Digital twin of a marine diesel engine

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Synopsis

Considering the high operating costs of a marine two-stroke engine, any kind of testing needs to be planed carefully. A cost-effective alternative for a brought field of testing activities is a digital twin based on a hardware in the loop (HIL) system. This set-up provides the possibility to perform tests on the original engine control system (ECS) with very low operation expenses and minimal risks. New ECS generations inlcude also smart signal monitoring. As a consequence, within the HIL system, a sensor or actor has to be replaced by a appropriate signal treatment by use of hardware and software. Combined with this signal conditioning, off-the-shelf hardware can be used for the simulation input and output. With the use of field programmable gate array (FPGA) and real-time technology, the ECS signals are interacting with a real-time software model of the engine and peripheral systems. This model needs top be validated in continuous iterations with measurement data from the field. Furthermore every new generation of ECS contains new and more complex software functionality and enhanced hardware. The modular set-up of the real-time software model and the hardware components on the HIL system allow to fulfill the needs of every new ECS with a fast reaction time. These adaptations are downward compatible for continuous support of the older generation ECS. This prevents also an early obsolescence of the HIL system. The HIL set-up allows the operator to run and test an ECS set-up with original software, configuration settings and hardware. Additionally it minimizes differences in utilization between virtual and real world. Designed as a mobile unit, it is a versatile testing installation which is as well an adequate tool for troubleshooting and education. It provides a higher level of safety, reduces the testing hours on the engine and avoids the risk of costly shut-downs and test interrupts.

Keywords: Digital Twin; Signal conversion; Marine systems; Process simulation

1 Introduction

The running hour of a marine 2-stroke engine - diesel or gas - is cost intensive. With the introduction of electronically controlled engines, a cost effective way to test new control software and its related hardware is a mandatory requirement. To fulfill such an integration-test specification, it is essential that the control hardware and software set-up on the engine simulator is identical with the original installation. To cope with this requirement, a digital twin of the engine was developed. All dynamic signals are generated according to the simulated engine state. The engine model for this simulation is based on a real-time system connected to FPGA controlled I/O modules. This allows the simulation of functions and failure cases to be tested with an authentic cross signal impact. The model is validated iteratively with real measurement data from existing engines. The more advanced new engine control systems (ECS) become, the higher are the requirements for the dedicated test environment. Modern ECS are monitoring actuators and sensors by means of intelligent I/O channels [1]. In specific cases, commercially available HW products can't be used for simulation as they are not covering all ECS HW requirements. Means e.g. to create an actuator twin, it is essential to develop corresponding signal converters. Those are on one side covering the ECS requirements such as resistance, inductance etc. and on the other side providing standardized signals for the simulator input. Another example are signals from resistance temperature detectors (RTD), which are quite numerous on a modern engine. To add this feature to the dynamic simulation, a tailor made hardware was developed and introduced to drive up to 23 RTD channels from the simulation controller over a serial interface. At the moment the simulation platform copes with three generations of ECS. All systems do run with the standard control software on the ECS. The simulation software for these three types is based on the same model, whereas the hardware layout for each system is adapted to its specific needs. These systems can be used for testing, troubleshooting or education with no change in their set-up.

2 The digital twin

Digital twin is a widely used term and many different variations and interpretations do exist. The abstraction level and also the development state of the original system defines the kind of digital twin which should be used. During a development process model-in-the-loop (MIL), software-in-the-loop (SIL) and hardware-in-the-loop(HIL) are the three most common used test variants [2]. The system which is described in this paper, is the

HIL model. Figure1 represents the finalised digital twin. This means that either a prototype or the finalized variant of both, the control software and hardware do exist and it will then be connected to the digital twin of the engine. The MIL and SIL testing is part of the control system development process. These tests are usually performed by software engineers at the system supplier and therefore they are not further treated in this paper.

