Real-time digital twin of research vessel for remote monitoring

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KEYWORDS

Virtual Prototyping; Digital Twin; Remote Monitoring

ABSTRACT

Real-time digital twins of ships in operation find many applications such as predictive maintenance, climbing the ladders of ship autonomy, and offshore operational excellence. The literature describes a focus on digital twinning of individual equipment such as navigation, propulsion, engine and power system, or crane. Yet, digital twinning and virtual prototyping for offshore operations are in their infancy and the onboard digitisation hardware and the telecommunication infrastructure are becoming accessible and affordable. Previous work has failed to address the need for building a holistic model and thus contextualising the equipment with the state of the whole vessel. A prototype of an online digital twin of a research vessel is proposed, its architecture described and its suitability for virtual prototyping demonstrated in a remote control centre. The study shows a viable proof of concept for remote monitoring and crew assistance in nominal and contingency response for offshore crane operations.

INTRODUCTION

Offshore operations in wind blown areas such as wind mill parks often involve a lot of downtime for offshore service companies, which have to wait up to 8 weeks at quay to have a proper weather window for installation. The saying is "99 % boredom, 1 % action". To increase the asset utilisation, offshore crews have to optimize installation, maintenance, and decommissioning procedures, test the limits of the system, and design contingency plans. As it is too expensive to be performed with the real assets, the state-of-art is to create digital twins of the system: {ship + equipment + machinery + payload} and use them to simulate the operations in their socio-technical context with hardware-in-the-loop (HIL) and humans-in-the-Loop (HITL), Major et al. [2020]. Digital twins of offshore systems integrate thus physical models of various domains such as the ship's hydrostatics and hydrodynamics, power management systems (PMS), propulsion, ballasting system, dynamic-positioning (DP) system, and machinery such as offshore cranes and winches. Furthermore, the operational procedures to be designed often involve chains, wires, cables, risers and umbilicals. This increases the complexity of the simulation. There is thus a need for integration of multi-domain physics with interaction between rigid bodies and wire-like entities on one side and hydro- and aerodynamics on the other side. Finally, to be useful for hardware integration and human training and design, the performance of the simulation should be real-time or faster, without impairing its fidelity. To respond to these stringent requirements, a modular approach is needed.

As autonomy is gradually becoming a reality for cargo, ferries, and passenger ships, a system of remote monitoring centers will be necessary to watch the remote systems' trajectory, health, and overall functioning. Such an infrastructure is already common in the aerospace industry, with earth crew monitoring the health and activities of space-borne systems 24/7 from launch to decommissioning. Much like air traffic control, vessel traffic service (VTS) centres are a network of onshore based centres monitoring the traffic near the coasts and in vicinity of offshore platforms. The service relies on voice communication and mainly on automatic identification service (IAS) to transmit information mainly limited to navigation and draught and excluding the health of the waterborne systems and their sub-systems. Many research projects are thus tackling the task of building monitoring systems of the remote systems: power, propulsion, ballast, etc. Such an approach allows for predictive maintenance, incident and fault prevention, better fuel consumption through better route planning and less port congestion, and safer offshore operations in an industry where between 75% and 96% of maritime incidents are related to human error All [2019].

This study goes a step further by creating the digital twin of a research vessel, integrating its crane system and transmitting the whole state of the ship via a 4G communication line to an onshore simulator and remote control centre (SRCC). The whole scene is then reconstructed, visualised with a truthful digital twin of the {ship+crane} system, together with a simulation of the system for navigational purposes and a simulation of the crane system.

