# Introduction to Model-Based Design

## for Offshore and Marine applications

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# Disclaimer

# 1. Introduction

## 1.1. What is Model-Based Design

Model-based design is a technique that is used for the development and testing of systems under design. With model-based design text based specifications, operational procedures and performance descriptions are replaced by models and simulations. Model based design originates from the aerospace and automotive industry and is now spreading out to every industry where complex computer controlled machines are designed.

This technical paper focuses on the application of model-based design for offshore and marine applications. In offshore and marine engineering, control systems and mechanical structures are generally designed in parallel. Testing of the control systems is only possible after integration. As a result many errors are found that have to be solved during the commissioning, with the risks of personal injuries, damaging equipment and delays. With model-based design, the testing is done throughout the design, resulting in fewer errors during commissioning. That is why model-based design is now gaining widespread attention.

This paper will show the benefits that model-based design can bring to offshore and marine engineering and describes the technology that is needed. Several cases are described how Controllab has successfully applied model-based design in the marine and offshore industry in the last 10 years.

## 1.2. How is it used?

Controllab uses model-based design for the development of machines and control systems during the whole design cycle. This is best explained using the V-model for design.

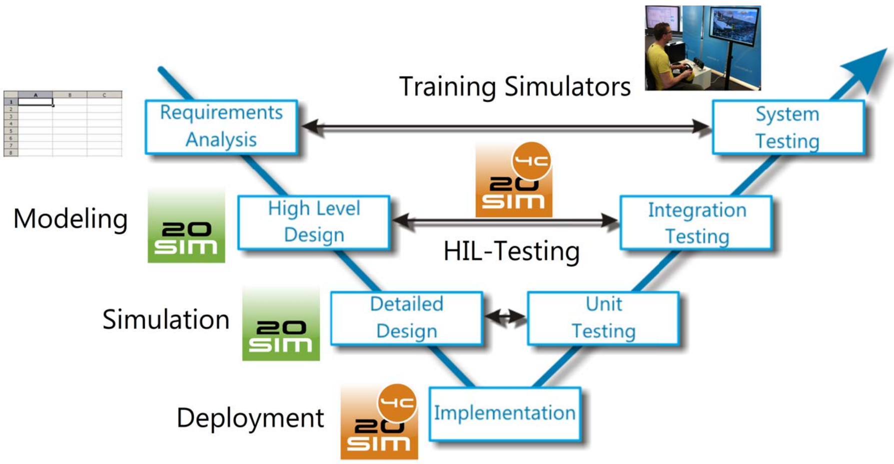



*Figure 1: The V-model for design.*

After the requirements have been made, a simulation model of the physical part of a machine is created. Then a control system is added. Using simulations, the correct operation of the control system and the machine can be tested. If design alternatives are foreseen, this procedure can be repeated for every alternative. Using simulations, trade-offs can be made to find the optimal machine and control system.

Finding the optimal system may require several iterations, adding more and more detail to the models at each iteration step. When the optimal design is found, C-code can be generated from the control system. This code can then be deployed on the control hardware (PLC’s or embedded systems).The control hardware will contain much more than only this generated C-code. Software will be added for the human machine interface, the safety layer, IO handling etc. To test if this is all working in harmony, the simulation model of the physical part of the machine is be reused. This is called hardware-in-the-loop (HIL)  simulation. With HIL simulation, the control hardware can be tested using a simulated machine.

During the integration of all the hardware components and the building of the prototype, tests will be applied to verify the correct operation of the machine. For computer controlled machines with many sensors and actuators, this can be quite a challenge. Therfore the simulation models can be used to develop a test plan and show the desired responses to the tests. This is called model-based testing.

*Figure 2: Training in VR using a simulated ship and passengers crane.*

Finally future users of the machine have to be trained to operate the machine. This is most effectively done by Integrating the HIL simulation with a 3D graphical display. This will show the simulated machine in 3D responding to the commands of the operator. This application of model-based design is called a training simulator.