Figure 1: The complete digital twin of a marine mixed fuel engine

2.1 Cost factor

A two stroke marine engine is one of the most efficient combustion engines. Owed to it's vast size and the power output of several MW, the sum of the consumables reaches a high level. The most obvious of these consumables are fuel-oil and cylinder lubricating-oil. In terms of shaft output power, a six cylinder installation was taken as a reference for these estimates. According to the technical information of several engine types the following numbers were taken for calculation [3] [4]:

- Diesel consumption: 180g/kWh
- Lubrication oil: 1g/kWh per Cylinder or 6g/kWh for the engine

Taking these numbers and the average annual price for these two oils [5], the following cost comparison can be made: After 60 to 160 running hours on full load, just these two consumables reached approximately the price for a digital twin installation. The span between these two numbers is the difference between a big- and a small-bore engine. The output power difference of these two engines is approximately 20MW, 7MW for the small-bore and 27MW for the big-bore engine. All the other expanses such as operator and testing staff, electricity, water etc. to run such an engine are not taken into consideration. Taking these numbers, it should be the target to lower the running hours for test purpose to a needed minimum. This is the case for test-bed engines and even more for engines in service. A digital twin can help to fulfil this target if it is used for all ECS related test cases. Mechanical and performance related tests still have to be performed on real engines.

2.2 *Safety aspects*

At the beginning of each test, a specific outcome is expected by the test engineer. Increased complexity of a system leads to increased risk of a wrong prediction and therefore a unexpected test result. In case of a marine engine, this can lead to a sudden test stop or even material damage which both is costly and time consuming. In worst case such kind of malfunctions can cause some harm to the operating crew. With the use of a digital twin in advance of such complex testing on the real installation, unexpected scenarios can be avoided, the failure risk is minimized and field testing time costs are minimized.

2.3 *Real control elements*

A main point in the specification of this digital twin was the use of original control components and system layout. This means that the complete control hardware and wiring is as close as possible to the one which is mounted on the engines. In addition the software which is loaded on the control modules is configured as for an equivalent engine. So the actual control system software is tested and the risk of software changes from test to real environment is avoided. An other benefit is that the ECS interfaces are the same as on the real installation. Means the test engineer is gaining experience with it in advance to the real running trials. There is also the potential to enhance the testing level on the digital twin by connecting it to real peripheral components such as e.g. remote control or safety system.

3 The working principle of the digital engine twin

Figure 2 illustrates the structure of the digital twin. The basic parts are the real-time model, the signal conversion and the ECS. These blocks are described in detail in this section.

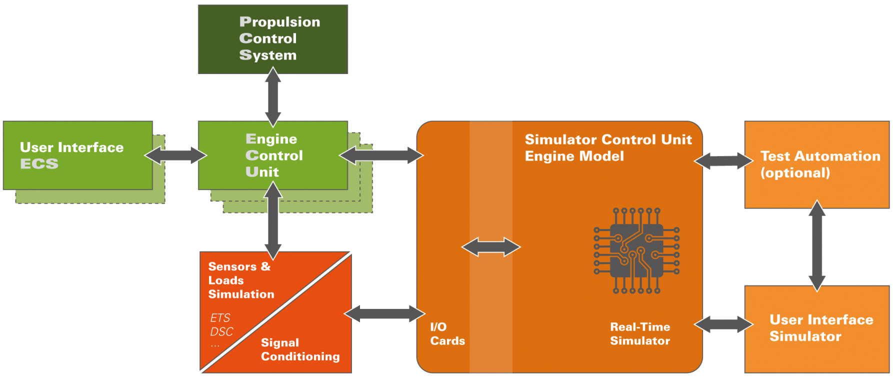

Figure 2: Block diagram of the digital twin

3.1 *3 System Layers for Simulation*

The core of the simulation is a cRIO Controller based I/O system from National Instruments [6]. Its field programmable gate array (FPGA) based I/O ports allow a individual treatment, calculation and processing for each channel type in order to fulfill the specific requirements e.g. for injection, combustion , exhaust valve etc. modeling. This FPGA layer interacts with the real time core of the controller unit where all the engine related main calculations are. The modular, LabView based model architecture offers the benefit of scalability - e.g. number of cylinders or bore - and efficient adaptability on new ECS requirements like dual fuel applications etc. It is crucial that signal resolutions and processing cycle times of the digital twin are matching the real environment as close as possible so that the ECS operates normally without taking any special measures. The top layer of the simulation is the graphical user interface, which is placed as a runtime executable on a Windows host PC. Based on these three layers FPGA, RT, Host all necessary functions can be simulated with the required level of process modeling.

3.2 *Converting signals*

There are two main reasons to convert signals from the ECS before passing them to the Simulation hardware. First, the ECS and its monitoring functions should be able to work as intended. This means driver currents and voltage levels have to be identical as if real actuator or sensor was connected. This leads to the second reason, often such values are out of range for off-the-shelf laboratory hardware. So signals need to be converted in order to cope with the ECS and the simulator system. Based on the ECS layout, signal converters can be designed in smart and compact multichannel layout. Like this one piece of hardware can handle a larger number of channels. With this workaround the price per signal can be kept low and design remains compact.