This paper is organized as follows. Related works are first presented, after which the framework and infrastructure is introduced. The results of a live demonstration are then presented. Finally concluding remarks

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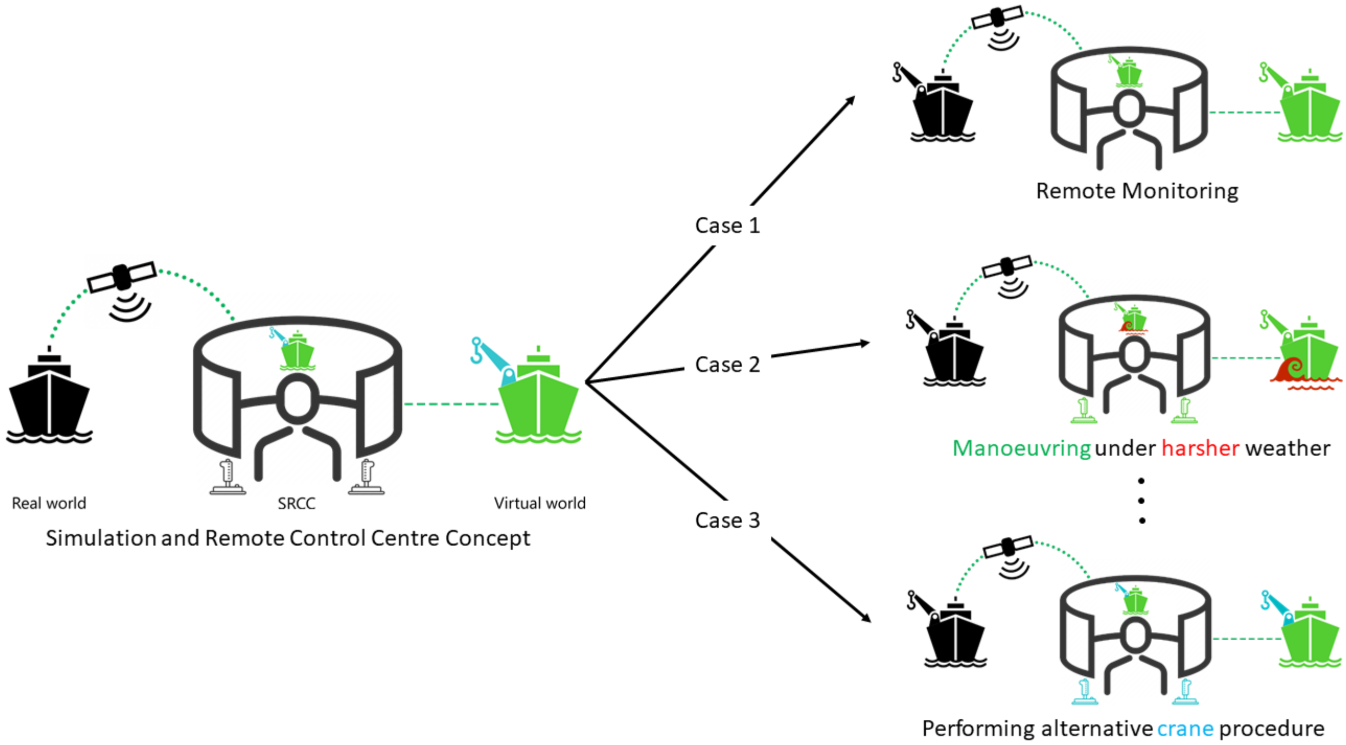

Fig. 1: Digital twin and remote control centre concept, with illustration of cases

and future work are presented.