# 2. Benefits

A paper written by M. Broy et al, describes an independent study in the car industry into the benefits of model-based design. The outcomes of this paper are confirmed by Controllabs 20 years of experience with model-based design in industrial projects. The paper states that model-based design will bring greater costs in the early stages of a design project, but these are more than recovered by the savings in the later stages. In this chapter we will describe the advantages and disadvantages of model-based design in more detail.

## 2.1. Process Redesign

Implementing model-based design in a company in general means a redesign of the existing design process. People have to be trained and new software has to be purchased and deployed. This will bring costs. It is our experience that this redesign will cost more than it saves when model-based design is not used intensively. The design team will then toggle between the old paper based design process and the new software based modelling process. The paper method will not be able to follow the quick iterations of the software and errors will creep in.

*Figure 3: Training on the job.*

Controllab helps companies to overcome problems that come with this redesign. We will temporary increase the design staff with our engineers and gradually introduce model-based design. By working on real projects and training on the job, the benefits and pitfalls of model-based design are well understood. The transfer of knowledge is done step by step, giving ample time to digest all the new information. It is our experience that within two years after starting with model-based design it becomes profitable. This is confirmed by M. Broy et al where it is found that on average, companies that are using model-based design intensively, have amortized the costs of process redesign in 3.5 years.

## 2.2. Saving Time

The cost of errors increase with the time it takes to discover them. Errors which are found late in a design project are notorious for the problems they can cause. They will require measurements, re-designs and testing. This means re-scheduling of the work, re-assignment of people working on the project and stealing away engineers from other projects.

In traditional design, testing of the specifications is done during commissioning. This means that errors in the product related to the specifications are found late. Companies not doing model-based design, on average find 30% more errors during commissioning. This is the main reason why companies implementing model-based design, report a significant decrease in missed deadlines.

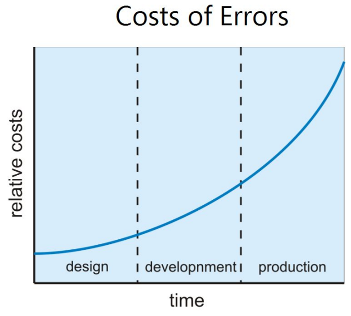



*Figure 4: Increasing costs of errors.*

## 2.3. Saving Money

Model based design will require greater development costs in the early stages of design because of the work involved in developing and testing models. These costs can be earned back and more. The first cost saver is a significant decrease in commissioning time, because of the significant reduction of errors. Another money saver is found when the real product is expensive. It may require many costly prototypes, the running costs may be high or expensive safety precautions may have to be taken. Model based testing will significantly reduce the number and length of the tests on the real product.  Significant money can be saved when the product is enhanced with new functionality. The re-use of models and simulations save a lot of effort during all phases of the design process. M. Broy et al, describes that on average, intensive model-based development gives cost saving around 27% and time savings around 36%. Overall maintenance costs are reduced about 15% compared to classical development and savings of 20% are reported when enhancing the functionality.

## 2.4. Increase Safety

In systems like offshore access bridges, where personnel safety is of the utmost importance, model-based design is extremely useful. Testing these machines for offshore is potentially dangerous and requires extensive safety procedures. By Using model-based design, tests can be run effortless during all stages of the design.

*Figure 5: Access bridges for personal transfer must have the highest safety precautions.*

HIL (Hardware-in-the-loop) simulation allow tests that would normally destroy or damage the real machine. Testing beyond the normal range of operation will reveal that if the control system can safely operate the machine. This is closely related to failure mode and effects analysis (FMEA). With FMEA  all possible failures in a design are identified and taken care of. HIL simulation allows to test all the items in the FMEA that are related to the control system.

## 2.5. Enhance Quality

The quality of products are closely related to the number of tests that have been carried out. Using model-based design, testing is carried out throughout the design process. If tests are carried out automatically a significant increase in quality can be achieved.