3.2.1 Driver signal converter

The driver signal converter (DSC) is designed for fast and accurate current measurement of pulse width modulation (PWM) current controlled drivers. All real components such as injectors and hydraulic valves are replaced by dummy loads. Dummy loads can be simple resistive loads or - more advanced - coils, in case inductive loads are mandatory. The current measurement device is based on the proven hall sensor technology method. This way, the impact on the current circuit is minimized compared to a conventional shunt-resistor measurement. The converted signals on the simulator side are provided as an analogue voltage (0...5V) and a digital signal (5/24V). The analogue output represents the measured current curve on the driver channel. The digital output is available as 'High Threshold Logic' (HTL) or 'Transistor-Transistor Logic' (TTL) level in case only the timing of the driven signal is needed. The module in Figure 3 can convert six high side driver signals and two PWM signals.

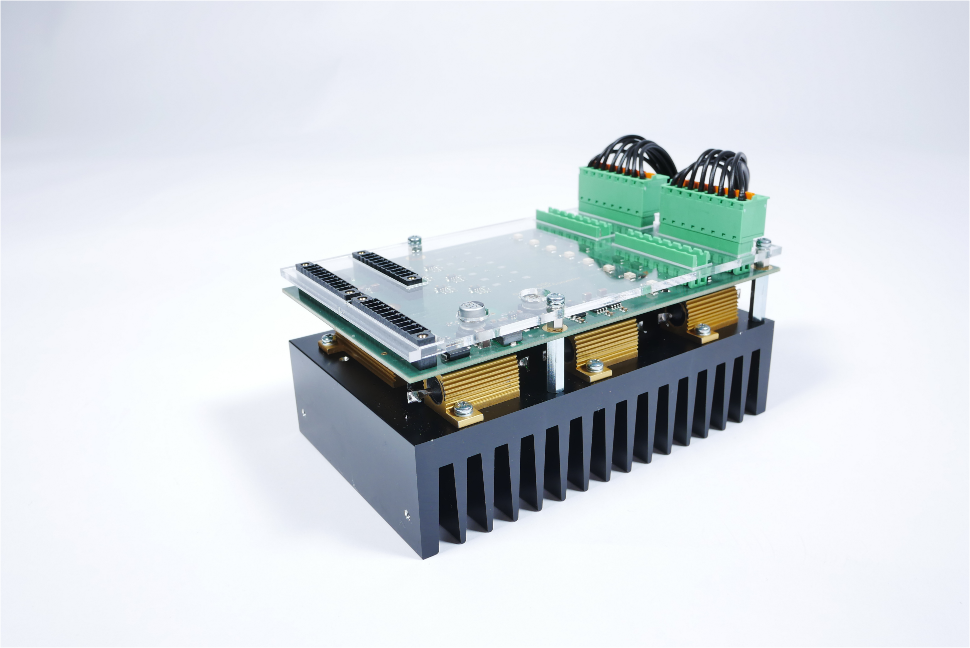

Figure 3: Finalised DSC module

3.2.2 Engine temperature simulator

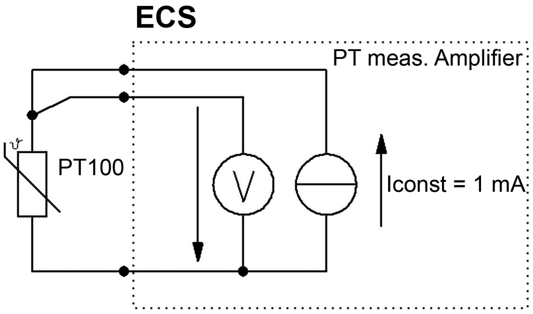

Figure 4: Simplified PT100 measurement standard amplifier discrete electric circuit

Figure 4 illustrates the simplified principal of temperature measurement with a resistance temperature detector (RTD) and a discrete electronic circuit. Within the digital twin the PT100 and PT1000 RTD methods were used, these signal types are called PTX to include both. Without any error handling and plausibility checks. The sensor driver supplies a constant current of 1 mA for the measurement circuit. This 1 mA is the fundamental constant for the Temperature calculation related to the voltage drop over the PTX resistor, which is variable. If the resistor value varies according to the surrounding temperature, the voltage drop is changing according the ohm law. By post processing the voltage values, the effective temperature can be calculated.