RELATED WORK

Digital twins are mostly used during at design-time for virutal prototyping. To mention just a few recent publications: Nikolopoulos and Boulougouris [2020] present ship design using an holistic digital twin, Perabo et al. [2020] take profit of the functional mockup interface (FMI) for co-simulation to design and build a testable virtual prototype of a ship with its propulsion system. Likewise Chu et al. [2015] introduces a design system for cranes using FMI. Digital twins find also applications during the operative phase for repeatable operations: Listou Ellefsen et al. [2020] presents an online onboard and onshore fault-prediction and remaining useful life estimation system, Green [2016] showcases an onboard fault prediction maintenance system, finally Coraddu et al. [2019] illustrate the use of data-driven methods for bio-fouling detection and fuel efficiency. Furthermore, Li et al. [2016] present an Agx-based virtual prototyping framework for offshore operations. But in this study, we address unique and non-repeatable operations based on the digital twin of an offshore system. A first of its kind offshore operation was monitored from an onshore remote control center in real-time operation-time via a satellite link, as reported by Time and Torpe [2016]. Underwater Remotely Operated Vehicles (ROVs) operations can not only be performed from the offshore system but also from onshore remote operation centers for ROVs [Oceaneering]. This is case, only the ROV systems are monitored and remotely controlled and not the entire {ship+crane+ROV launcher+ROV} system. Finally, to measure the surrounding state of the ship, Halstensen et al. [2020] illustrates the use of radar-based short term wave prediction for an onboard decision support system using a digital twin of a crane and ship, but without onshore control centre and analysis of scenarios. In this paper we propose a remotely monitored digital twin of the ship and crane systems and illustrate its benefits for advanced offshore operations.

CONCEPT AND ARCHITECTURE

Fig. 2: Crane and Ship Control SRCC

The stretched dome depicted in Figure 2 is one of the SRCCs of NTNU Ålesund research laboratory. Equipped with one crane control chair for commanding a crane with crane joysticks (right on the picture) and one control chair (left on the picture) for controlling the propellers of the ship with maritime lever, it can perform virtual prototyping and remote monitoring of offshore operations, as depicted in Figure 3, where the experimental setup is composed of a sailing ship (left) and the SRCC (right). The ship's systems are monitored by two onboard management systems, one for navigation information (OLEX server) and for the crane system (MQTT broker). The navigation server gathers data from sensors via signals following the MMEA protocol, which is a text-based low rate protocol, at the rate of 1Hz. The sensed data include global positioning system (GPS), wind speed and direction, and motion reference unit (MRU). The state of the OLEX Server is cloned to an onshore mirror (OLEX Mirror), via a 4G connection and the NMEA signals are interpreted by the OSC Simulator. The simulator can thus reconstruct the current state of the ship's position, orientation and their first and second derivatives (speed and acceleration). A textured and detailed digital elevation model (DEM) of the environment with bathymetry, topography, and built infrastructure is used to contextualise the operation near the shores. The digital twin can thus be placed in the virtual world with the correction position (latitude and longitude) and orientation (roll, pitch, and yaw). Furthermore more, the Navigational Screen (Nav Screen) displays contextualized information such as sea-bottom depth and AIS-based surrounding ship traffic information, and provides even more contextualized remote monitoring information.

