This report documents the outcome from a project funded by «Utlysning av midler til innovativ utdanning for prosjekt med rektorstøtte inntil 250000 kroner og varighet inntil 2 år.»

Report on the use of digital twins in engineering education

R/V Gunnerus in marine technology course material as a use case for development of digital services

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Abstract:

This report documents the outcome of a pre-project for innovative education that develops a basis for a digital twin of NTNU's research vessel R/V Gunnerus, and the use of that in the marine technology study string courses. Five engineering students at NTNU in Trondheim conducted the development tasks during the summer and fall of 2018. This report primarily documents the development work conducted, and the identified possibilities for use of a digital twin of R/V Gunnerus in education, with particular emphasis on specific courses offered as part of the 5 year Master of Science programme at the Department of Marine Technology. The conclusion is that the use of digital twin support in engineering discipline education can contribute to both strenghtened discipline insight, and also insight into digitization of products and engineering processes. The report has been produced at Department of Marine Technology and Department of Mechanical and Industrial Engineering at NTNU in Trondheim. A summary video of the project can be found here: **Gunnerus Digital Twin Demo Video**.

Utvidet sammendrag

Denne rapporten dokumenterer resultatene av et rektorfinansiert prosjekt for innovativ utdanning, som legger grunnlaget for en digital tvilling av NTNUs forskningsfartøy Gunnerus. Formålet med prosjektet er etablering av en digital tvilling som kan være et innovativt bidrag i ingeniørdisiplinutdanning. En digital tvilling av FF Gunnerus vil gi nye muligheter for studenter til å tilegne seg kunnskap, både disiplinkunnskap, gjennom økt innsikt i skipets sammensetning og funksjonalitet, samt kunnskap om sensorinstrumentering, dataanalyse og generell digital kompetanse. FF Gunnerus er et spesielt godt utgangspunkt for prosjektet, ettersom NTNU besitter et fysisk skip, i tillegg til en digital tvilling av det fysiske skipet, og vil ha tilgang på begge. Aktiv bruk av en digital tvilling av FF Gunnerus vil gi innsikt i fremtidens ingeniørplattform, og bedre studentenes evne til å koble disiplinkunnskap med digital kompetanse.

Fem ingeniørstudenter ble ansatt sommeren og høsten 2018 for å starte arbeidet med utviklingen av den digitale tvillingen av FF Gunnerus. Studentene jobbet om sommeren ved DNV GL ved deres hovedkontorer på Høvik, og fikk også veiledning av Siemens NX-leverandør Digitread i Sandvika. Leveransene gjennom sommerjobben inkluderte 3D-modell av FF Gunnerus, utvikling av produktmodell for FF Gunnerus, oversikt over sensorinstrumentering, strukturering og etablering av tilgang til sensordata, samt integrasjon av disse elementene gjennom DNV GLs Veracity dataplattform. I løpet av høstsemesteret har studentene jobbet videre med integrasjon av den digitale tvillingen av FF Gunnerus i fagplanen innen det fem-årige masterstudiet i marin teknikk, samt med eksempler for bruk av den digitale tvillingen i fag innen produktutvikling og produksjon, og ingeniørvitenskap og IKT. Denne rapporten omfatter både beskrivelser av det grunnlaget som er lagt for en digital tvilling, samt de mulighetene som er identifisert for bruk av en digital tvilling av FF Gunnerus i studieprogram innen ingeniørvitenskap. For enkelte fag, spesielt innen maskineri og hydrodynamikk, kan en digital tvilling av FF Gunnerus allerede tilføre stor verdi, ettersom sensordata samlet inn fra fartøyet kan benyttes i det eksisterende undervisningsopplegget.

Prosjektet har vist seg å være svært lærerikt både for de studentene som har stått for utviklingsarbeidet, for de vitenskapelige ansatte som har veiledet arbeidet, og for de industrielle samarbeidspartnerne i DNV GL og Digitread. Sett fra studentenes side har arbeidet med en digital tvilling av FF Gunnerus allerede gitt et konstruktivt bidrag til læring av disiplinkunnskap innen ingeniørvitenskap og økt digital kompetanse. Videre innarbeiding av digital tvillinger i utdanningsløpet i marin teknikk, produktutvikling og produksjon, samt ingeniørvitenskap og IKT, kan forventes å gi tilsvarende læringseffekt til et langt større antall studenter.

Veien videre etter dette rektorstøttede prosjektet vil omfatte oppgaver som må til for å sikre en fullverdig digital tvilling av FF Gunnerus. For det første vil det være nødvendig med videre sensorinstrumentering av FF Gunnerus, og etablering av kommunikasjonsplattformer for kontinuerlig tilgang til sensordata fra fartøyet. For det andre vil det være nødvendig med videre utvikling av matematiske modeller for økt innsikt også fra prosesser som ikke måles direkte, det vil si etablering av virtuelle målepunkter gjennom simulering. For det tredje må det etableres tilgang til den digitale tvillingen for studenter, enten gjennom en web-basert løsning eller en mobilapp. Dette vil muliggjøre innføring av digitale tvillinger for aktiv bruk i ingeniørutdanning, og gi studentene muligheten til å «adoptere et skip» i eget utdanningsløp.

En video av FF Gunnerus digital tviling utviklingen er laget av studentene i prosjektet, og kan finnes her: **Gunnerus Digital Twin Demo Video**.

Video summary: R/V Gunnerus Digital Twin Innovative Education Project

An information video for the R/V Gunnerus Digital Twin Innovative Education Project can be found here: **Gunnerus Digital Twin Demo Video**.

The information video is a supplement to this report documenting the work of the Gunnerus Digital Twin project. In the video, different building blocks of the digital twin foundation are illustrated, as well as the resulting digital twin viewer. The building blocks include the sensor information and data, the 3D model made in Siemens NX, and the product model from DNV GL's Nauticus Production System.

A digital twin is a digital representation of a physical asset, its related processes, systems and information. There are many use-cases for a digital twin, such as condition monitoring and simulations. The objective of the project was to begin the creation of a digital twin and demonstrate the potential of such a twin for educational purposes.

The digital twin is made up of three main components; sensor information and data; a 3D-model made in Siemens NX; a product model from Nauticus Production System. Different sensors transmitting data are placed in the model, and the properties and data of relevant sensors is available in the Digital Twin viewer. Examples of components with sensors include the Azimuth Permanent-Magnet thrusters, the motion reference unit, and the bow tunnel thruster. The 3D-model was made as an as-built model of the vessel through Siemens NX, including general arrangement and basic design. The product model is based on a DNV GL standard, providing a generic structure of all relevant information about the vessel, including a decomposition of ship and system functions. The product model is accessed through the digital twin viewer.

The Digital Twin viewer is a web-based solution that allows quick and easy access to the digital twin through DNV GL's Structure Insight software. The user-interface is smooth and intuitive, and is customised to the properties of the vessel. In the viewer, each component can be selected and isolated, and there exists a detailed mode which brings up known information about a component. There are several filters that can be applied, such as a sensor filter. Applying the sensor filter highlights different sensors, where the red colour marks that the data of the sensor can be extracted.

The detailed mode can also be applied to sensor components by choosing the desired component in a menu to the left. The detailed mode includes the name and function of each sensor at the chosen component, as well as data visualisation, the product model, and active workspace in Siemens NX.

For the data visualisation, a digital dashboard appears, where different historical data is visualised. Multiple parameters such as the position, engine speed, and power is included. The dashboard has several different visualisations available. An example is the data from the motion reference unit, where the motions of the vessel are show together with their rate of change.

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1. Introduction

Digital competencies is already an important part of engineering education, but the full potential of digitalization has yet to be taken advantage of in the teaching of marine technology discipline knowledge. Learning outcomes in marine technology and other engineering disciplines can be greatly enhanced by reducing the distance between theory and practice. A reduction of the distance between theory and practice can be enabled by active use of digital twins as a source of practical examples, letting students essentially "adopt a ship", in turn making the key theoretical learning points stick. This has the innovative potential of truly digitally enabled engineering education.

NTNU's research vessel Gunnerus constitutes a first asset upon which a digital twin for educational purposes can be developed. This is an asset for which NTNU owns the data, and an asset which students can access through courses and project work already. A digital twin of R/V Gunnerus will further increase the student access to, and use of R/V Gunnerus. Hence, a significant added value can be extracted from the existing vessel, beyond its current use, by increasing the digital accessibility to R/V Gunnerus, including shipboard sensor data and digital ship models. Additionally, by gaining experience with development and operation of a digital twin of R/V Gunnerus, future projects can be undertaken to develop digital twins of other assets as well, including vessels and other marine structures to which access can be supplied by industry.

The purpose of the current Rector-funded project is therefore i) to establish the foundations of a digital twin of NTNU's research vessel Gunnerus for use in engineering education, and ii) to increase the level of knowledge about digitalization in marine technology, in particular to understand the value chain from shipboard sensors to digital maritime services, with a particular emphasis on education.

The remainder of this report will i) document the background for the Rector-funded project in further detail, including previous R/V Gunnerus-based marine technology research, and the foundations for the digital twin, ii) document the results of the project, including the digital twin functionality that has been developed so far, and outline the use cases for the R/V Gunnerus digital twin in the 5-year MSc study programme in marine technology.

2. R/V Gunnerus

2.1. Vessel description

NTNUs research vessel Gunnerus is a platform for marine research, including biology, chemistry, technology, geology, archaeology, oceanography and fisheries research. The vessel was designed by Polarkonsult, built by Larsnes Mekaniske Verksted, and put into operation in 2006. The ship has a dynamic positioning system and a Kongsberg HiPAP unit for high-precision acoustic positioning, useful during ROV operations and for positioning of other equipment. The vessel is shown in Figure 1.

Figure 1: Research vessel Gunnerus.

The complete technical specifications of R/V Gunnerus are found in NTNU (n.d.). Note that certain changes has been done, since the vessel was delivered. First, the propulsion system was retrofitted in 2015, when Rolls Royce Permanent Magnet Thrusters (PMT) were installed, with R/V Gunnerus acting as a test platform for this new equipment. To adjust for the added weight of the new propulsion system, the trim was subsequently adjusted by adding lead plates at the tank top near the bow of the vessel. To improve vessel performance, a lengthening of the vessel is planned. The lengthening is expected to be finished during the spring of 2019.