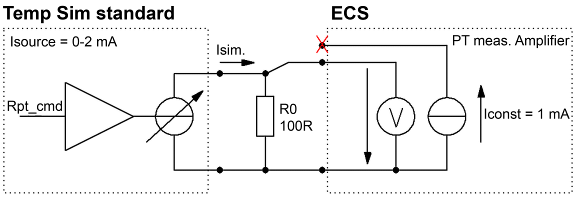

Figure 5: Simplified PT100 signal simulation for standard discrete electronic circuit

For the temperature simulation, the constant current pin is not connected, as figure 5 indicates. Older ECS do not monitor the output of this constant current. In this case an external current source with the range of 0 - 2mA can be connected. R0 is selected according the zero Value of the PTX at 0°C, which is 100Ohm or 1000Ohm. The variable PT100 resistor is simulated with this external current source. In Table 1 the correlation of these three values is illustrated.

Table 1: PT100 ranges

Simulation current $[mA]$	**V drop 100R resistor** $[mV]$	**Temp.** $[C]$
1.0	100	0
1.5	150	131
2.0	200	266

The temperature calculation is based on the constant current of the measurement circuit (1mV). The standard circuit does not monitor that the constant current of its circuit is not in use and a manipulated current is used instead (Figure 6).

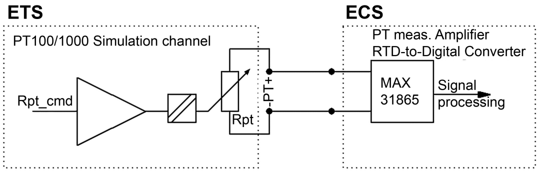

Figure 6: PT100/1000 signal simulation for RTD MAX31865

The more advanced and complex the ECS gets, the more effort for the signal simulation of certain sensors is required. Often these complex systems use e.g. the temperature measurement chip MAX31865. This chip performs a lot of plausibility checks and error case controls. Based on this, the sensor signal conversion of the simulation needs to be enhanced too. Due to the very specific application, the electronic components for the PTX signal conversion are operated out of manufacturer specification.

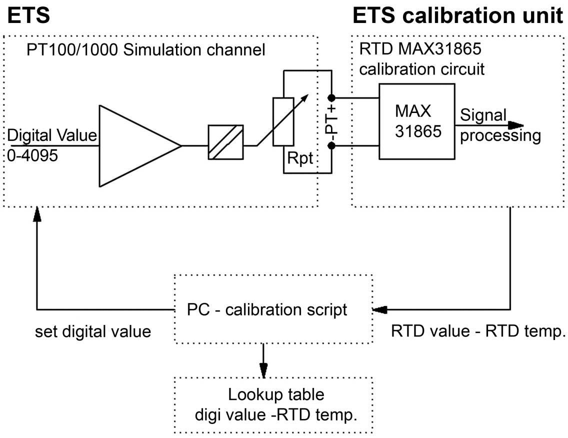

Figure 7: Calibration process for each channel

A channel individual signal calibration before commissioning is required. This includes also the on-board reference channel on the ETS (Figure 7). This calibration is performed once before the card is used in the digital twin. The calibration procedure leads top a look-up table, which is part of the simulating software. With each start of the simulation the correction values are loaded and the corresponding value is applied to its channel. With this solution, manufacturing tolerances of the build in components are compensated. To avoid a signal drift caused by variation of the ambient temperature, the ETS is equipped with a reference channel. This reference temperature is used to adjust the simulated temperature outputs according to the environmental temperature inside the digital twin.

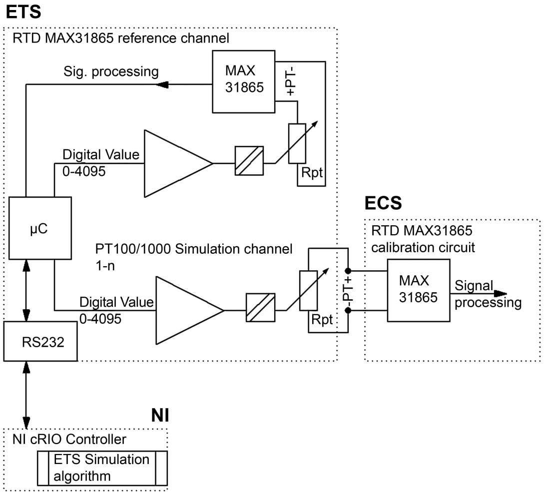

Figure 8: ETS simulation set-up

Figure 8 represent the simplified hardware architecture for temperature simulation with all corresponding components which are the ECS, the real-time controller with the physical model and the ETS for the electrical signal generation to supply the sensor inputs at the ECS.