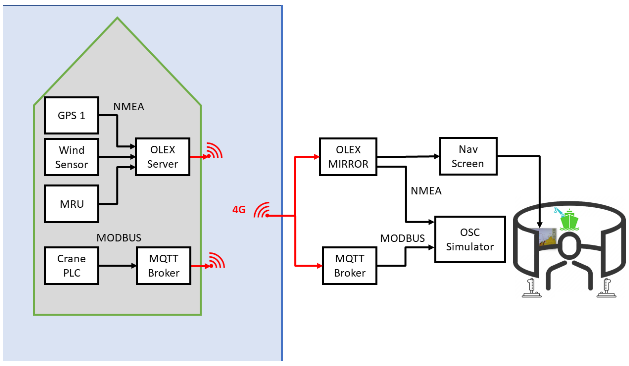

Fig. 3: System Infrastructure

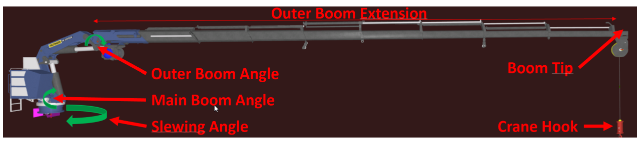

Fig. 4: Palfinger Crane In Simulator

The state of the offshore crane is replicated onshore in a similar fashion via another system and following the Modbus protocol through an MQTT infrastructure mirrored over 4G. The OSC simulator polls the state of the crane at regular intervals (1Hz) and reconstructs the crane in the virtual world based on the slew angle of the crane relative to the ship, the angles of the booms and the extension of the boom tip (in meters), as shown in Figure 4. Figure 1 schematizes the concept: the virtual environment, ship, and crane mirror the real world systems and allows different scenarios. To fully take profit of the simulator centre and simulation engine, it is possible to decouple the visualized models from their real data streams and simulated their behaviours based on physics engines and user control command. Case 2 of Figure 1 illustrates such a case where the position of the virtual crane relative to the ship mirrors the real crane, but the ship responds to harsher environmental conditions (waves, wind, and current), as waves are depicted in red and the ship thrusters are controlled by joysticks (in green). Another possibility is to mirror environment and ship, but control the crane via joystick, as shown in case 3 of Figure 1, with the virtual crane pedestal following the ship movement via mathematical constraints.

The software architecture of the simulation engine (OSC Simulator) is schematized in Figure 5, the data from the real sources or from the mathematical models are fed into an abstraction layer which allows various feeds, with various frequencies and spacial resolutions to be combined into one coherent simulation. Table I summarizes the data source for each case. In case 1 of Figure 1, the visualised data mirrors the offshore ship and crane. In case 2 of Figure 1, the onshore personnel controls the wave height and direction, and the virtual ship behaviour is controlled by a ship engine called FhSim and the handles control the ship's propellers. Finally, in case 3 of Figure 1 the virtual crane is commanded by onshore personnel via crane chair joystick, with the behaviour computed in the physics simulator AgX and the virtual ship truthfully follows the offshore ship.

TABLE I: Case data or physical model source

	Crane	**Ship**	**Environment**
Case 1	Real Data	Real Data	Real Data
Case 2	Real Data	FhSim	Instructor
Case 3	AgX Model	Real Data	Real Data

RESULTS

The experiment was performed November 24th 2020, when the RV Gunnerus was stationed in Trondheim Norway and chartered by the Ocean Space Department of NTNU. Figure 7 shows images from case 1: 7 A, is a snapshot of the simulation, 7 B is a live-feed from phone camera, and 7 C is a picture taken in the dome during the experiment, with one of the developers inspecting the crane behaviour and the viewpoint of the simulation taken from a "free-flight" view. If the live-feed was sometimes faster, it experiences more jitter than the digital twin. This seems paradoxical since, as described in the previous section, the data stream for the digital twin goes through more nodes than the video stream (phone to phone) incurring inevitable latency, but the bandwidth usage on the 4G system of the digitized state has a much lower footprint than the video stream. As a matter of fact, parallel channels of a few kbit/s (NMEA and Modbus messages) are used for the digital twin, while the video feed require 100kbit/s to a few Mbit/s on a single channel. Furthermore, once they have reached the onshore simulator centre, the states