2.2. Use of R/V Gunnerus as a ship technology research platform

The primary, intended use of R/V Gunnerus was originally as a platform enabling different forms of marine research. To the extent that it has been used for marine technology research, the main focus has been on testing of underwater vehicles like ROVs. The ship has only to a limited extent been used for a purpose of researching ship technologies.

The use of R/V Gunnerus as a platform for research and education purposes is now increasing. Important results of the work stems from two research initiatives. First, the use of R/V Gunnerus as a test platform for the PMT propulsion system generated research in hydrodynamics. Second, the Center of Autonomus Marine Systems and Operations (AMOS) conducted testing of dynamic positioning algorithms developed in PhD research projects. A collection of cases from research is presented in Table 1.

Table 1: Overview of previous use of R/V Gunnerus as a ship technology research platform.

Marine technology domain	Description	Reference
Hydrodynamics	Sea trials to document speed and maneouverability before propulsion system retrofit	(Selvik, Berg, and Gavrilin 2015)
Hydrodynamics	Sea state estimation based on data from sea trials (pre-propulsion retrofit)	(Nielsen, Brodtkorb, and Sørensen 2018)
Hydrodynamics	Sea state estimation based on data collected during testing of new control algorithms for dynamic positioning	(Brodtkorb, Nielsen, and Sørensen 2018)
Machinery systems	Co-simulation studies of the effect of the propulsion system retrofit	(Skjong et al. 2017)
Control systems	Testing of new observers and control algorithms for dynamic positioning	(Brodtkorb et al. 2018; Skjetne et al. 2017)

The first example are the sea trials conducted during 2013, before the ship was equipped with the new Rolls Royce PMT propulsion system. The sea trials at that time were conducted to document speed and maneouverability before changing the propulsion system (Selvik, Berg, and Gavrilin 2015). The sea trials also aimed to generate data to make comparisons between full-scale measurements, model tests and simulation of ship maneouvers (Selvik, Berg, and Gavrilin 2015).

The seakeeping data collected during these sea trials were later used for sea state estimation by Nielsen et al. (2018), who develops a brute force approach to estimate waves based on measured vessel motions. Sea state estimations were also conducted by (Brodtkorb, Nielsen, and Sørensen 2018). In this example, the measured response while in DP mode is benchmarked against calculations from ShipX and a closed-form expression.

The effect of propulsion system changes were also studied in the ViProMa project, which aimed to improve co-simulation technology for supporting virtual prototyping (Skjong et al. 2017). This work built on the use of the functional mock-up interface (FMI) standard to facilitate co-simulation. Models of R/V Gunnerus from the aforementioned sea trial simulations were then combined with controller algorithms written in Matlab and C++, and with physical models developed in 20-Sim, entering the co-simulation set-up as so-called functional mock-up units (FMU). The co-simulation set-up enabled easy replacement of the original propulsion system with the PMT system, due to the modular FMI/FMU structure. Hence, the effects of propulsion system retrofit could be easily studied in a simulator setting.

Another example was the use of R/V Gunnerus as a full-scale test platform for dynamic positioning algorithms initiated by AMOS (Skjetne et al. 2017). Due to the proprietary nature of DP software, researchers within marine control systems have normally not had the opportunity to test their algorithms in full-scale. This constituted a limitation to model validation. In the AMOS project, Kongsberg facilitated student intervention into the control software. The PhD students were hence able to plug-and-play using their own DP algorithms. Among the software systems that were tested during this research cruise was a new hybrid controller concept, which aimed to improve transient vessel responses (Brodtkorb et al. 2018).

2.3. R/V Gunnerus as the embodiment of the "*adopt-a-ship*" vision

R/V Gunnerus is the ideal candidate for realizing the first steps in the "*adopt-a-ship*" vision. A key reason for this is that NTNU can access the vessel, and owns the data. An interface is found with other digitalization initiatives at the Department of Marine Technology. A first step towards this was an undergraduate research opportunities programme (UROP) with six 3rd year students in the spring of 2017, which aimed to research the basis for establishing a digital twin of R/V Gunnerus. This was followed by the summer project in collaboration with DNV GL and Digitread, followed by the current Rector-funded project.

Additionally, a KPN application was submitted in collaboration with Stellenbosch University, DNV GL, and the Ulstein Group in September 2018, for which the research topic is to develop digital services that meet the need for improved decision support. That application is currently under review with the Norwegian Research Council. An overview of the proposed scope for the KPN-project is shown in Figure 2.

Figure 2: Sensor-to-service vision.

The “*adopt-a-ship*” vision, in which digital twins enable every student to get increased access to data and models of actual vessels, can be seen as a special instantiation of the more general “sensor-to-service” vision outlined for the KPN-application. The elements of the “adopt-a-ship” vision utilizing R/V Gunnerus is outlined in Figure 3. Starting from R/V Gunnerus itself, real time sensor data are fed into a digital representation of the ship, the “digital twin”, which combines information, mathematical and visual models. Managed through a digital platform, the digital twin can then be used in courses throughout the marine technology study programme and in related fields. This will improve student knowledge of both their own domain, as well as data analytics more broadly. The digital twin can then finally be taken into MSc and PhD theses, resulting in even better engineers graduating from NTNU.

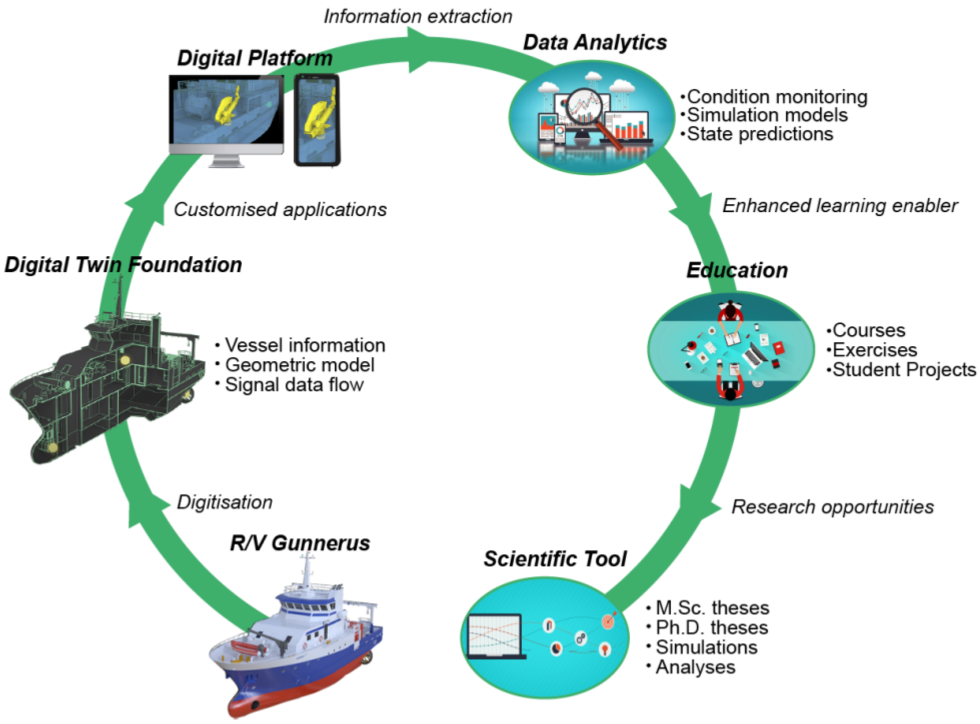

Figure 3: The "adopt-a-ship" vision for R/V Gunnerus.

2.4. Full scale sensor data analyses from other research vessels

There exist complementary experiences with full-scale measurements on advanced research vessels in other parts of the world. It is useful to learn from these experiences when it comes to developing a digital twin of R/V Gunnerus. There are currently applications for funding of additional research in place, which include plans for collaboration between NTNU and the University of Stellenbosch, South Africa, which has experience from conducting full-scale measurements from the South African research vessel S/A Agulhas II (SAA II).

The S/A Agulhas was outfitted with multiple sensors for its 2012 delivery from STX Finland Rauma shipyard (Anriëtte Bekker et al. 2018). Full-scale ship measurements aimed at improving the understanding of vessel responses. In particular vessel operations in ice, human factors, and the environmental context of the vessel, have been performed since then, starting during sea trials in the Baltic Sea. The ship is mainly used for research and resupply voyages to South African bases in Antarctica (A Bekker 2018), and is outfitted with eight research laboratories and advanced equipment for marine research. (A Bekker 2018) explores the potential of developing a full digital twin of S/A Agulhas. Several additional research articles documents the research results from the extensive full-scale measurements, with a summary given in Bekker et al. (2018). We mention some highlights below:

- Accelerometer measurements to quantify the impact of slamming on people on board.
  - Vibration measurements were subsequently related to survey data and complaints regarding slamming (Omer and Bekker 2018).
  - Vibrations were compared for passage in calm water, rough open water, and in ice (A. Bekker, Soal, and McMahon 2017).
- Strain gauge measurement to quantify ice-induced moments on the shaft line (de Waal, Bekker, and Heyns 2018).

The wide variety of publications that have resulted from increased monitoring of full-scale vessels, show that there is a great potential to learn more about marine technology from data. We believe that this extends to engineering novices like students, if the data is set into the right context.

3. Digital twins

3.1. Definitions of the digital twin

The term digital twin is traced to a conference presentation to industry at the University of Michigan, given in 2002 by Michael Grieves (Grieves and Vickers 2017). At its initiation, the concept was considered the "conceptual ideal" for product lifecycle management, in which a real space and a virtual space were connected by flows of data from the real space to the virtual space, and flows of information from the virtual space to the real space. The virtual system would hence mirror the real system perfectly. Further, the digital twin was not meant as a static concept. As the system changed through its lifecycle, the digital twin would change too, through design, production, operation and disposal, reflecting its value for product lifecycle management. Several terms for the concept were proposed through the 2000's, including the "Mirrored spaces model", and the "Information mirroring model" (Grieves and Vickers 2017), but the "Digital twin" is the term that has stuck. It has subsequently been adopted by many organizations involved in the engineering of complex systems, ranging from NASA, Siemens, General Electric, SAP (Marr 2017), and in the maritime industry notably DNV GL (Ludvigsen et al. 2016). A collection of more recent definitions of the term "digital twin" is presented in Table 2.

Table 2: Some definitions of the digital twin.