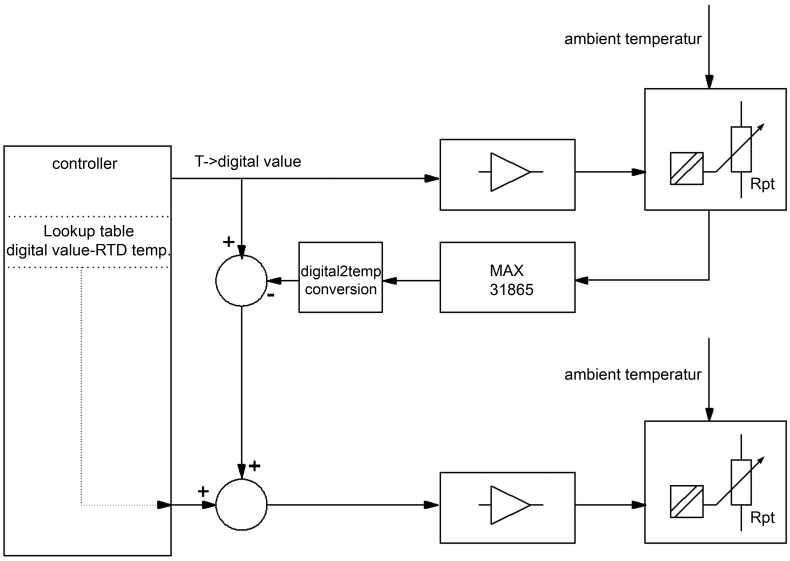

Figure 9: simplified control process temperature simulation

Figure 9 above presents the simplified control process to keep the simulated temperature signal stable and compensate the temperature drift caused by the influence of the ambient temperature. Based on the calibration look-up table all temperature channels are set to the correct and individual output level. The reference channel provides the correction for the thermal component drift due to ambient temperature variation. This signal correction value is applied to all channels.

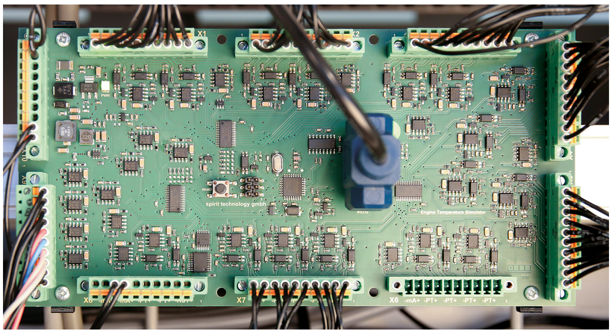

Figure 10: Engine temperature simulation card

Additionally, the ETS also includes 16 analogue 0-20mA outputs which can be used to cover other monitoring channels to the ECS. The ETS outputs are controlled via standard RS232 interface and can be used as a stand alone desktop unit or integrated part within a simulator.

Table 2: ETC card specification

Number of channels	**Description**	**Type**
31	PTX	Output
1	Reference channel PTX	Output *On-board only
16	0 - 20 mA	Output
1	RS232 interface	-

3.3 ECS

The engine control system is a network of various control modules distributed over the engine. As such, the architecture guarantees the engine availability function in case of a module break. All these modules communicate over a serial communication interface with each other. Additional redundant field-bus interfaces allow the communication to propulsion control, ship automation and other peripheral systems. For best test coverage it is important to leave the architecture for the digital twin as close to this original layout. Nevertheless, depending on various aspects like intended use, available space, budget or required mobility of the system, certain compromises need to be done. This might be the case in optimizing the power supply concept, cable length and cross-sections or the number of cylinders. But optimization must not compromise the use of standard ECS SW application and configuration.

3.4 Engine Model Validation

The validation of the physical engine model is a continuously ongoing process. There are several aspects which have to be validated. Most obvious for validation is the comparison of simulation signal outputs with real engine measurements. A good example for such a signal is the firing pressure. Compression and firing pressure calculation needs to be not only on the right level throughout the whole load range. Also the shape of the pressure-curve , representing heat development over one revolution, must represent the physical process as close as possible. This is important because the modern ECS require accurate mean effective pressure (MEP) calculations e.g. for operation with alternative fuels. Another example is the fuel pressure regulation system for a common rail injection system. Depending on Fuel type, temperature and therefore viscosity and also the condition of the fuel pumps the control loop varies its transfer function parameters.