Using scripts, simulations can run automatically and the outcomes can be tested against the requirements. Scripts can be bundled and automated by including them in the built system that runs the scripts every time a change has been made to the models. These scripts can verify if the control system still meets the specifications and check the response against failure modes. In this way, a control engineer gets an immediate response to the changes made to the design and allows him to make corrections if required.

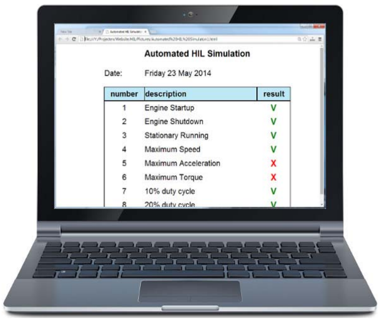



*Figure 6: Automated testing.*

# 3. Technology

During every step of a model-based design project, models are used. Time and money are saved when these models can be re-used. Controllab therefore uses specific software tools.

## 3.1. Requirements, Specifications and Design Descriptions

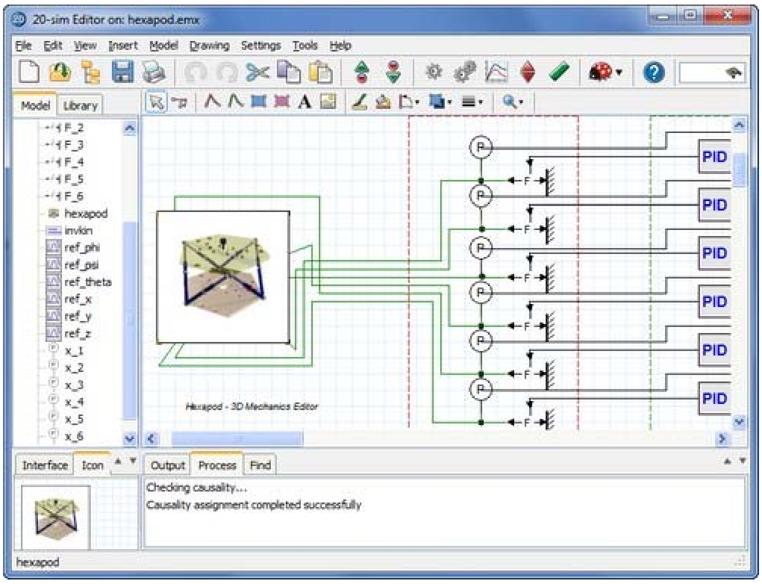
Every company has its own standards for describing requirements, specifications and designs and will use specific software tools to handle these. Controllab will generally adopt these standards and software. If no preference is made, we generally use spreadsheets for requirements and specifications and word processors for design descriptions

## 3.2. Modelling and Simulation

For modelling and simulation, Controllab will adopt to the standard software that is used by the customer. If no preference is made, we prefer to use our in-house developed simulation software “20-sim”.

### 20-sim

20-sim is a software package that allows the construction of machine models by combining physical building blocks. 1D and 3D building blocks allows an easy creation of 1D and 3D models of complex machines. 20-sim also has blocks to develop control systems.




The power of 20-sim is its ease of use and the large number of built-in tools that give support during all stages of a model-based design project:

1. Easy development of physical system models and control system models
2. Fast simulation with outputs of plots, files and 3D animation.
3. Tools for control system design
4. Tools for system optimization
5. Tools for the import and handling of measurements
6. Scripting and test automation
7. Tools for C-code generation for the deployment on PC’s and PLC’s (requires 20-sim 4C).
8. Tools for running of code and creation of measurement data (requires 20-sim 4C).
9. Tools for real-time HIL simulation
10. Tools for 3D displays and 3D VR

All tools except 20-sim 4C are built-in 20-sim. 20-sim 4C is an in-house developed extension to 20-sim.