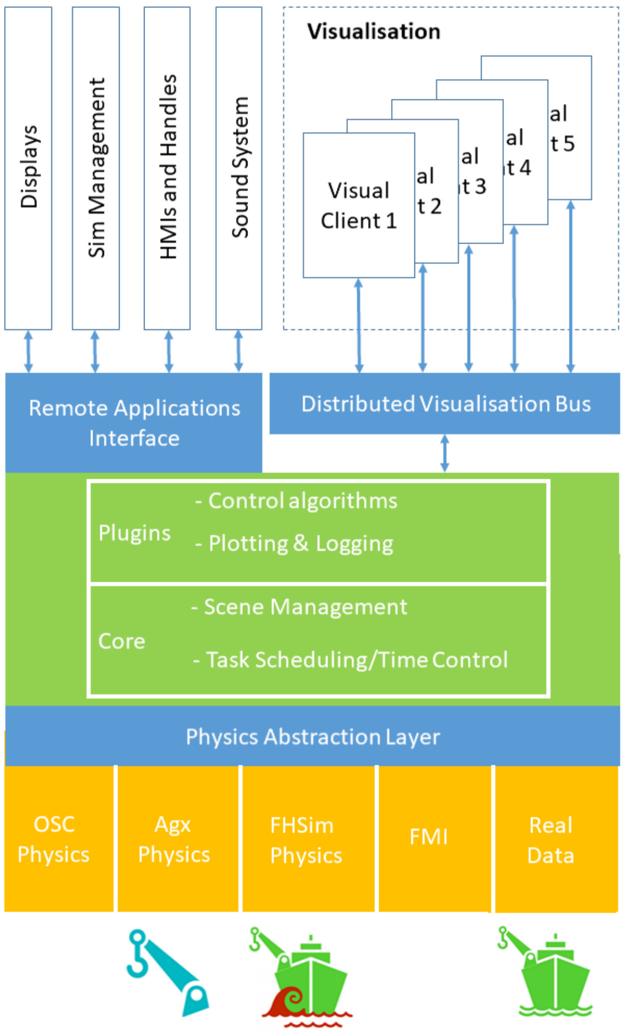

Fig. 5: Architecture and Models for the cases

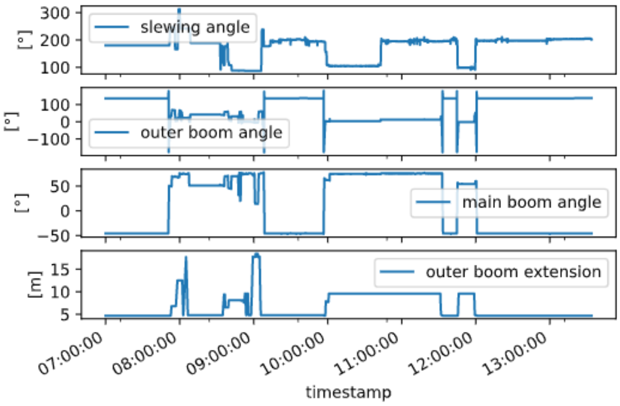

Fig. 6: Experimental data received in real-time

Fig. 7: A) Digital twin viewed from instructor panel, B) Visualisation the a stretched dome of the NTNU Ocean Space Lab, C) Live-feed from the ship during operation

of the ship and crane are filtered in time and space (via physical constraints in Agx) to smooth the visuals. If the few seconds latency are inevitable, the quality of the digital twin visualisation is comparable to the quality of the video feed: it is hard to distinguish the real from the virtual in Figure 7. Furthermore, bandwidth efficiency is an advantage when using satellite links.

Figure 8 shows a map with the scatter plot of the position of the Gunnerus vessel during operations, the color levels correspond to different outer boom extension ranges. The green color denotes the crane in standby, the blue color indicates that outer boom is extended until 10m (mid range) and the red dot corresponds to the peak when crane boom reached its maximum extension 14.8m as show in Figure 6 at 8:00 and 9:00. The ship and crane were both in activity between 10 and 12 (blue line).

The system presented finds many applications. Figure 9 illustrates difference between case 1 and case 3. In case 3, it is possible to run the crane independently and add overlays marking the safe weigh limits. One can see the boom crane of the green ship is higher than the mirror ship. Virtual prototyping applications such as just-in-time operation preparation, tool-box-talk, alternative operational path, and contingency procedures can thus be tested by senior onshore personnel and communicated to the offshore crew. One senior officer could thus stay onshore and be in charge of multiple ships in service. This is both a productivity boost for the service company and an improvement of work life balance of the officer, since she does not have to work many weeks offshore.

As depicted in Figure 10, for case 2 the sea is rougher with higher waves than in the real and mirror case. This allows onshore personnel to test the limits of the equipment and operation and determine the remaining safety margins if the weather was getting worse. This also allows to visualise the effects of performing the operation outside the safety zone such as reaching the safe working load on the crane due to splash zone effect where the immersed crane load in the wave zone is experienced to be much heavier than it own weight due to unfavourable hydrodynamic pressure and rolling of the ship.