Reference	Definition of digital twin
(Tuegel et al. 2011)	"an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin."
(Ludvigsen et al. 2016)	"a model of a physical asset, implemented for example as a mathematical model, information model or a visual model."
(Erikstad 2018)	"a digital model capable of rendering state and behavior of a unique real asset in (close to) real time."
(DNV GL 2018)	"a digital representation of a physical asset, its related processes, systems and information."

Beyond the definitions, several authors have proposed essential characteristics for digital twins (Cabos and Rostock 2018; Erikstad 2018). According to Erikstad (2018), digital twins possess five core characteristics:

- **Identity**: Digital twin represents a "single, real and unique physical asset"
- **Representation**: The physical manifestation of the assets is captured in a digital format (CAD or other engineering models), with corresponding metadata.
- **State**: Rendering of quantifiable measures of the asset state in (close to) real time.
- **Behavior**: Reflecting basic responses to external stimuli in the present context.
- **Context**: Description of external operating context.

Cabos and Rostock (2018) suggests three essential constituent elements:

- **Asset representation:** "i.e. a digital representation of a unique physical object (e.g. a ship or an engine or part of it)"
- **Behavioral model:** Encoded logic to allow predictions and/or decisions on the physical twin (e.g. realized through simulation capability for optimizing maintenance activities)".
- **Condition and configuration data:** "Data reflecting status of and changes to the unique physical object during its lifecycle phases (e.g. captured through inspections or measurements, updates in case of modifications)"

Further, the extent to which digital twin is an accurate description of what is actually needed to create value for organizations should be subjected to scrutiny. The word "twin" implies that an accurate copy of the physical asset is obtained, irrespective of the costs and benefits of creating and maintaining such a model. In order to capture all information that may actually be useful to stakeholders, there may be no need for a "mirror", if all relevant information could be communicated through simpler means. Hence, in this report, we will use the digital twin as a term that encompasses models that meets the characteristics presented by Erikstad (2018) and by Cabos and Rostock (2018). Note that this does not necessarily imply that we want to represent a one-to-one “mirror” of the actual asset. Rather, it is useful to think of the digital twin as encompassing all *relevant* information about an asset to the stakeholders, making it a “single source of truth” for that asset (Bone et al. 2018). As stated by Dr. David Walker of the US Air Force, “*we need to return to where we understand our systems, and digital twins are one of the tools that enable that*” (Warwick 2015). Hence, digital twins shall improve the knowledge base of engineers and designers, as pointed out by Tao et al. (2018), who use the classical function-behavior-structure framework from design theory (Gero 1990) to show that digital twins reduce the distance between the intended and obtained performances of designed systems**.**

On this basis, the key question for the developer of a digital twin should be: “What information are most relevant to the digital twin stakeholders?” The answer to that question should dictate the further development, and captures much of the motivation for the innovative education project. A necessary step towards digital twin maturity is clearly the development of new use cases, one of which is innovative engineering education.

3.2. Key developments towards the digital twin

This section recapitulates the history of key enablers of digital twins within the maritime industry, connecting these to the deliverables of the current project. Erikstad (2018) presents the historic and projected development as shown in Figure 4.

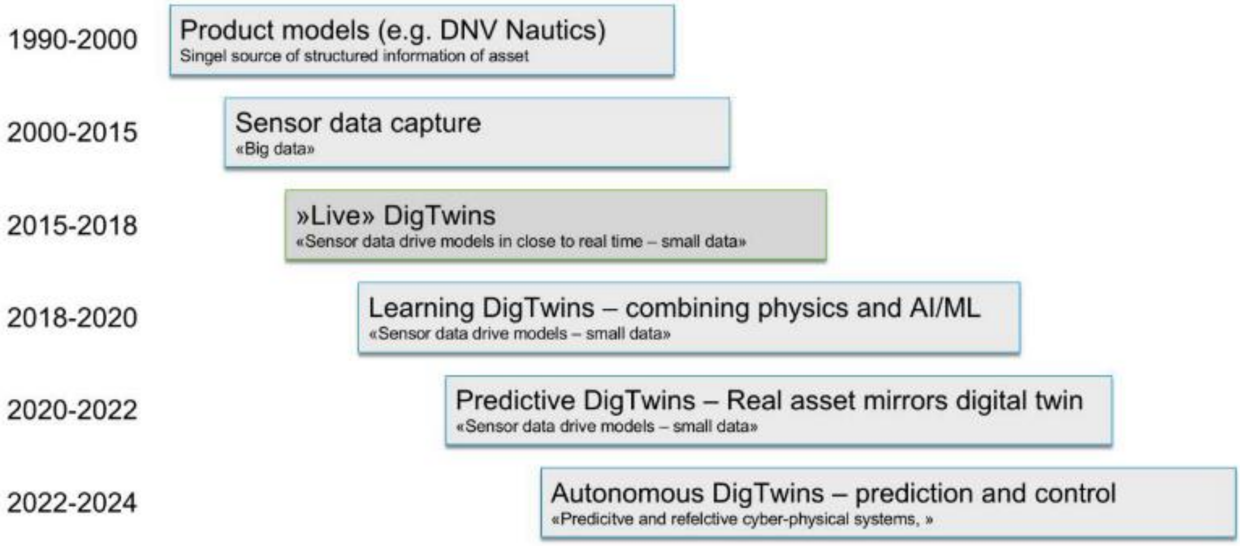

Figure 4: Historic and projected development of digital twins (Erikstad 2018).

Product models are an early enabler of digital twins, exemplified by the generic product models developed by DNV GL, applied to all ships in DNV class since 2005 (DNV GL 2017). These models are intended to structure information that relates to classification of ships, and contain this in a common repository (Erikstad 2018). VIS/GMOD[1] provides a generic structure for documenting all relevant data about the ship, including decomposition of ship and system functions. VIS/GMOD is favored over other system taxonomies in the maritime industry, like the SFI system originally developed by Marintek, as it provides improved semantic naming rules (DNV GL, 2017). For this reason, the VIS/GMOD structure is currently one of the underlying “naming rules” used in development of an ISO-standard for shipboard sensor data (DNV GL, 2017). In the VIS/GMOD paradigm, the product model for a single ship instance is referred to as a PMOD. While product models alone do not make a digital twin, they represent a key enabler, in that they bring all available information about an asset together in a single system (Erikstad 2018). **Laying the foundations for a digital**

[1] VIS – Vessel Information System
GMOD – Generic Product Model

twin through development of a product model for R/V Gunnerus, has been a key part of the student project this report documents.

Sensor data capture is the key next enabler: This is connected to rapid development of cheap sensors and communication technologies, which has lead to huge amounts of data being logged (Erikstad 2018). Sensors often exist in vessel systems for the purpose of providing signals to other systems, which indicate that some automatic function should be performed. Many such sensor signals are not recorded, and for good reason: Many are worthless to decision-makers, and would not give insights to engineers. However, from many other sensors data is recorded and could provide great insight, which leads us to the challenges of "big data": Volume, velocity, variety, and veracity (DNV GL 2014). Large volumes of data are collected, for which timely analyses are needed for the data to create value. Further, there is little structure to the data, as addressed by the current work on data standardization (DNV GL 2017). Finally, there is the question of veracity; "why is a certain source of data relevant?" In the current student project, historical sensor time series have been structured and analyzed.

"Live digital twins" and onwards: The increasing amounts of data can also come live, creating the additional challenges of connectivity to enable real-time replication of the state of the real asset. Real-time access to sensor data requires that systems on vessels come online, and data transmitted to shore for further analysis. This can be achieved by installation of high-speed, high-capacity communication platforms like Kongsberg Maritime's Maritime Broadband Radio (MBR). To reduce the number of new, costly sensor installations, it is also desirable to derive responses at locations within the asset where no sensors are located from physics-based models. This requires that the necessary computations are sufficiently simple, allowing low latency, close to real-time state representation. Furthermore, this hinges on the ability to model the physics at a sufficient fidelity without introducing excessive complexity. For physical processes that are sufficiently complex, it may add excessive costs to attempt to model the actual physics. For these, it is more favorable to use machine learning techniques to derive the behavior of the asset, based on statistical analysis of physical measurements. These techniques can then be coupled with physics-based models for the physical processes that are better understood, which in turn could enable predictions (Erikstad 2018).

The scope of the current student project ends at the "live digital twin" stage, with some physics-based modelling, but there is much remaining work to further develop the necessary mathematical models that could generate interesting insight. For example, no machine learning techniques were applied in the current project.

3.3. Digital twins as a learning platform for engineering education

The purpose of digital twins is, as shown, to improve the state of engineering knowledge, which in turn will lead to better decisions throughout the product lifecycle. The current project aims to develop a learning platform for engineering students based on the digital twin of R/V Gunnerus. The objective is thereby to improve the learning outcomes for engineering students, by improving the access to existing marine systems, in this case R/V Gunnerus. Improved access to existing systems like R/V Gunnerus will in turn reduce the distance between theory and practice, to an increasing extent illustrating the relevance of traditional engineering curriculum to the students. As pointed out by Rhodes (2018), engineering students who are exposed to practical cases while working with the more theoretical classroom material, will become more aware of the key learning points, as they possess some concrete examples with which to match the theory. **Fundamentally, the more domain experience students are able to obtain, the better they are enabled to relate contextual issues to understanding of related theoretical concepts.** Engineering students who are proficient with use of digital models are also likely to become more aware of the limitations and assumptions that underlie the model, as they discover what context and purpose the models were built for (Rhodes 2018).

There are hence at least two major reasons to use digital twins as a learning platform in marine technology education:

1. To improve the understanding of domain knowledge among marine technology students

2. To improve the digital and modelling competencies of marine technology students

4. Digital twin of R/V Gunnerus

The basis for a digital twin of R/V Gunnerus was developed in a collaborative project between NTNU Department of Marine Technology, Department of Mechanical and Industrial Engineering, DNV GL Group Technology & Research, and Digitread. The modelling basis for the project was supplied by ship design company Polarkonsult, and shipyard Larsnes Mekaniske Verksted. The sensor data for the project was supplied by Kongsberg Seatex and Rolls Royce Marine.