### Matlab / Simulink

The Matlab / Simulink tool-suite is extensively used in the aerospace and automotive industry. The capabilities of the tool-suite are comparable to 20-sim, but in general much more expensive because of the many toolboxes that have to be purchased separately. The tool-suite is better than 20-sim, in generating certified C-code for the aerospace industry and is less suited for 3D display and VR.

### LabView

LabView was originally designed as a graphical programming tool for measurement data. This is were the package excels and outperforms 20-sim and Matlab/Simulink. The modelling and simulation capabilities of LabView requires extensions to the package and are less well designed.

## 3.3. C-code deployment

Most control systems in the offshore and marine sector are implemented on PLC's. A Programmable Logic Controller or PLC is a digital computer dedicated for the control of machines and systems. PLC's have a widespread use in industry because of their rugged design which make them suitable for operating in severe conditions.

*Figure 7: PLC controlling a ship propulsion.*

Most PLC brands support the five programming languages defined in IEC 61131-3: function block diagram (FBD), ladder diagram (LD), structured text (ST), instruction list (IL) and sequential function chart (SFC). Modern PLC's like the Bachmann M1 also support programming in C-code.

Much of the code running on PLC’s can be made perfectly well using structured text. This is code for handling the communication, reading and handling sensor data, monitoring the health of the system etc. The loop controllers and motion controllers of modern machines are better designed in a modelling and simulation package like 20-sim. This package allows you to simulate the response of these controllers and has special tools to assess the stability and performance. 20-sim can export control systems as C-code to the PLC.

## 3.4. HIL Simulation

Modern machines and systems are steered by computers (e.g. a PLC) with complex control systems. HIL simulation is a technique that used for the development and testing of these control systems.

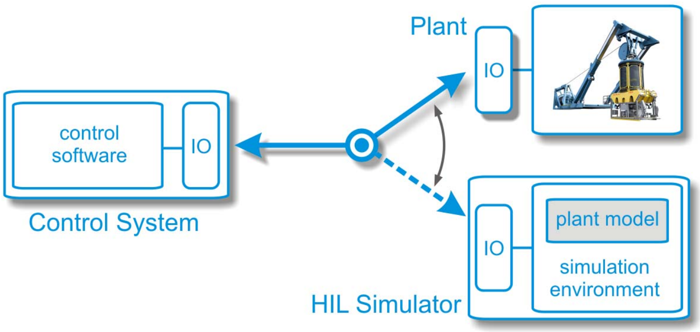



*Figure 8: Connecting the control system with a simulated plant.*

The machine or physical part of the system (which we call the *plant*) is connected with the *control system*, through actuators and sensors. With HIL simulation the plant is replaced by a simulation of the plant (which we call the *HIL simulator*). If the *HIL simulator* is designed well, it will accurately mimic the real *plant*, and can be used to test the *control system*. Therefore it is also named *HIL testing*. Some HIL simulators are equipped with 3D visualization and represent the plant so well that they can be used for training. These HIL simulators are called *training simulators*.

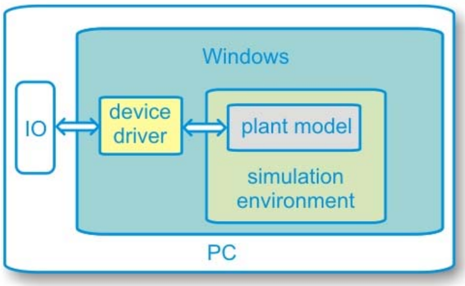



*Figure 9: Components of a HIL simulator.*

### Windows based Simulators

Controllab can build HIL simulators with the package 20-sim. The HIL simulator that Controllab usually provides is a PC with the Windows operating system and 20-sim. 20-sim is used to run the plant model. The connection with the control system is provided by IO from 20-sim which is connected with the control system. The simulation environment provides the proper communication between the plant model and the IO.

### High Speed Simulators

Windows is a not a real-time operating system. With special care it can be made fast enough to simulate in real-time most of the offshore systems. In some cases this is not good enough:

- The control system runs at high speeds ( > 100 Hz).
- The plant model has fast dynamics and only runs well at high simulation speeds.
- There is too much jitter (time delay between control system and plant model) which will make the system unstable.