CONCLUSIONS

A concept of simulation and remote control centre (SRCC) of {ship + crane } system was demonstrated in three different cases, the experimental setup and ar-

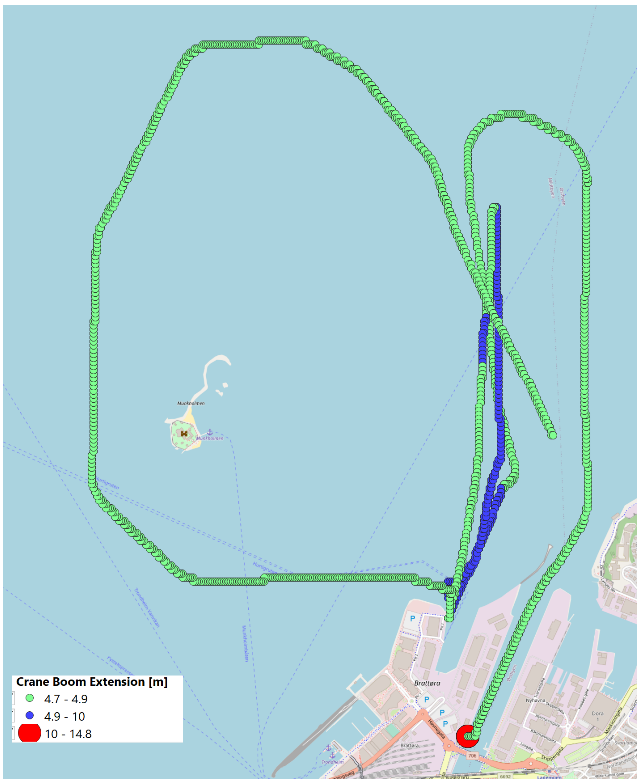

Fig. 8: Geolocalised scatter plot showing crane boom extension during operation. Map credit: Open Street Map

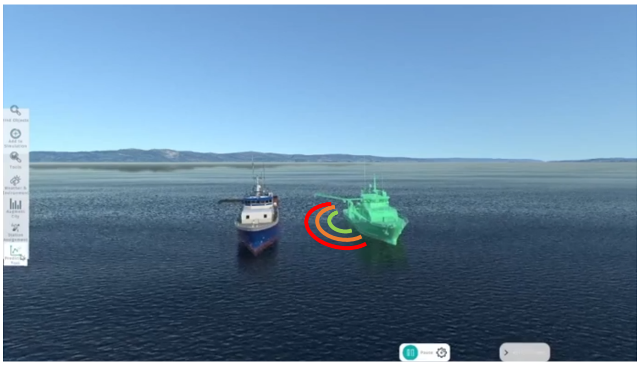

Fig. 9: Mirror digital twin (left), Case 3 (right) with overlayed SWL

chitecture were presented and the results illustrated in form of various visualisations. The main potential applications of such a system are remote monitoring and virtual prototyping aided by augmented reality. The potential can also be further developed by integrating more onboard systems such as propulsion, PMS, and alarm systems.

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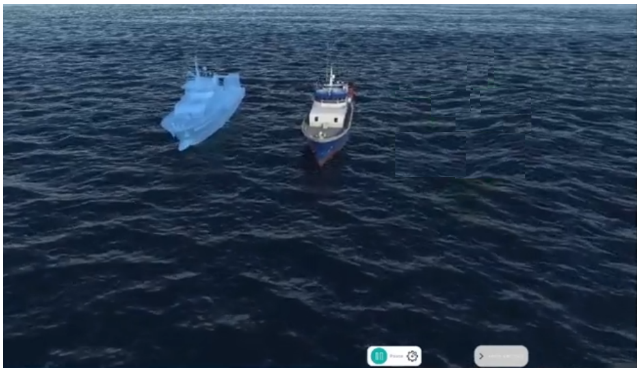

Fig. 10: Case 2 (left) experiencing harsher weather, Case 1 (right) mirroring real weather

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