During the summer of 2018, five NTNU students from Department of Marine Technology and Department of Mechanical and Industrial Engineering were involved in a student project aimed at developing the digital twin of R/V Gunnerus, and developing use cases for the digital twin in engineering education. The purpose of the R/V Gunnerus Digital Twin Innovative Education project was to i) establish a basis for development of R/V Gunnerus as a digital twin into the marine technology course string at Department of Marine Technology, and ii) increase the knowledge relevant for digitization within marine technology – the chain from measurement techniques, sensors, data capture from systems and equipment onboard a ship, including external influences, via structuring and analysis of data, to use of derived information for decision support.

The digital twin of R/V Gunnerus can be used for a variety of purposes as a learning platform in marine technology education. On a high-level, the following points should be mentioned:

- Improved access to data from a real asset in operation.
- Visualization of ship structure, ship systems, and components for improved understanding of naval architecture terminology and understanding of basic ship architecture.
- Sensor data streams for enhanced insights in relationships between different aspects of physical system state and performance measures.

4.1. Project overview

The summer project during the summer of 2018 encompassed several deliverables, contributing to the foundations for an architecture of the R/V Gunnerus digital twin. The distinct building blocks for the project were:

1. A detailed 3D-model of R/V Gunnerus
2. Vessel/component information and documentation
3. Sensor data and information

These distinctive elements were managed and synthesized through DNV GLs Veracity data platform, which supports the use of Sesam Insight as a Digital Twin viewer, as well as analytics tools like Power BI. The workflow connecting these building blocks is shown in Figure 5.

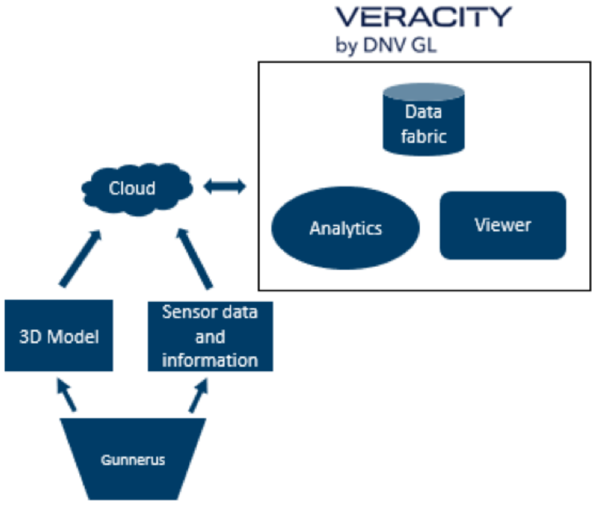

Figure 5: Workflow for digital twin development.

The 3D model was developed in Siemens NX under the supervision of Digitread in Sandvika. The model incorporates several smaller assemblies from Digitread's component assemblies, whereas other systems had to be explicitly modelled. Besides modelling the ship, the locations of sensors in the vessel were represented in the model. The finished model was exported to DNV GLs Sesam Insight, which is a web-based viewer, in which it was coupled to a vessel information model (product model).

The vessel product model (PMOD) was developed at DNV GL at Høvik, in accordance with the DNV GL VIS/GMOD framework, in which all vessel information is to be entered. This also encompassed available sensor data from the vessel, where data exists for some but not all of the interesting vessel subsystems. Making sense of the available sensor data was a significant challenge, as data stems from systems delivered by several vendors, with little standardization in naming of sensor signals. Many signal names were ambiguous or nonsensical, and some signals gave little insight into the physical state of the vessel but only triggered some other control system function. Yet other signals did not seem to give any nonzero value at all. Still, for some sensors it was possible to extract useful information about the state of R/V Gunnerus. These sensor signals were shown to be useful, giving an understanding of the system state of R/V Gunnerus. Overview of important vessel systems, with corresponding status of sensor measurements are provided in Figure 6. As seen from these figures, a variety of active sensor signals are found from the Motion Reference Unit, the dynamic positioning system, and the Azimuth thrusters. Additionally, AIS data is available. Unfortunately, no sensor data is logged at the generator sets. Still, this status with respect to sensor signals means that several sensors are ready to provide data for use in courses where vessel motions, propulsion, machinery or control systems design are relevant.

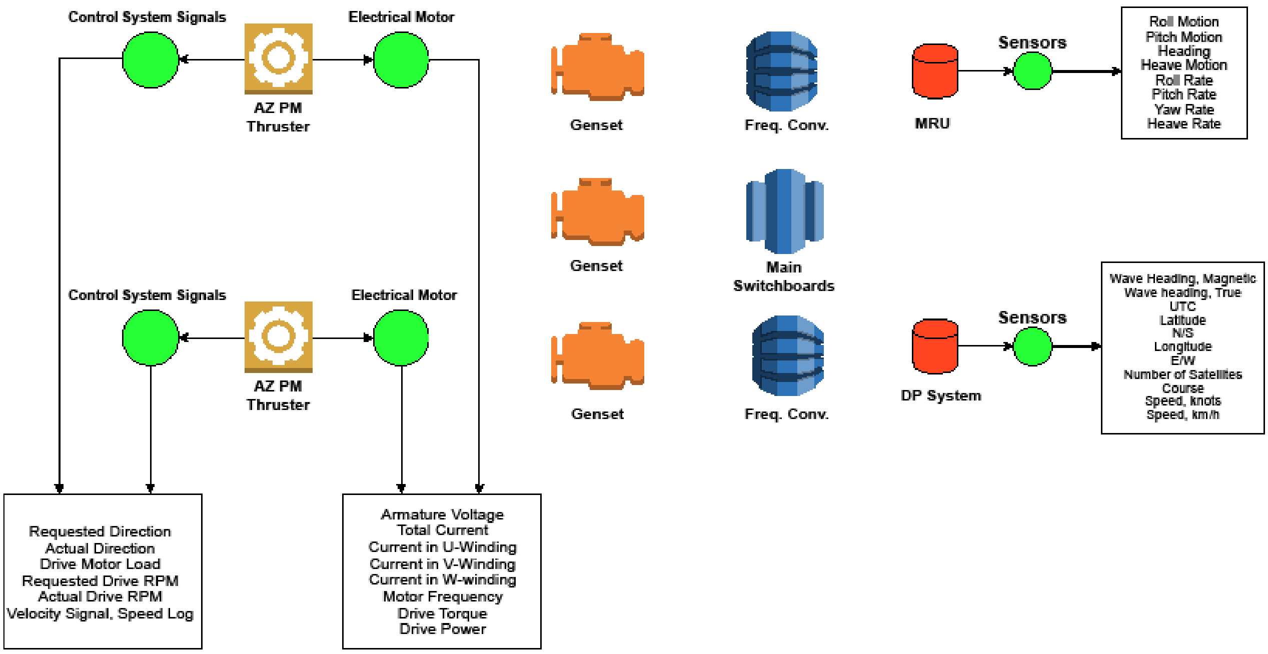

Figure 6: Overview of sensor instrumentation and status.

4.2. Gunnerus digital twin functionality

The R/V Gunnerus digital twin can be used for a variety of purposes. First, it can serve simply as a platform for learning about basic naval architecture and terminology related to ships. In its simplest form, this is enabled by offering a more interactive (and clickable) visualization of a vessel. By clicking selected ship components in the 3D model of R/V Gunnerus in Sesam Insight, it is in principle possible to access all available information about the component, as each component has a reference in the product model (PMOD). The vessel model in the Sesam Insight interface is shown in Figure 7.

Figure 7: R/V Gunnerus modelled in Siemens NX and exported to DNV GLs Digital Twin Viewer in Sesam Insight.

Beyond the access to ship metadata and overview of system architecture, the sensors are embedded within the visual model in Sesam Insight, as clickable spheres. Like other vessel components, these spheres are clickable, and links to overviews of relevant metadata, and time series analyses for the relevant sensor signals. Some of the sensors found in the vessel are shown at their location in Figure 8.

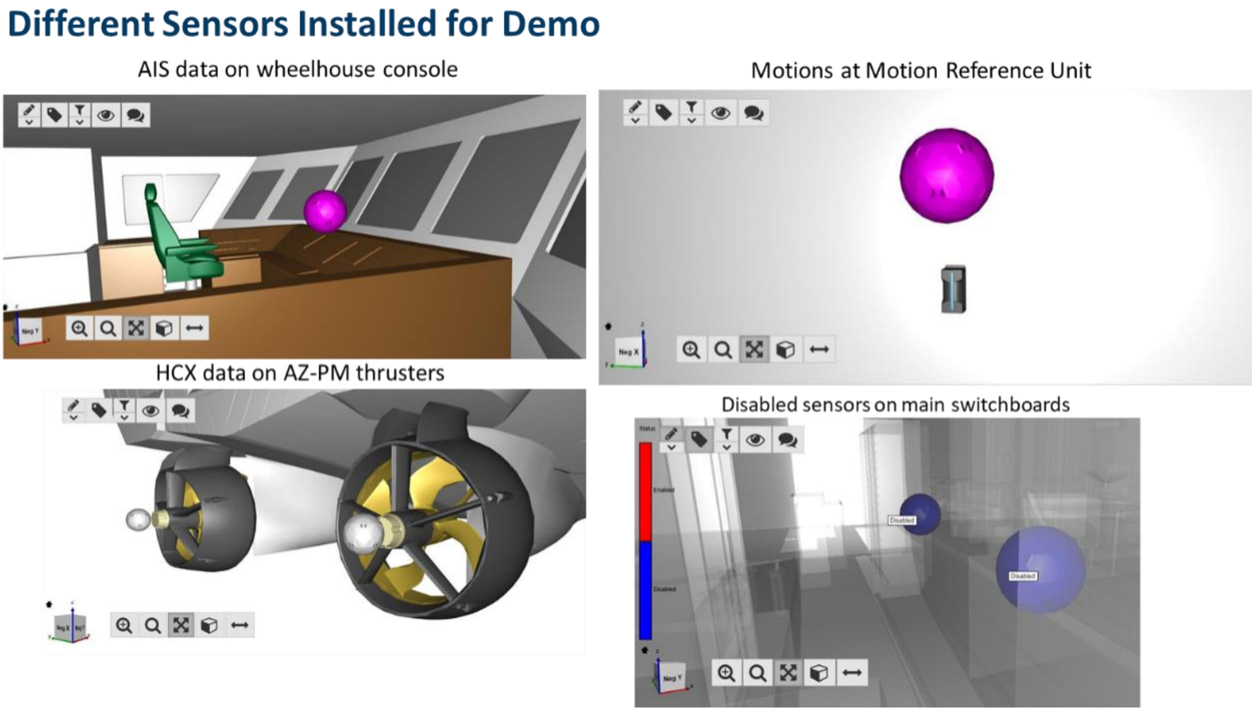

Figure 8: Location of sensors and other data sources embedded in the visual ship model.

