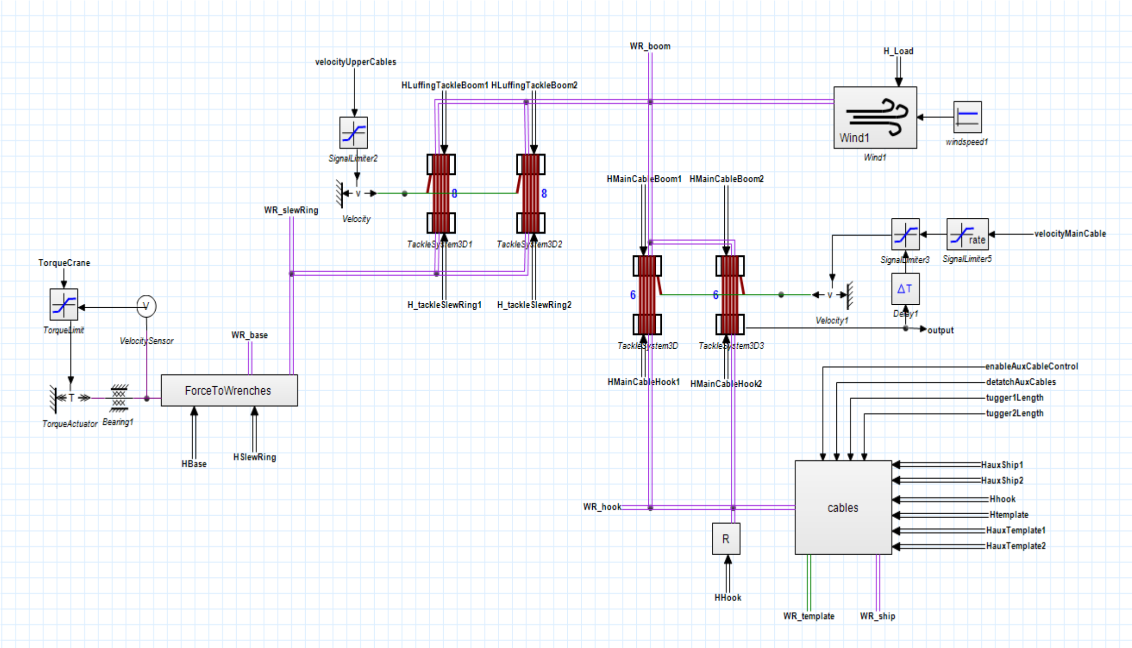


Figure 8: Crane model in 20-sim.

All cables are connected to winches that are hand operated. The crane operator gives a speed setpoint which is transferred to the winches.

Figure 9: Crane loading the template with the main hoist and tugger lines.

3.5. Pre-Piling Template

A pre-piling template is a steel structure that is placed on the seabed to guide and position piles accurately before they are driven in the seabed.

Figure 10: Pre-Piling Template.

We have created our own template in Blender, based on existing templates such as those used at the Saint-Brieuc and Wikinger wind farms. Figure 11 gives an impression. The template consists of a central frame with a lifting eye. Six thrusters attached to the central frame are used to manoeuvre the template while it is submerged. Thruster positioning with thrusters is necessary because the template may rotate and drift due to waves and currents. Three legs connected to the central frame guide the piles. Three feet are attached to the central frame via a linkage and can be adjusted vertically using hydraulic cylinders. This adjustment is necessary if the seabed is uneven.