Controllab can also provide a HIL simulator based on a PC with Real-Time Linux, which allows communication with a field-bus at high speeds (> 5 kHz) and has low jitter (< 0.1 ms).

## 3.5. Training Simulators

*Figure 10: Training simulator for an offshore crane.*

When a HIL simulator is equipped with 3D visualization and a human machine interface, it can be used for training. These HIL simulators are called *training simulators*. It allows operators to be trained in a secure environment without the risks of damaging the real machine and without the costs of the real machine.

Controllab can provide tailor made training simulators. The customer has to provide its control system including operator manuals and interfaces. Controllab will connect this with a custom built HIl-simulator and extend it with visualization modules and a trainer interface.

The visualization module will provide the operator with a 3D visualization of the plant interacting with the environment. The trainer module will allow the trainer to start, stop and monitor training sessions and store the results for later use. Various scenarios can be developed, allowing the trainee to learn to operate the machine and gain experience step by step.

# 4. Applications

The following applications show how Controllab has used model-based design in various projects.

## 4.1. Offshore Access Bridge

SMST is a company located in Drachten, the Netherlands which specializes in the delivery of lifting, transportation, drilling and pipe lay solutions, particularly for the maritime and offshore industry. SMST provides a range of Telescopic Access Bridges (TAB) that can transfer personnel safely to an offshore structure or the quay side. A recent introduction is the motion compensated TAB-M series. Controllab has designed the motion compensation control algorithms for this bridge.


*Figure 11: The TAB-M offshore access bridge.*

### Access Bridge

The TAB-M can be operated by vessel's crew, doesn't need large generators and is inexpensive to operate. Due to these key assets, SMST access system M series has gained a lot of interest from multiple offshore operators. The first bridge is already in operation and six more are being built. The M series is part of a range of four types of access bridge system offered by SMST. These include the S, M, L and XL, which vary in length from a minimum of 4m up to 58m, and can be active or passive motion controlled. One of the challenges for SMST was to develop a control system for the TAB-M, that is safe and can be re-used for the other types of bridges.

### HIL Simulation

With model-based design, a simulation model was used to design the control system of the bridge. This allowed a large set of destructive and non-destructive scenarios to be simulated to test the performance and safety of the control system. After the control system was been successfully tested using simulations, C-code was be exported to the PLC and coupled with the safety and communication modules. The resulting PLC was again tested by coupling it with the simulated bridge (HIL simulation). This allowed SMST to test large part of the FMEA tables weeks before commissioning.

### Operation

The commissioning was a large success. The bridge was delivered on time and has been successfully applied in a number of jobs. Convinced by this success, SMST has fully adopted model-based design and HIL simulation to develop a whole range of motion compensated access bridges and cranes.

## 4.2. Ship Propulsion

### Introduction

Kwant Controls was raised in 1937 as a manufacturer of nautical instruments. The company is located in the northwest of the Netherlands. With a worldwide market share of 30%, Kwant is one of the world's leading manufacturers of state-of-the art high-end nautical controls and systems.

### Propulsion Controller

One of the core products of Kwant are control levers for the remote control of marine propulsion plants. Marine propulsion systems typically consist of a combination of engine, propeller, gearbox, clutch and sub-assemblies. Remote Control is done from bridge level (WH Fwd, WH Aft, Port side wing or Starboard side wing). To achieve this, the levers are equipped with signal transmitters for engine RPM, clutch direction etc. that are wired to the propulsion plant control system.