Figure 9 presents a detailed overview of the port side Permanent Magnet Azimuth thruster. Sesam Insight provides further data relevant for this system. The digital twin viewer in Sesam Insight links to the Power BI dashboard that visualizes sensor data time series and AIS data. These are provided in Figure 10 and Figure 11.

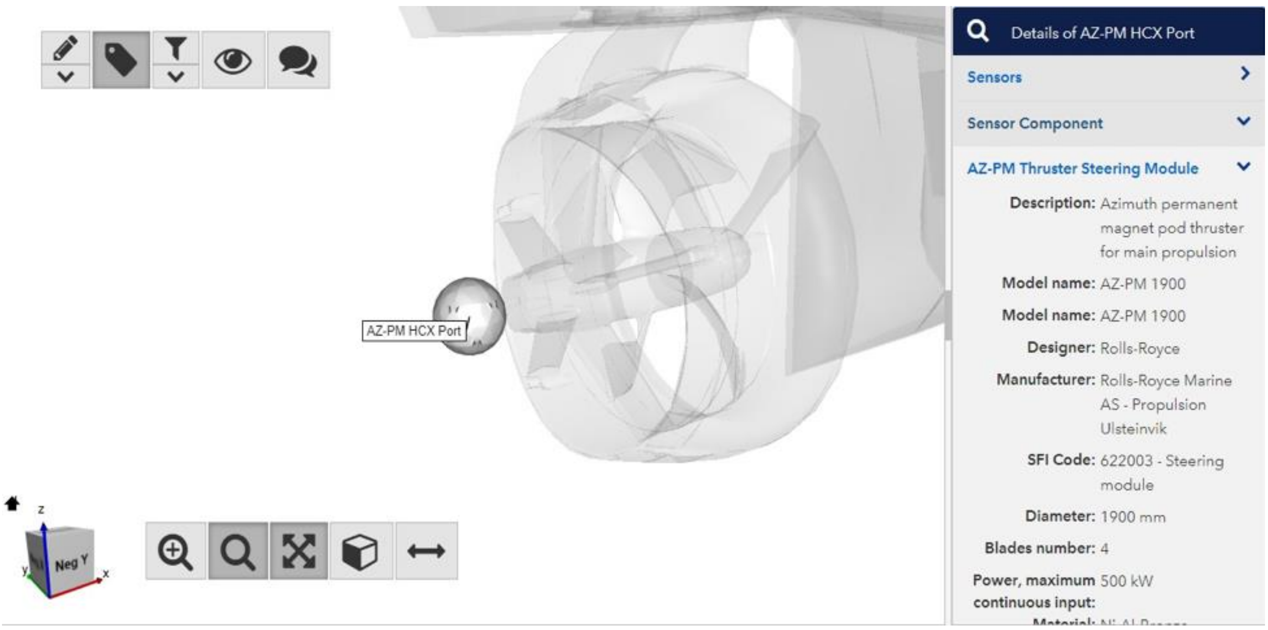

Figure 9: Detail view of azimuth thruster with sensor and metadata from product model.

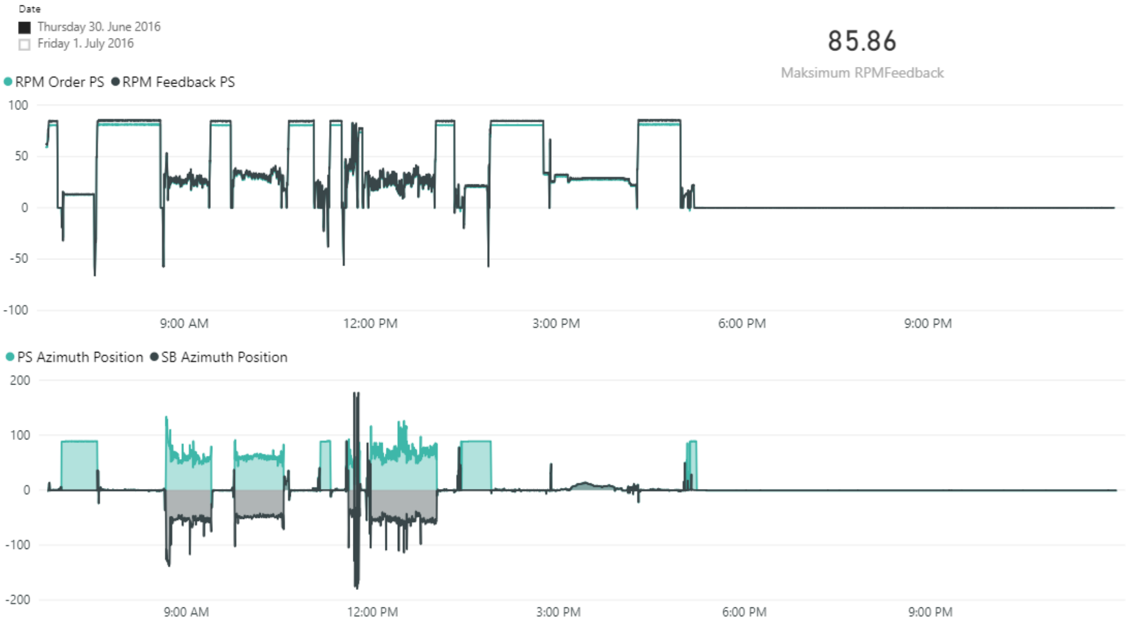

Figure 10: Rotations per minute, time series for azimuth thrusters.

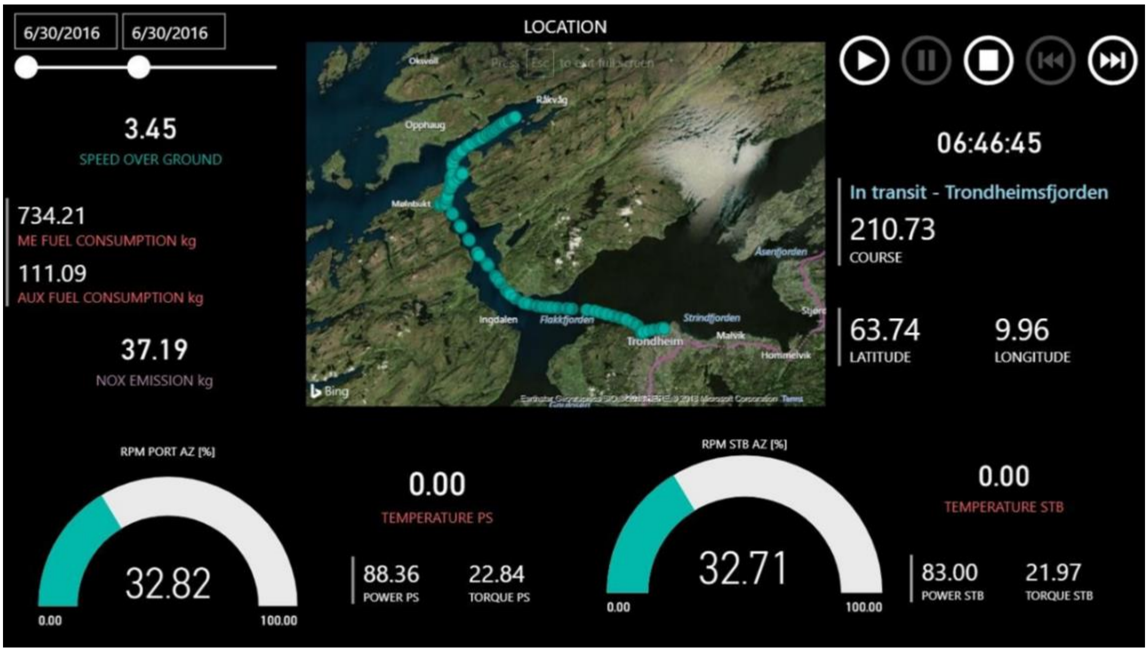

Figure 11: Power BI dashboard visualizing some Gunnerus AIS and sensor data.

It is evident that these tools can have a variety of applications in marine technology education, and the goal is to make the tools that have been developed open to all students of marine technology. There are plans to further develop the functionality that has been developed so far.

5. Uses of digital twin of R/V Gunnerus in education

We now turn to the specific use of the R/V Gunnerus digital twin in the study programme. These use cases were developed by the five students, consulting the course responsibles for each of the courses. The feedback from professors was generally very good, and uses for the digital twin was found for most courses. Still, the maturity of digital twin aplicability in courses varies, with the most positive prospects found in relation to machinery and propulsion systems, control systems design and hydrodynamics. The courses reviewed in are given in Table 3.

Table 3. Courses covered in this review. Study level; FC1 Foundation courses, level 1- FC1; Intermediate course level II – IC2; Third year courses level III – TC3; Second degree level – 2nd DL

Course code	**Course name**	**Course responsible**	**Study level**
TMR4105	Marine techn. –Elementary course	Svein Aa. Aanondsen	FC1
TMR4167	Marine techn. – Marine structures	Jørgen Amdahl	IC2
TMR4247	Marine techn. – Hydrodynamics	Bjørnar Pettersen	IC2
TMR4335	Marine techn. – Propulsion Systems, Safety and Environment	Ingrid B. Utne	TC3
TMR4320	Simulation based design	Ekaterin Kim	TC3
TMR4254	Marine systems design	Svein Aa. Aanondsen	TC3
TMR4222	Machinery and maintenance	Eilif Pedersen	2nd DL
TMR4220	Naval hydrodynamics	Kourosh Koushan	2nd DL
TMR4240	Marine control systems I	Asgeir Sørensen	2nd DL
TMR4243	Marine control systems II	Roger Skjetne	2nd DL
TMR4235	Engineering and ICT, Introduction	Håvard Holm	FC1
TMM4115	Engineering modelling	Knut Einar Aasland	FC1
TMM4155	Finite element applications in mechanical engineering	Terje Rølvåg	2nd DL

A description of the use of digital twin as a platform for learing enhancement in each course is given on the following pages.