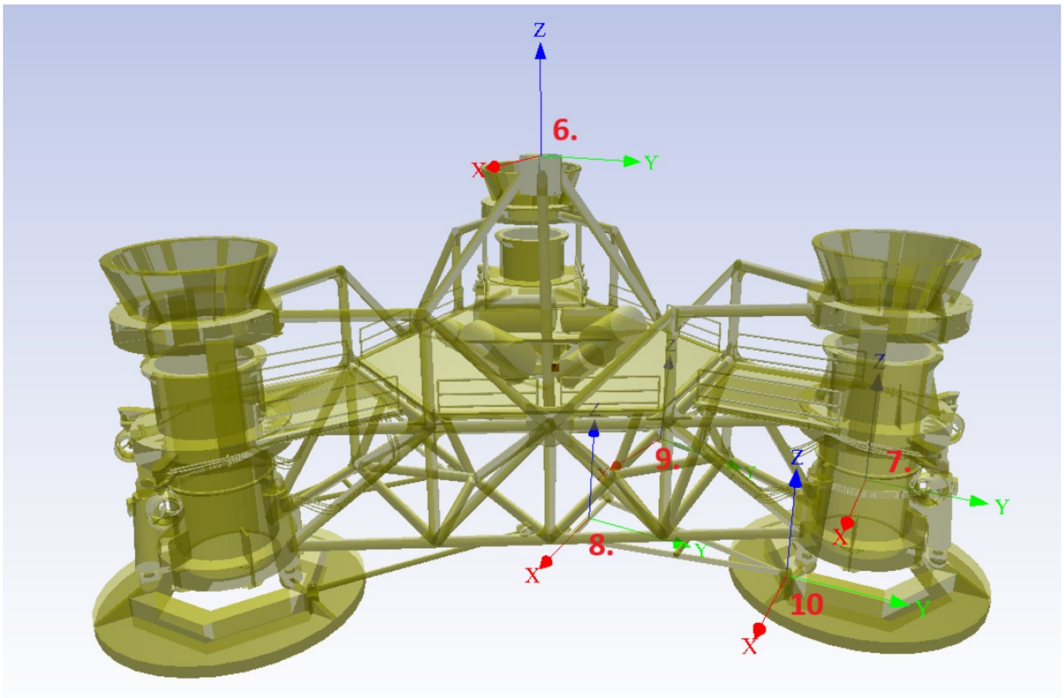


Figure 11: Definition of the parts and reference frames.

The following parameters were used.

Weights		**Actuators**	
Central frame	311 mT	hydraulics cylinders (12)	800 kN
Linkage and legs (3)	187 mT	Thrusters (6)	90 kN
Feet (3)	130 mT		

The model generation was done in a same way as for the vessel:

1. Import the template in Blender
2. Assign reference frames to the individual segments
3. For every segment: define weights and inertias, collision shapes, buoyancy
4. Assign joints
5. Generate a 3D mechanics model in 20-sim
6. Add thrusters and cylinders
7. Add control systems

Two control systems were used. The first operates the thrusters. It functions similarly to the DP control system for the vessel, except that the thrusters have a fixed orientation. This control system uses setpoint positions (x and y) and orientation around the z-axis to calculate the desired thrust for each thruster. Figure 12 shows the thruster models in 20-sim.