*Figure 12: Assembly of ship bridge equipment with propulsion control units.*

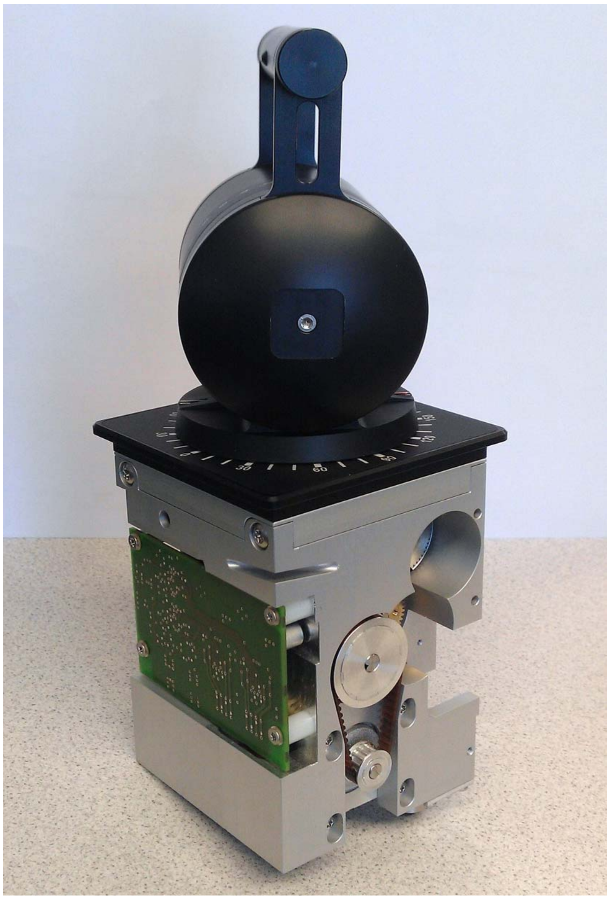


*Figure 13: Motorized Lever.*

The control levers are electronically connected. This means that all connected operating levers have the ability to synchronize the position of the operating lever, which enhances the use and increases safety in emergency situations. This synchronization also enables switching of the operating position without changing the control signals for propulsion plant (bumpless take-over). To achieve this synchronization, the control units are equipped with servomotors (see figure 2). Kwant Controls has enhanced the use of these servomotors by allowing them to give 'haptic feedback' to the operator. This will prevent the operator to push a lever outside the operating area by inducing vibrations. All control levers are connected to a propulsion control system which contains the main propulsion controller software. This controller translates the lever position into an engine speed and propeller pitch.

### Model-Based Design

The growing complexity of the propulsion control systems and the striving for continuous improvement led Kwant Controls to the adoption of model-based design. The modelling and simulation software 20-sim was adopted to form the cornerstone of a new design approach. One of the most important arguments for this was the fact that 20-sim uses a graphical representation of all the model components. Furthermore, 20-sim supports code generation, code deployment and HIL-testing for a range of embedded systems and industrial controllers. This allows Kwant to use a single software platform for the generation of a broad range of propulsion control systems.

## Lever Unit

The first experiences with 20-sim were gained with the design of a new operating lever. The lever mechanics, servomotor and drive were modelled in 20-sim and coupled to a controller model that not only allows lever synchronization but also gives haptic feedback to the operator by inducing vibrations and detents.

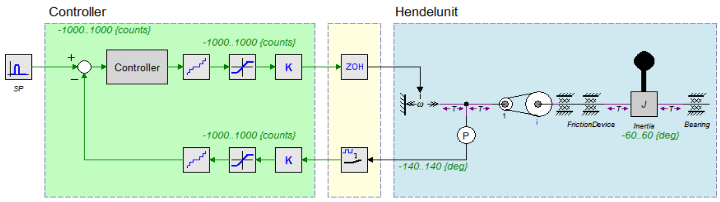



*Figure 14: 20-sim model of the servo controlled lever.*

After simulations showed the feasibility of the design, the controller code was exported to the program "20-sim 4C". 20-sim 4C is an extension to 20-sim which allows the deployments and testing of code on hardware. 20-sim 4C supports a range of hardware varying from low cost embedded systems to high grade industrial computers. For the lever unit, an embedded board with an ARM microcontroller is used. The code was directly deployed on this controller, showing a successful operation in tests.