5.1. Study programme: 5-year MSc in Marine technology

TMR4105 – Marine Technology – Elementary Course

Course Coordinator: **Svein Aanond Annondsen**

Course Description

Marine Technology – Elementary Course, also known as Marine 1, is the marine students' first encounter with marine technology at NTNU. The elementary course gives a broad introduction to maritime fields related to naval architecture, as well as surface knowledge of different marine technology disciplines and specialties explored in later courses. The elementary course is an essential basic course as it gives a foundation for understanding important concepts in marine technology. Furthermore, the course is a foundation for developing individual interests within the industry. The course introduces a variety of topics such as naval architecture and ship design, propulsion, resistance, machinery, stability, structural properties of ships, life cycle operation and maintenance, and relevant industry terminology.

Learning methods and activities

The course uses exercises to support lectures, and includes a course project accounting for 40 % of the final grade. Most of the exercises encourage manual problem solving of realistic – albeit fictitious – engineering problems. There are four practical exercises, and the course has a hull modelling tutorial in *DelftShip*. Other than demonstrating how to perform experiments in a laboratory, the practical exercises is intended to give a physical understanding of some important theoretical concepts, such as a heeling test and cavitation. Additionally, there is an obligatory excursion with a *Hurtigrute* vessel, which provides a practical connection to the theory from lectures.

Application of Gunnerus Digital Twin

Due to the broad nature of the course curriculum, many possibilities arise for utilising a digital twin vessel. Below are some potential areas of application for a digital twin in the elementary course.

- Introduce a laboratory exercise with an RV Gunnerus excursion trip.
- A complementary exercise can use the digital twin to analyse the excursion trip, with available parameters such as power, torque, vessel motions, and AIS data.
- Use realistic data from Gunnerus to compare theoretical methods – or empiricism – with actual measurements. It is considered especially relevant for resistance and propulsion exercises.
- Use the digital twin to familiarise the students with a complete vessel system.
- Display advanced geometric models made through computer-aided design.

Motivation

The maritime study program must adjust to the digital shift. Therefore, students should be introduced and accustomed to resulting implications as early as possible. A digital twin vessel provides many of the technological implementations that is becoming increasingly relevant. Active use of signals to monitor the well-being of a vessel can lead to immense cost reductions, and with today's prominent focus on digitisation, big data, and machine learning, the ability to process and make use of sensor data can become a major focal point for cutting expenditures, increasing automation, and making way for a safer and more efficient industry. The vessel is already utilised in later courses, and with the supplement of a digital twin, students can benefit from familiarizing with the vessel in the elementary course. Lastly, adjusting to the digital shift will show the students that the study program is willing to change to keep up to date with technological advances, maintaining relevancy through adaptation.

TMR4167 – Marine Technology - Marine Structures

Course Coordinator: **Jørgen Amdahl**

Course Description

The subject provides a review of the structural construction and functioning of ship hulls, truss platforms and floating drilling platforms. It also includes an introduction to basic methods for static elastic analysis of stresses and forces in beams and frame structures, plastic analysis of maximum capacity, resistance against buckling, as well as application of these methods in structural analysis. The most important learning outcomes are to be able to do calculations on the hull girder and calculate the requirements for thickness of plates and stiffeners, based on hydrostatic data and load condition. The students should also be able to calculate the loads on statically indeterminate structures, and be familiar with plastic and elastic analysis.

Learning methods and activities

The learning methods in this course are lectures, exercises and a project assignment. The project are carried out in groups of 2 or 3 students and it counts for 25% or the grade in the course. The project involves making a program in Matlab for analysis of a statically indeterminate structure and writing a technical report.

Application of Gunnerus Digital Twin

The Digital Twin can be used to better visualize the structural configuration of a ship, which is one of the main learning outcomes of this subject. The students can work with the 3D model of Gunnerus one by one or in group and use it to get familiar with the basic structure of a ship. The 3D model shows how the structure is built up, and can be a helpful tool when investigating how the forces are distributed in the hull and structure. As the course focuses mainly on less complex vessels than Gunnerus, a digital twin of a container vessel would be most relevant for this course, but DT Gunnerus is a good place to start.

A suggested task that the Digital Twin can be used for: Calculate the required thickness for the stiffeners and plate at a certain location at Gunnerus given the hydrostatic and local loads. Compare the results from the calculation with the actual dimensions of Gunnerus and do an assessment of the real/as built values compared to the calculated requirement.

Motivation

Using the Digital Twin of Gunnerus will be motivating for the students because they get to know the components and the structure of the hull and girders in new ways and gives a more visible representation than the drawings and 2D figures that are used today. If the students already are familiar with the Digital Twin through the first Marine Technology course, it will be easier to relate new ship technical terms to RV Gunnerus.

To be able to do structural analyses based on data from Gunnerus Digital Twin, more sensors needs to be installed on the ship, so that the tensions in the hull are monitored and logged. The information from these sensors needs to be implemented into the digital twin.

TMR4247 – Marine Technology – Hydrodynamics

Course Coordinator: **Bjørnar Pettersen**

Course Description

Marine Technology – Hydrodynamics, also known as *Marine 3*, expands upon marine fluid mechanics, linear wave behaviour and wave loads, and in-depth resistance and propulsion theory. The first part of the subject is mostly comprised of hydrodynamic potential theory, which emphasises fluid particle dynamics, wave theory, and equations of motion for ocean vessels and structures. The second part of the course seeks to introduce resistance, propulsion, and foil theory. This part of the course includes both potential theory and empirical correlations. The empiricism, often developed from model testing, can be applied to realistic marine operations, and can be used to estimate propulsion demands and resistance in early design processes.

Learning methods and activities

The course uses written exercises as a supplement to lectures. The course also contains practical laboratory exercises, which demonstrate fluid flow around a cylinder, and propeller cavitation. Many of the theoretical exercises are built around the fundamental understanding of potential theory. Hydrodynamic analyses, such as response calculations due to wave-induced motions, and resistance calculations based on geometric definitions, are briefly introduced in *ShipX*.

Application of Gunnerus Digital Twin

A digital twin in a course such as marine hydrodynamics has a multitude of possible applications. However, many of the applications demand that the twin can run simulations, especially related to computational fluid dynamics (CFD) analyses. The threshold is significantly reduced by the fact that the hull model has already been completed. Although it is difficult to create a joint platform for condition monitoring, structural analyses, and fluid analyses, a feasible alternative would be to implement fluid and structural analyses in separate environments. Exercises related to potential theory will benefit less from a digital twin as viscous effects are disregarded. However, viscous effects included later in the course are highly relevant for physical properties and performance, and can be evaluated by a digital twin model. Below are some potential areas of application for a digital twin in the marine hydrodynamics course.

- CFD analyses of the hull. Different methods lectured in the course can be used to compare results, and see potential deviations between potential theory, numerical methods, and empiricism.
- Signal data from motion reference units can be used to analyse wave states and their statistical properties, such as response amplitude operators.
- Case study of the permanent magnet azimuth thrusters, which is a display of new and innovative thruster technology. An exercise assignment can be made to compare the efficiencies of different thruster types, and use thruster data to benchmark thruster performance.
- Data sets can be used to look at the fluctuations in torque when a vessel attempts follow a desired speed, which can cause substantial damage to a thruster over time. This would allow for a discussion about whether a vessel should favour constant torque or constant speed during operation.
- Simulate and visualize the flow around RV Gunnerus in realistic conditions, and compare simulation results to measured signal data.

Motivation

Many problems in maritime engineering are approximated by results that are derived empirically. For students who are used to connecting a physical understanding to the theory they learn, empiricism can be a discouraging factor. By applying the extensive empirical theories presented in the course to an actual vessel, the students can compare calculations with realistic data sets. This will illustrate the accuracy of empirical methods, and prove the value of empiricism to simplify and estimate how complex physical systems will behave.

TMR4335 - Propulsion Systems, Safety and Environment

Course Coordinator: **Ingrid Bouwer Utne**

Course Description

Introduction to and design of power systems for ships and offshore installations. Power consumption and operating profiles as basis for design and performance analysis of machinery systems.

Characteristic properties, design and typical limitations of prime movers as diesel-, gas engines and gas turbines. Main factors affecting power, efficiency and exhaust emissions. Marine fuel types and primary energy conversion by combustion.

Air pollution and regulations.

Understanding, application, and analysis of electric power systems and electric machines in propulsion and power generation systems onboard ships and general marine systems. Basic introduction to electric generators, converters, motors and electric drives including control.

Introduction to concepts, definitions, models, and methods for system reliability, risk and safety assessments. Methods for calculating and assessing basic system availability, and economic analyses.

Learning methods and activities

Lectures, project assignment, laboratory exercises and conventional exercises. The project assignment and laboratory exercises carried out in groups, and some exercises are mandatory. 75% of the other exercises are required for access to the exam.

Application of Gunnerus Digital Twin

The Digital Twin is a good opportunity for students to see a detailed model of a vessels power system. Possible to see detailed models of different components onboard, including thrusters, diesel engines, generators and other electrical motors. Good tool to better understand the electric power system and power generation onboard.

This can be done by giving the students access to the Digital Twin viewer in Veracity. Detailed models of genset and thrusters can also be made available. Will also be possible for the students to access the visualized sensor data in the Veracity App. Another proposal is for the students to do some exercises where they for instance use some of the sensor data to calculate some performance factors. For example, use data from the thruster drive. We have measurements of voltage, current, frequency, torque and power that can be used in assignments.

Another proposal is to look at the power generation aboard. There are no data from the genset, but the students can calculate the required power from the generators based on the data from the thrusters. Then find out the best solution to generate this amount of power. Could also see how batteries can affect the power system, and how they can better optimize the operational profile. For instance, running one main engine full speed with help from batteries instead of running two engines.

Motivation

- Will give the student a better understanding of these kind of systems.
- Motivating for students to work with real systems that they can study in 3D.
- No further work on the twin required for this to be possible.

Detailed description of possible application

Exercises:

1. Calculate the fuel consumption of Gunnerus based on sensor data from the thrusters. Do this for different operational profiles.
   Fuel consumption = $b_e \cdot P \cdot t$
   - We have access to the power consumption of the thrusters. We also have estimated fuel consumption from AIS data, that can be compared to the results.
   - Draw the fuel consumption for the different profiles.
   - It will be good for the students to be able to see the detailed 3D model in order to understand the system better.
2. Calculate the Torque of the thrusters based on the power data and RPM.
3. Find out the required machinery power for Gunnerus' DNV GL class and compare with the real vessel.