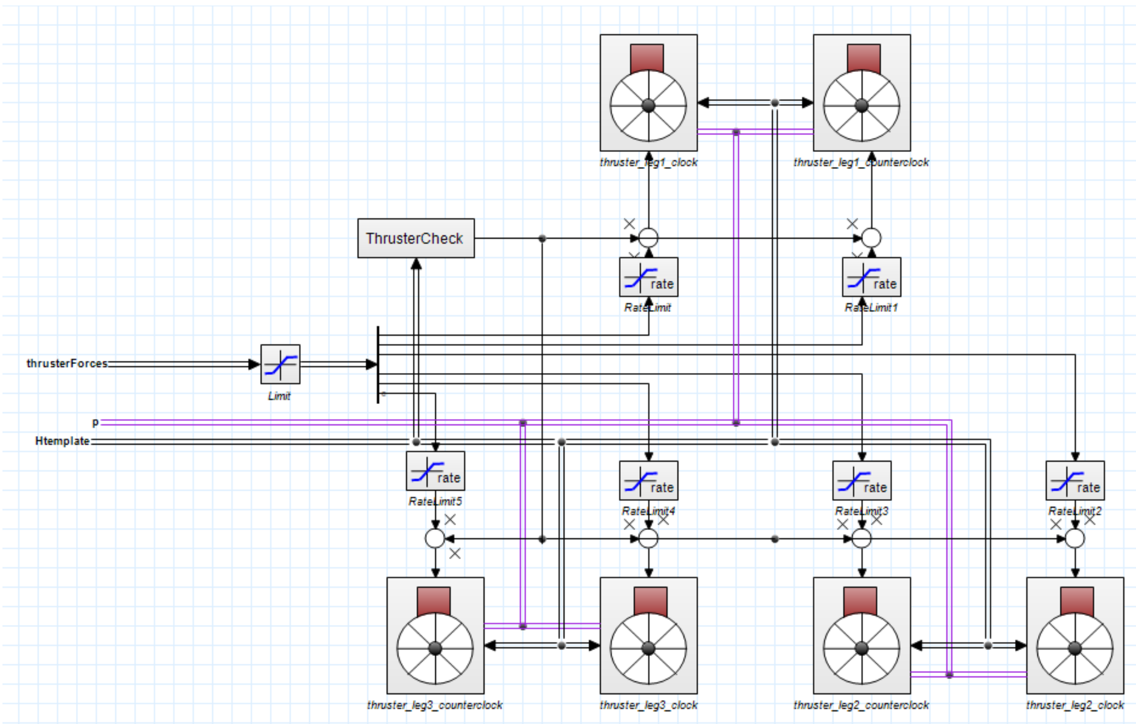


Figure 12: 20-sim model of the thrusters.

The second control system controls the extension of the feet. Based on the orientation (rotation around x- and y-axis) the extension of the feet is calculated and steered as a setpoint to individual PI controllers for the hydraulic cylinders.

3.6. Final Model

After all component models were developed and tested, an assembly model was created. Figure 13 shows the top level view of the assembly model.

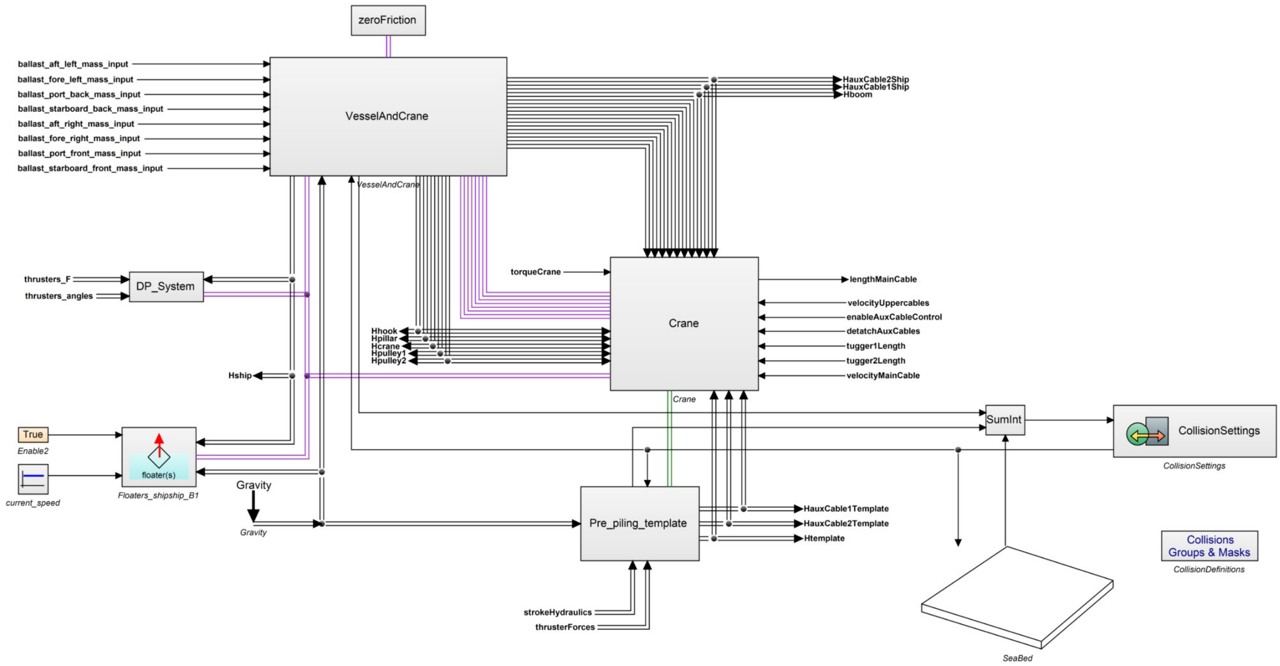


Figure 13: Final assembly model in 20-sim.