## Case study

As a manufacturer of propulsion control systems, Kwant Controls has delivered and commissioned a lot of control systems for various types of vessels. The existing range of controllers were implemented in 20-sim and coupled to a model of the propulsion system. Figure 4 shows an overview with the controller (green background) and the propulsion system (yellow background). Simulations were performed to validate the correct implementation of the controller and test its correct operation under normal and abnormal conditions.

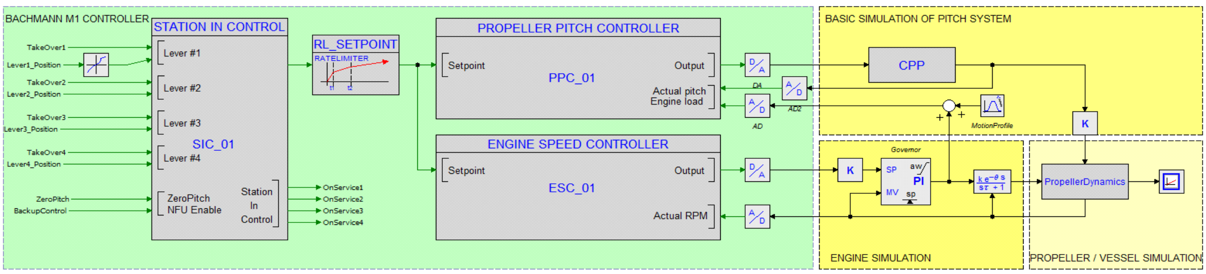



*Figure 15: 20-sim model of the propulsion system and controller.*

## HIL-testing

Kwant uses the Bachmann M1 controller hardware for its high end products. The M1 controller combines a traditional PLC with the ability to run custom C-code. The Bachmann M1 controller is supported by 20-sim 4C and this allowed Kwant to directly convert the controller model (green part of figure 4) from 20-sim to C-code that was deployed on the Bachmann M1 system.

Traditionally the propulsion control system would have been tested during a factory acceptance test and during commissioning onboard of the vessel, to gain confidence in the system. Instead, Kwant took a different approach using Hardware in the Loop (HIL) testing. With HIL testing, the ship hardware is replaced by a simulation model of the propulsion system.

*Figure 16: Propulsion control system.*

First C-code was generated from the 20-sim model of the propulsion system (the yellow part of figure 4). This C-code was deployed on the

Bachmann M1 system using 20-sim 4C. By exchanging the I/O signals of the ships propulsion system with the I/O signals of the simulation model, HIL testing could be applied. A batch of tests were carried out showing the correct implementation of the control system and validating it under a number of conditions. The HIL-tests were carried out in the factory of Kwant Controls.

### Results

To assess the benefits of model-based design, two versions of a propulsion control system were designed in parallel. One using the traditional tools of Kwant and one using the 20sim model-based design software and the HIL simulation. Comparing the results showed that:

- The design of the propulsion controller using 20-sim took some extra time. This was partly caused by design of the propulsion system model, partly by the simulations that were carried out to test the controller.
- Traditionally the controller was hand coded on in Bachmann M1 controller. Significant time (approximately one week) was gained with model-based design because of the automatic code generation out of 20-sim.
- Traditionally the generation of the controller documentation according to the applicable standards, would take quite some time because of the manual labor involved. Using the documentation features of 20-sim, this was done automatically.
- HIL-testing saved a considerable amount of time for the commissioning of the propulsion controller on board of the vessel.
- Future savings are expected because of the reuse of controller and propulsion models.


*Figure 17: One of the ships that is equipped with products from Kwant Controls.*

# 5. More Information

For more information on model-based design and the application model-based design in your company please contact Controllab.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|---|---|
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## Literature

M. Broy et. al, "What is the benefit of a model-based design of embedded software in the car industry", Emerging Technologies for the Evolution and Maintenance of Software Models, IGI Global, pp 410-443, 2011