Possible project:

- Design and optimize a hybrid drivetrain of RV Gunnerus based on operational data from the real vessel.
- How would this system look? Is this system more optimal than the original design?

TMR4320 – Simulation-Based Design

Course Coordinator: **Ekaterina Kim**

Course Description

The course gives an introduction to simulation as a way of determining the feasibility of designs, which is highly relevant today as there are more and more designs that does not fit with the standard rules and regulations that are used today. The course consists of two parts, where one is theoretical and the other one is a project. The course stars with an introductory phase which introduces a generic structure that are to be used as an example throughout the course for the course project. The theory part of the course covers the theory needed and basic modelling principle, and are thereby providing support to the project.

Learning methods and activities

The primary learning methods are lectures and the project. The student shall be able to identify requirements for simulation-based design of large complex ship and offshore structures in terms of CAD/CAE tools and first-principal based analysis methods. Basic finite element analysis are carried out form a basic CAD model and used to optimize the given structure for the given loads. The modelling, analysis and optimization in the project are carried out by use of Inventor, Ansys and Matlab.

Application of Gunnerus Digital Twin

A typical project problem in this course addresses a ship deck/or part of a ship deck that are to be modelled to withstand a certain load. A proposal for a task in this subject is to design and model the elongated part of the main deck of RV Gunnerus. Commenting on the effect of this change on the existing vessel, e.g on the stability and trim of RV Gunnerus, will give the students good insight into how the old and the new system works, and how changes to designs affects the seakeeping capabilities. The students could also investigate the consequence of the elongation in relation to the tension in the hull, and compare it with real values from measurements.

A new way of implementing the digital twin of Gunnerus is to give the students the possibility to extract a part of the model that they are interested in, and do an optimization of this part based on the loads in this area. This will change the course by starting with an overview of Gunnerus and narrowing it down to the theory, instead of the other way around as it is today.

Motivation

- By creating the task related to RV Gunnerus the students will use a ship they already know from the earlier marine courses, and will easier be able to put the results of their project into a context.
- To be able to do compare results from the project with real data from Gunnerus Digital Twin, and use real data from the ship, more sensors needs to be installed on the ship, so that tension in the hull are monitored and logged. The information from these sensors needs to be implemented into the digital twin.
- For the students to be able to compare the two versions of RV Gunnerus there must be developed a model or a method for implementing the model part the students have created, or the information they have obtained from their results, into the existing model.

TMR4254 – Marine Systems Design

Course Coordinator: **Svein Aanond Aanondsen**

Course Description

The aim of this subject is to provide students with practice on designing a marine system by applying previously acquired knowledge. Students are also required to evaluate the need for acquiring new knowledge, and obtaining this new information. Lectures on less common topics will be provided. Students will receive tuition on how to carry out a market survey and how to develop, evaluate and choose ideas.

Learning methods and activities

When finishing this course the student should be able to solve a design task of a marine system within a specified deadline. The students will be working in groups on an assignment. Lectures, supervision and tuition will be provided on the project. The course involves:

- Performing a market study
- Developing ideas by using different methodologies
- Developing relevant design criteria and evaluating the ideas based on these
- Detailed concept design
- Using software tools actively in the design process

The use of new programs/software will help improve this course. There is a need for modernization when it comes to the design software used in the course. This is where the use of the Digital Twin will be relevant.

Application of Gunnerus Digital Twin

In this course the Digital Twin of Gunnerus can mainly serve as an inspiration for the groups when it comes to how to model the ship that the group is designing. It will also provide them with a good example of a general arrangement of a vessel. It is also possible to show the students how a digital twin is built, and what is required for them to build a twin of their own design. Different sensors could be studied, and the use of AIS data for research of reference vessels could also be a use case.

For this course it is first and foremost the program Siemens NX that is relevant. Today there are several programs that are used in this course, and it would be beneficial for the students to be able to use one program for all the different tasks in the course. The use of one program will provide a better overall understanding and visualization of the ship that is designed, and it gives the possibility to combine the structure of the ship and the general arrangement.

Motivation

- For it to be possible to use Siemens NX in the course it needs to be investigated if the program can carry out the needed calculations on the model. There will also be needed student assistants that are familiar with the program, who can help the students in the modelling process.
- By modelling everything in the same program, it will be easier to see the connections between the different parts of design.

TMR4222 – Machinery and Maintenance

Course Coordinator: **Eilif Pedersen**

Course Description

Introduction to machinery dynamics, vibration and vibration isolation, and condition monitoring as part of maintenance management. Torsional vibration, modelling and analysis including lateral vibration of shafts. Thermal engineering basics - heat transfer, heat exchangers, system design and energy optimization. Introduction to thermodynamic condition monitoring of machinery systems and main machinery in particular.

Learning methods and activities

Lectures, exercises, computer exercises, lab and project work.

Application of Gunnerus Digital Twin

The Digital Twin is a good opportunity for students to see a detailed model of a vessels power system. Possible to see detailed models of different components onboard, including thrusters, diesel engines, generators and other electrical motors. Good tool to better understand the electric power system and power generation onboard.

This can be done by giving the students access to the Digital Twin viewer in Veracity. Detailed models of genset and thrusters can also be made available. Will also be possible for the students to access the visualized sensor data in the Veracity App. Possible for the students to do exercises based on the sensor data from the vessel. For instance, perform simple modeling tasks on the Thrusters. This will be a good opportunity to get to know the dynamics of modern propulsion systems like AZ PM thrusters.

After speaking with Amir Nejad, he presented the idea of doing some measurements on Gunnerus and using the results on a project. NTNU have access to portable sensors that can be used to perform ex. Noise or vibration measurements in the engine room. The system can also to some extent be modelled in a test lab at Tyholt. This can give a good basis for a student project.

Motivation

- Will give the student a better understanding of these kind of systems.
- Motivating for students to work with real systems that they can study in 3D.
- No further work on the twin required for this to be possible.

TMR4220 – Naval Hydrodynamics

Course Coordinator: **Kourosh Koushan**

Course Description

Application of lifting line and lifting surface theory in the design of propulsors, rudders, foils etc. Application of theory and experimental methods in calculation of resistance and in calculation of hydrodynamical characteristics of propellers, tunnel thrusters, azimuth thrusters and waterjets. Propeller induced vibration and noise. Influence of fouling, wind and waves on resistance and propulsion. Propulsor dynamics in waves.

Learning outcome

To have detailed knowledge about the hydrodynamics of ship propulsion, ship resistance, hydrodynamic lift, hydrodynamic principles of propellers, including cavitation and ventilation.

To have knowledge about the special considerations regarding the hydrodynamics of thrusters, waterjets, operation and maneuvering of ships and propulsion systems in a seaway.

To be able to do computations of resistance, propulsion power of ships by use of experimental, empirical and simple numerical methods.

To master the choice of main dimensions of propellers, as well as simple propeller design.

To master the concepts and terminology of naval hydrodynamics.

Application of Gunnerus Digital Twin

The digital twin of RV Gunnerus could be a good chance for the students to perform resistance computations of a vessel they have good knowledge of. The 3D model can be used as a tool for the students to familiarize with the vessel, while data from the sensors can be analyzed. Since the model test of Gunnerus was performed at the house, this can be a good opportunity for the students to compare model test results with empirical and numerical methods as well as real, operational data.

In addition to this, the model can be used to visualize a modern, state of the art diesel electrical propulsion system with permanent magnet technology. Also, the reason for the elongation of the vessel is the over dimensioned thrusters. Calculations could be done do find a more suitable size of the azimuths.

Motivation

- Will give students a relation to the data they are working with.
- Motivating for students to work with real systems that they can study in 3D.
- No further work on the twin required for this to be possible.

Detailed description of possible application

Exercises:

- Perform computations to choose an optimal choice of main dimensions of thrusters.
- Do resistance computations on Gunnerus.

Project:

- Perform resistance computations on Gunnerus using results from the model test, empirical and numerical methods. Use the sensor data from the vessel to compare results and evaluate the quality of the different methods/measured data.

TMR4240 – Marine Control Systems I

Course Coordinator: **Asgeir J. Sørensen**

Course Description

Marine Control Systems I is a fundamental building block in the maritime branch of cybernetics. Marine control applications play an important role in the control of special-purpose vessels and structures, such as platform supply vessels, deep water drilling rigs, cruise ships, and research vessels. The course is based on classical control system design and mathematical modelling for a variety of marine operations. Accordingly, it contains topics related to station keeping, motion damping, thrusters, machinery, electrical power distribution, and potential operation hazards. Moreover, the course explores design of controllers and observers, filtering methods, state estimation, power management systems, thrust allocation. Implementation of these phenomena, and the synergies between them, is an essential part of the course.

Learning methods and activities

The course has theoretical exercises to support the lectures. The exercises often make use of *MATLAB* and *Simulink* to create control environments, solving engineering problems related to the course curriculum. In addition to the exercises, the course includes a project accounting for 33 % of the final grade. The purpose of the project is to design and test a control system relevant for maritime operations. The assignment includes *Simulink* implementation and testing of a controller, reference model, observer, and thrust allocation algorithms.

The course offers an excursion trip with Gunnerus, since the research vessel exhibits state of the art dynamic positioning (DP) technology. The students get to speak with the crew and test the manual control station. Although Gunnerus is a smaller vessel, the excursion will – for many – be the first exposure to a real-life DP system, which is a central part of the course.

Application of Gunnerus Digital Twin

Gunnerus provides a unique collection of systems relevant for marine cybernetics. Therefore, a digital twin is of significant interest. Below are some potential areas of application for a digital twin in the first marine control systems course:

- Create a control environment where the students can explore vessel dynamics and the affect of different control applications.
    - Such an environment could be closely connected to the *Simulink* block diagramming tool.
- A laboratory exercise related to the excursion would enhance the learning outcome of the excursion.
    - Signal data from the students' own excursion with the vessel can be extracted and analysed.
- Implement the model into a realistic reference frame and environment, which would allow the students to see simulation results from exercises and the project more clearly.
    - *Simulink* is a powerful tool, and enabling a cross-platform cooperation through *MATLAB* would enable visualisation of simulations.
- Display the presence of signal faults such as frozen signal, wild points, and high variance.
    - Students could implement algorithms to detect and filter out signal faults.
- The digital twin can be used as a supporting tool in the compulsory course project.