A further very important aspect for model validation is to continuously gain practical experience with marine engines in the field. Feedback from service, measurement and test engineers is a valuable source to improve the engine model of the digital twin. Reported cases from the field are a very important and efficient way for validation and improvement of the engine model on the digital twin. Improving the model by above case and data sources over more than a decade, the digital twin achieved a high level operational compatibility to a real installation.

4 Use cases

4.1 Testcases

There are different demands on testing, depending who is performing the test. Following are some test procedures which can be preformed with the digital twin.

- Configuration test
  With this test a ECS software configuration can be tested preliminary to field deployment. It is performed to make sure that a new configuration is working as expected and all parameters are set correctly.

- Functionality and integration test
  During development of a new ECS functionality, the developer do mostly work with SIL tests. If these tests are satisfying, a new software version of the ECS can be produced and this one is then operational for the first time on the digital twin . With the functionality test the interaction with the control hardware and also with a different engine types can be tested. Beside the new functionality aspects also Processor load and data communication are tested and recorded.

- Complementing field test
  Field testing and development teams do have tight time schedules during engine running shifts and the focus usually lies mainly on performance and mechanical component aspects. The digital twin can hereby improve the efficiency by providing a parallel testing facility with focus on automation and ECS software. This allows the ECS development crew to reproduce used cases and continue testing whilst the engine is under inspection, in preparation or running up.

- Manual and automated test
  In addition to the manual test, where the operator defines the running states of the engine an automated test can also be performed. Preliminary to the test, a test sequence will be defined. This sequence can then be replayed on the digital twin, as often as required. This means that dynamic long time tests can be performed without an operator at the digital twin. All test results will be logged during the test and is analysed after finishing the sequence. Automated test sequences increase the repeatability of cases.

- Service claims
  ECS related service claims from the field can be reproduced and investigated on the digital twin. This supports the service engineer analysing a case and identifying the root cause of it. It is also supportive to see if specific cases are really automation related or potentially caused by other, e.g. mechanical or hydraulic phenomenons.

4.2 Education and training

A HIL digital twin with the original ECS hardware on it, can very well be used to educate different levels of engine operators.

- Crew education
  Ship crews can be educated in different fields. One aspect is the normal operation. Here the operator learns how to handle the engine equipped with a specific ECS type. This experience can be gained without the risk of breaking anything. A further training aspect is the recognition and correct reaction on malfunctions of the engine. To train this specifically, sensor feedbacks can be adapted from a third PC by the trainer. On top of this the crew can also learn how to perform investigations and measurements on the ECS modules during engine operation.

- Service personal
  On this education level the focus lies clearly on handling modules, downloading ECS software and perform a commissioning as well as troubleshooting, analysing and performing measurements. Since all modules are the original ones with their respective cabling, all measurements can be taken with the correct service tools and the results can be interpreted immediately. Some actions on the ECS may cause an engine slow- or even shut-down if they are preformed incorrect. These hands-on training sessions give the service personal the possibility to learn critical procedures in a realistic environment but low risk. So they will perform it later with other stress impacts on the vessel with good confidence.

- As part of a complete ship simulator
  All interfaces provided by the HIL system of the described digital twin, are considered to deliver all necessary data for any additional system on board of a vessel. This means the digital twin can be well integrated in a virtual vessel simulator and is therefore a perfect complement to purely virtual training facilities.

5 Conclusion

Due to the long product life cycle of a marine engine, a variety of generations of control systems are in operation. The continuous feedback from operators provides a proof of concept at one point. But it also allows a continuous adaptation, expansion and improvement of the engine model and the actual functionality of the digital twin. Special tools for training were developed to improve the training contents on operator and expert level.

To cope with constantly growing requirements in terms of monitoring and safety on ECS side, also the the digital twin needs to improve. In that respect, not all features can be covered by only adapting the engine model or adding some off the shelf I/O modules. It often requires also some customized and smart interface engineering

A close contact with control system makers made it possible to react fast on changes in the ECS modifications. Using these systems allows to improve both sides, the HIL system and the ECS in the same time. Adaptations of the digital twin, on hardware and software side can be made time efficient, as the modular and scalable set-up of the installation allows to focus direct on the part to be improved. To provide even more flexibility of this digital twin, solutions for remote access are considered. On one hand for online support and upgrades of the software, on the other for live assisting tests and trainings.

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