The assembly model was turned into a recipe and from this stage on is generated automatically using the physics builders. This gives a tight grip on the development process and ensures that no bugs will enter the model at this stage. After checking the model against a set of tests and ensuring it runs in real time a DLL is generated that will run the model in Unity.

4. Visualisation

Unity was used to create the 3D visualisation of the crane vessel and the 2D visualisation of the HMI.

3D visualization

The 20-sim DLL gives the position and orientation for every part of the system:

- vessel: hull, thrusters
- crane: luffing platform, boom, hoist blocks, cables, tag lines
- template: central frame, legs, linkages, feet.

In Unity these positions and orientations must be connected to objects which are enriched with shapes, materials and textures. Adding an environment containing waves, clouds and the sun brings the animation to life. Figure 14 gives an impression.

Figure 14: 3D animation of the crane vessel.

HMI

A human-machine interface (HMI) enables an operator to control a machine and check its current status. On a real vessel, there is an HMI for every component. Due to the limited time available for the internship, only one HMI was developed, showing the operation of the ballasting, crane and template functions together. Figure 15 gives an overview.

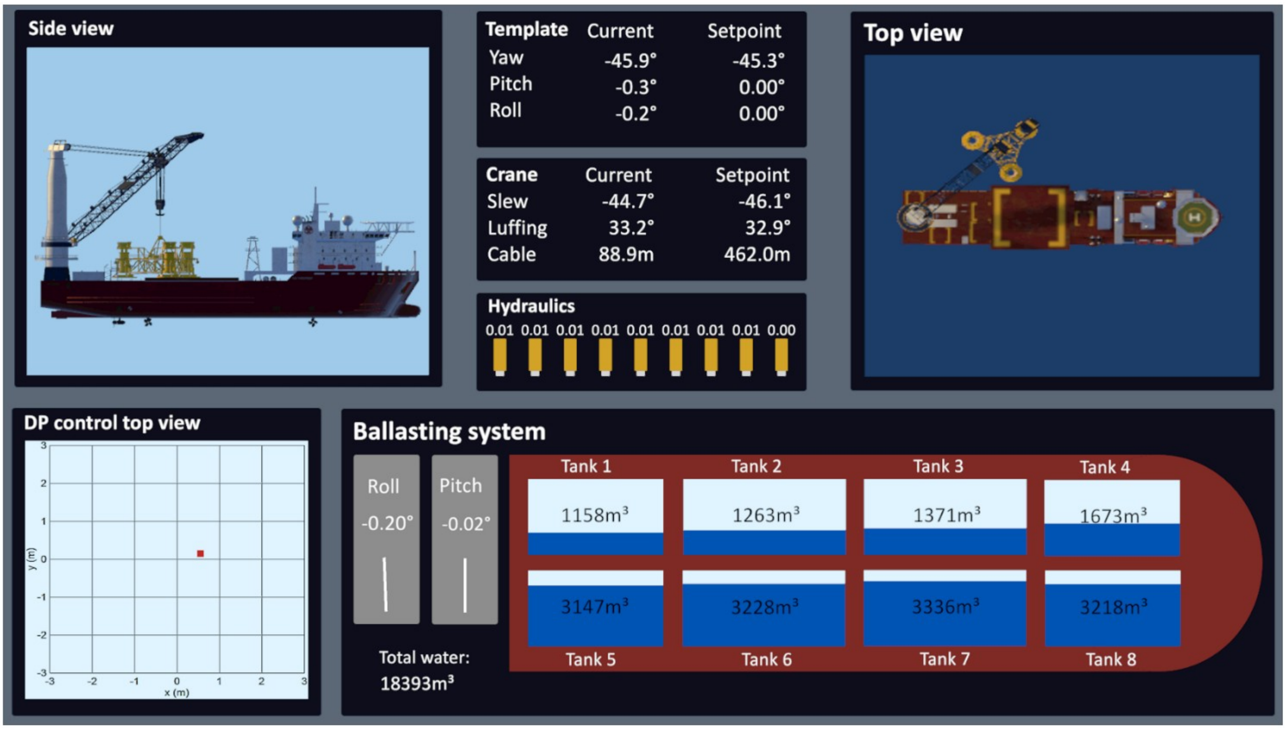


Figure 15: The HMI that was developed for the crane vessel.