Motivation

Marine control systems often consist of complex frameworks with many subsystems working together. This makes it challenging to achieve a complete overview of the different system functions. Introducing a digital twin as a supplement to the course material would improve the overall understanding of marine control systems, as it introduces a hands-on tool for the students to experiment with. Furthermore, the importance of data processing and analysis in control theory makes signal data from Gunnerus a valuable asset.

TMR4243 – Marine Control Systems II

Course Coordinator: **Roger Skjetne**

Course Description

Marine Control Systems II is a continuation of its predecessor. The course covers nonlinear systems theory and nonlinear robust control design, more specifically the design of non-linear regulator and observer algorithms used for automatic control and navigation of marine vessels and structures. The course includes topics such as estimation theory, observability, sensor fusion, adaptive control, and manoeuvring control theory. Dynamic positioning (DP) systems are used to exemplify much of the theory encompassed by the course curriculum.

The course takes a practical approach to marine control applications through different laboratory exercises. These laboratory exercises underline the focus on DP systems as a foundation for learning, allowing the students to produce and analyse physical realisations of the theory they learn, as well as the opportunity to implement the theory into simulators and models.

Learning methods and activities

As mentioned, the course includes several practical exercises intended to introduce realistic control problems for marine operations. These exercises are carried out in available laboratories facilitated by the Institute of Marine Technology. The Hardware-in-the-Loop (HIL) laboratory is available for testing control systems through simulations. The Marine Cybernetics (MC) laboratory is used to test motion control systems of vessel and structure models. Different laboratory exercises are concluded in a project report which accounts for 40 % of the final grade in the course.

Application of Gunnerus Digital Twin

A digital twin makes it possible to restructure the laboratory exercises in the course. The course focuses on using DP systems as a learning platform, which makes Gunnerus a relevant case study. Below are some potential areas of application for a digital twin in the second marine control systems course:

- Real data sets from Gunnerus can be used to test estimator algorithm functionality.
    - An example would be to evaluate observer design.
- The functionality of different DP regulators can be tested on a simulation model of Gunnerus.
- Can be a versatile tool for the theory provided by lectures and course material.
    - Enables visual representations of complex control problems and implementations.

Motivation

Advanced nonlinear control systems depend on simulation testing. Testing of implemented systems on real systems can damage the system and surrounding personnel, which is highly discouraged. As such, HIL-testing and model testing provides unique ways of determining control functionality with little to no consequences. A simulation model of RV Gunnerus would provide a powerful tool for analyses of control implementations, enabling a testing of a variety of control mechanisms. Such simulations would be a suitable complement to the course's practical laboratory activities, and could be a foundation for different laboratory assignments. As the laboratories is used extensively beyond the course, such a simulation model with access to transmitting signal data could benefit master and doctorate theses, as well as for general research purposes.

5.2. Other study programmes

TMR4325 - Engineering and ICT, introduction

Course Coordinator: **Håvard Holm**

Course Description

The course motivates for the study through basic training within ICT-methods and tools that are used by different study profiles at Programme for Engineering and ICT. This is realized through basic training in the use of tools and methods organized as small projects connected to different profiles. In some degree there will be a connection between the projects. The course will also include basic training in programming. Experiences from the course are valuable later in the study.

Learning methods and activities

The course gives theoretical and practical training in various computer-based methods and tools that are used by different study profiles. This can be ICT/CAE tools and tools related to the handling of geographic information, marine technology, petroleum engineering or production engineering. The education is based on lectures and sub-projects connected to different study profiles. The course also includes training in programming concluded by a practical task connected to one of the study profiles. The students need to pass all the sub-projects in the course. Assessment for the course is partially based on group projects. If significant differences in the contributions from group members have been documented, individual adjustment of final grading may be considered. The techno-start project is also integrated into the course.

Application of Gunnerus Digital Twin

The use of Gunnerus in TMR4325 is already in action. A model of Gunnerus will be used in CAD exercise where the students are assigned a task to add new components in the ship assembly. Examples of these components are thrusters, anchors, winches or a-frame.

Students will learn:

- CAD
- Working in assemblies
- Modelling
- Ship and component structure

Motivation

TMR 4325 is an introduction course and has its focus on showing the width of possibilities inside Engineering and ICT. By showcasing the importance of CAD and also in regards to a digital twin, the students are introduced to possible future master theses. Additionally, CAD has its advantages since students see the result of hard work increase with time spent. In this regard, motivating factors for the students is to observe this improvement of the model over time and therefore observe the potential of using digital CAD tools to create complex models. Furthermore, they will see the need of having a CAD model.

TMM4115 – Engineering Modelling

Course Coordinator: **Knut Aasland**

Course Description

Description of technical systems and products. Modeling as a tool for product development and production. Description of construction and function of technical products. Machine drawing. 3D modelling. Sketching and drawing as tools for documentation of products and processes (language and symbols). Techniques and methods for sketching and drawing. Eco-design and life cycle analysis.

Learning methods and activities

Lectures on terminology, description formats and techniques. Extensive exercises. A video-based self-study course on 3D modelling is included. There is also a teamwork project during the final phase of the course. Assessment for the course is based on group projects.

Application of Gunnerus Digital Twin

The Digital Twin is a good tool to show the students how big, detailed and realistic a 3D-model can be. By navigating through the whole ship, deck by deck, the students will get a better understanding of how an assembly structure should be organized. They will also get an impression of how important it is to use exact dimensions and a robust workflow. It is also a great tool to demonstrate the use of 2D-drawings and how important its is that they can be easily understood.

This can be done by giving the students access to the 3D-model, where they can investigate the ship in detail. They could then be provided with a simplified version, without interior and deck equipment, where the task is to modify or equip the ship with components made by themselves. After modeling, they will be asked to produce 2D-drawings of their components, which must meet specified requirements for production.

Another proposal is to provide the students with 2D-drawings of the equipment delivered by MBH (Cranes, winches, etc..) and ask them to model the components, based on the information in the drawings.

A VR-demo can also be executed, to demonstrate how a 3D-model can be presented in a powerful way.

Motivation

- Will give the students a better understanding of 3D-modeling, complex assemblies and the use of 2D-drawings for production.
- Motivating for the students to work with models and drawings from a real project, and to have the possibility to compare the 3D-model with the real ship.
- Need permission from Polarconsult and MBH to use their drawings in the course.

TMM4155 – Finite Element Applications in Mechanical Engineering

Course Coordinator: **Terje Rølvåg**

Course Description

The course will include the following subjects: "geometry idealization", "advanced meshing", "identification of FE based theory and tools for problem solving", "linear and non-linear Finite Element (FE) formulations", "static and dynamic FE formulations in time and frequency domain", "simple control system design for motor and vibration control", "guidance in NX, ABAQUS and FEDEM", "guidance in static, dynamic, contact, buckling and mechanism analysis", "FE based solution of previous exams in TMM4112 Machine Element" and "FE based solutions of advanced industrial applications"

Learning methods and activities

Portfolio assessment is the basis for the grade in the course. The portfolio includes compulsory work (50%) and five semester assignments each 10%. The results for the parts are given in %-scores, while the entire portfolio is assigned a letter grade.

Application of Gunnerus Digital Twin

The Digital Twin is a great tool for testing out different simulation solvers, for different cases and operations. Since Gunnerus performs different research operations, with several types of equipment, it will be useful to simulate some of these operations and study how the equipment and structure are affected.

This can be done by choosing a specific equipment type or the BD, share the 3D-model with the students and first ask them to mesh it. After meshing, different solvers in NX or FEDEM can be used to simulate an operation (e.g. crane) locally at the chosen equipment or globally, with the whole structure included. It would also be beneficial to include external factors, e.g. waves, in addition to the loads that occurs within in the operation. An Eigen Frequency analysis can also be performed on the structure.

Another, more ambitious suggestion is to perform a coupled analysis (e.g. Thermal and Electromagnetic) on the Thrusters, based on sensor data. A more detailed 3D-model of the PM-Thrusters in combination with real sensor data, will constitute a good basis for testing out Ansys Twin builder on an in-service component. This tool can then e.g. be used for evaluating remaining lifetime and different failure modes on the thrusters.

Motivation

- Will give the students a better understanding on simulation of complex operations and how different solvers can be used.
- Motivating for the students to work with real case operations, that can be faced later in their careers instead.
- Develop more detailed 3D-models of the equipment, with the necessary details included. (Cranes, thrusters, winches, etc.)

6. Conclusion

Important steps towards the digital twin of R/V Gunnerus has been accomplished through a summer project in collaboration with DNV GL and Digitread, and a Rector-funded student project during the summer and fall of 2018. The basic building blocks of a digital twin, in the form of product models, a 3D-model, and sensor data streams have been developed as part of the summer project. The product model and the 3D-model are connected to the sensor data stream through DNV GLs Digital Twin Viewer in Sesam Insight, and the overall capabilities of the Veracity data platform. This enables interactive visualization with links to sensor time series data. This yields valuable insight that can strengthen the learning outcomes for engineering students. Further support for this has been developed through the fall semester, during which the students have consulted with course responsibles to identify use cases in the individual marine technology courses. The digital twin of R/V Gunnerus can already as this stage be used for exercise work in certain marine technology courses, in particular those courses related to machinery and hydrodynamics, and in courses within mechanical engineering like finite element modelling. Hence, the results show that progress is being made towards the "*adopt-a-ship*" vision, in which digital twins are actively used throughout the marine technology study programme.

Most important is the experiences and the view of the students who have been involved in this project for innovative education. They clearly express their belief in digital twins as a positive contribution to engineering discipline study programmes.

6.1. Future recommendations

This report has documented that engineering students under guidance of industry partners and academics are fully able to provide a valuable contribution to what may become a fully operational digital twin. However, due to limited time and resources, work remains before a fully operational digital twin can fulfill its potential. There is still work remaining. Some of the main points for further work are:

- Sensor instrumentation at new points of measurement, e.g. machinery and deck equipment
- Set-up of communication equipment for transmission of sensor data from ship to shore, selection of shore-based storage and computation infrastructure
- Develop physics- and machine learning-based models for deriving "virtual" points of measurement
- Active use of the R/V Gunnerus digital twin in course material and in course work

Developing the digital twin capabilities of R/V Gunnerus will remain a priority for the Department of Marine Technology, and resources in the form of PhD candidates and post-doctoral researchers should be assigned to enabling the realization of the "*adopt-a-ship*" vision in the years to come.

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