The following elements are shown in the HMI:

- Side View: side view in 3D of the vessel.
- Top View: top view in 3D of the vessel.
- Template: The actual orientation and setpoint of the template.
- Crane: The actual values for the crane (as delivered by the 20-sim DLL) and the target values.
- DP: top view showing the actual position of the vessel (as delivered by the 20-sim DLL) and the setpoint (0,0).
- Ballasting System: The actual roll and pitch angle of the vessel and the level of the ballast tanks (as delivered by the 20-sim DLL)

All actual values and setpoints displayed in the HMI are calculated in the 20-sim DLL. Manual inputs like the crane operation can be done with keyboard keys or joysticks.

5. Simulation

With the model in 20-sim and Unity complete, simulations can be carried out. Simulations were done in various steps, as described in the following.

5.1. Manual Operation

During the initial simulations, we verified that the digital twin was operating correctly. Are the ballast pumps working? Does the crane respond to the joysticks? Are the values displayed in the HMI correct? During this phase, all connections between the 20-sim DLL and the Unity animations were checked.

5.2. Scripting

Manual operations on crane vessels are time-consuming and require significant operator input. To speed up the verification process, we use Python scripts to automate the simulations. These scripts provide repeatable input and save the resulting simulations as data files, plots, and animations.

5.3. Verification

To verify the correct operation of the model, simulations were performed at multiple levels:

- Vessel motions: Check the vessel's motion in waves. Compare with RAOs. Are the roll and pitch frequencies in line with the expected values?
- DP system: Check that it can maintain the desired location and orientation in the presence of waves and currents. Do the thruster forces remain within the expected limits? Figure 16 gives an impression of the outcomes of a DP simulation.

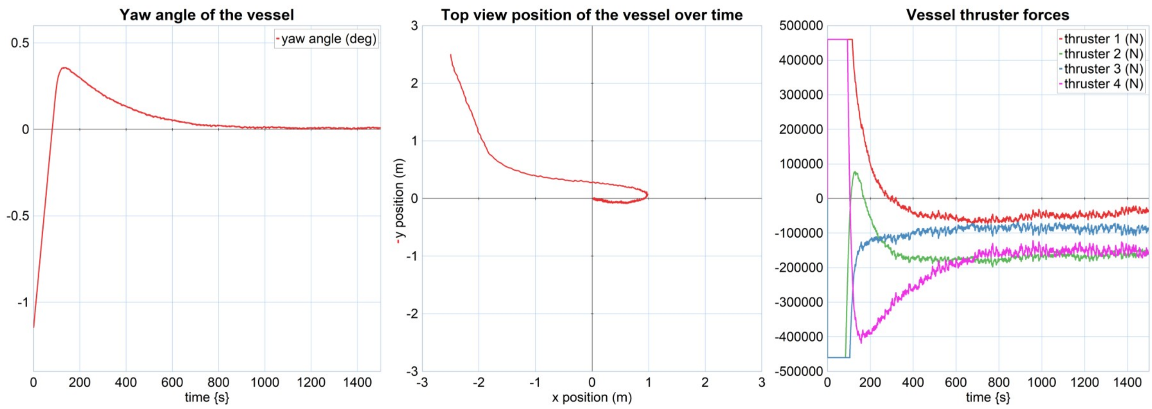


Figure 16: Verification of the DP system.

- Ballasting: Does the ballasting keep the vessel at the desired level? Compare offloading with and without ballasting.

Figure 17: Offloading with and without ballasting.

- Crane operation: Test hoisting with loads. Do the load cells give the expected values? Rotate the crane. Do the roll and pitch angles match the calculations?

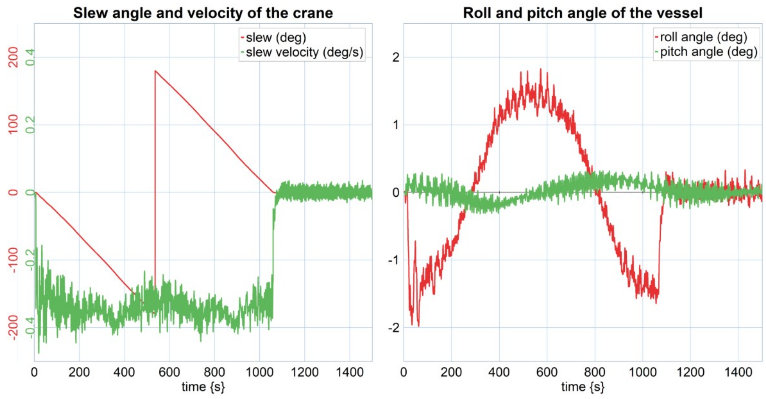


Figure 18: Roll and pitch angles during crane rotation with a test load.

- Template manoeuvring: Check that the desired location and orientation can be maintained under waves and currents. Do the thruster forces remain within the expected limits?
- Template levelling: Does the template level up to the expected values on an uneven seabed?

5.4. Operation

Finally the complete operation of lifting and placing the template was simulated. The process consisted of the following steps:

1. Turn on the ballasting system (automatic mode).
2. To prepare the crane, put the boom in the correct position and connect the main hook and tugger lines to the template.
3. Pull the tugger lines until they are no longer slack.
4. Lift the template to 1 meter and pull the tugger lines to the preset tension.
5. Lift the load to 5 metres and then rotate outboard.
6. Lower the load.
7. Remove the taglines once all thrusters are submerged by more than 3 m.
8. Turn on the thrusters and the thruster control system.
9. Lower the template to the seabed.
10. Level the template until it is upright.

The operation was carried out with 0.5 m significant wave height and a current of 0.1 m/s. Figure 19 shows four views of the operation. You can see a video of the operation on our website.

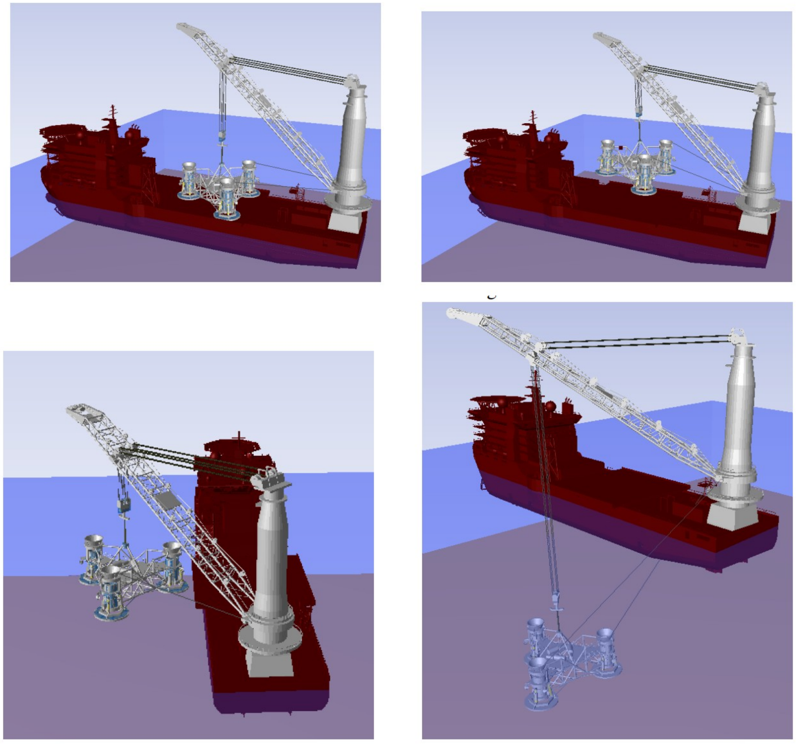


Figure 19: Various views of the operation.

6. Conclusions and Outlook

This project has demonstrated that, within a period of 14 weeks, two interns at Controllab can develop, verify and test a complete operation of a digital twin of a crane vessel with a pre-piling template. This demonstrates the maturity of Controllab's simulation tools and their ability to efficiently create digital twins of complex systems. At Controllab, we will continue to explore crane operations and develop digital twins. Our customers can use these to test lifting operations, train crane operators, and explore new equipment.

7. More Information

For more information on digital twins and their application in HIL simulation and training simulators in your company please contact Controllab Products.

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