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DIGITAL TWIN BASED STRUCTURAL HEALTH MONITORING OF OFFSHORE CRANE

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ABSTRACT

This paper presents a novel approach for implementation of digital twin (DT) based Structural Health Monitoring (SHM) of an Palfinger offshore knuckle boom crane. Contrary to most harbor gantry cranes, knuckle boom cranes are highly non-linear mechanisms that cannot be represented by static reduced order twin models. Such cranes need to be solved by non-linear finite element solvers. The digital twin representation of the Palfinger crane is modelled and simulated real-time in a nonlinear finite element (FE) program, driven by inputs from physical sensors. Model reduction techniques are applied to enable DT co-simulation running two times faster than the physical crane. The inputs from the standard crane instrumentation are processed for noise reduction and singularity removal and converted to hydraulic actuator inputs. A simple inverse method for estimation of the crane payload is implemented based on hydraulic pressures. Structural loads due to wave induced ship motions are predicted based on sensor signals from the ship IMU. Based on the standard ship and crane instrumentation, the digital twin allows for real-time determination of stresses, strains and loads at an unlimited number of hot spots. Hence, a digital twin can be an effective tool for predictive maintenance of real offshore knuckle boom cranes with minor additional costs. The presented approach is described in a general manner and is applicable for offshore cranes used in the industry.

Keywords: Digital Twin, co-simulation, FEA, SHM

NOMENCLATURE

SHM	Structural Health Monitoring
DT	Digital Twin
CP	Connected Products
ROM	Reduced Order Models
FEDEM	Finite Element Dynamics of Elastic Mechanisms

1. INTRODUCTION

Offshore cranes are critical in many offshore operations. The cranes operate in demanding environmental conditions and are subjected to dynamic wind and wave induced loads. In addition, cranes are often used for heavy-lift operations at different configurations, which makes it even more difficult to identify and determine the effect of the most critical load combinations based on standard OEM instrumentation.

To improve the utilization of NTNU's research vessel R/V Gunnerus [1], the ship crane was replaced by a larger knuckle boom crane in 2020. Due to a demand for lowering risks and operational costs, installing larger cranes on such supply vessels has become a common trend. Hence, the authors decided to benchmark a generic digital twin solution for failure mode detection of supply vessels and knuckle boom offshore cranes. The process of implementing a failure mode detection strategy for civil and mechanical engineering infrastructure is referred to Structural Health Monitoring (SHM) [2].

Most SHM systems originate from bridge and civil engineering, but SHM for large port cranes have been proposed by [2,3,4,5]. While most SHM systems [2,5] are based on instrumentation of physical assets, others are using reduced order models based on static FE models for predictive maintenance [3,4]. The authors have not observed SHM systems supported by nonlinear FEA executed as a co-simulation in real time.

In this paper the authors focus on how to model and implement a digital twin of the crane for SHM. The digital twin is represented by a non-linear FE assembly model in FEDEM [6,8,9] utilizing model reduction techniques to achieve real time simulation performance. Physical tests were conducted to calibrate the mass, stiffness, and damping properties at various crane configurations.

The SHM implementation is combining a fast edge and a slower but more scalable cloud solution. The edge solution runs real time at 100 Hz on a local computer, while the cloud solution is running at 1 Hz on an SAP EPD CP operated server [10]. Both solutions are triggered by a hydraulic pressure increase of the main crane actuator. The real time edge solution provides operational decision support to the captain during critical crane operations. Safety margins with respect to the measured roll motions and calculated structural loads are continuously visualized on a cloud dashboard. The edge solution is also embedding real time fatigue life computations and visualization. The cloud solution is performing more comprehensive off-line structural stress and fatigue life computations. Both physical sensor data and digital twin simulation results are simultaneously displayed on a cloud-based dashboard [10] as shown in FIGURE 1.

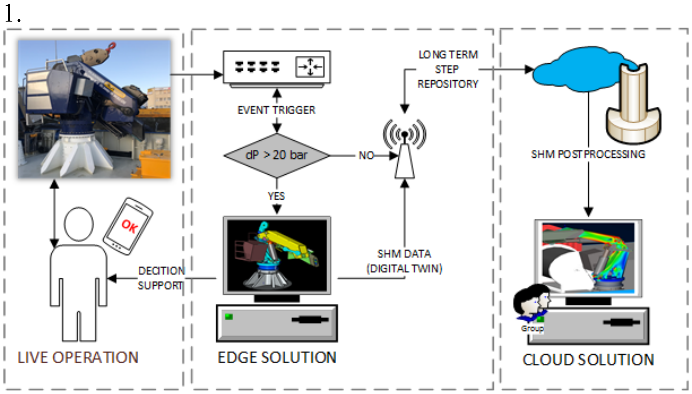

FIGURE 1: THE HYBRID EDGE AND CLOUD SOLUTION

The main contribution of this work is a novel approach for implementation of SHM for an offshore knuckle boom crane based on a non-linear FE formulation [6,9,13]. This work is an extension of the experimental study presented in [8]. The proposed digital twin solution is implemented for an industrial offshore knuckle boom crane and verified by full scale physical tests [14]. The proposed approach can be used for predictive maintenance and life-cycle management of cranes and their components, by continuously collecting physical and virtual crane data. These data are stored in an ISO 10303 supported framework for long term storage, developed by the ArrowHead Tools project partner JOTNE [11,12].

2. THE PHYSICAL CRANE INSTRUMENTATION

A new and larger Palfinger PK 65002M crane as seen in FIGURE 2**Error! Reference source not found.** was installed on the research vessel R/V Gunnerus [1] in 2020. The crane was ordered with the standard instrumentation with some extra sensors measuring the boom length, tilt and slew angles.

1. The physical crane boom length is measured by a wire system. The boom length is transformed to the sequential extension of the individual cylinders and applied on the digital twin model.
2. Two tilt angle sensors on the main and outer boom. These two angles are controlled by two telescopic hydraulic actuators and must be recalculated to the individual cylinder strokes. The sensor angles are coupled and passes singular positions that is identified and eliminated by a moving average algorithm.
3. One crane Slewing angle (encoder) gives the horizontal digital twin rotation directly.
4. One pressure sensor on the main hydraulic cylinder is used by a trigger function to start and stop the digital twin simulation.
5. One 6 DOF IMU / MRU which measures the ship heave, sway, surge, pitch, roll and yaw applied to the crane support. In bad weather conditions, this motion contribute to the structural crane loads.

FIGURE 2 PALFINGER PK 65002M

All physical measurements are filtered and translated to digital twin inputs by Python scripts. Low pass filters (10 Hz) are applied on the sensor data to smoothen the digital twin inputs in the cloud solution sampled at 1 Hz.

3. SHM METHODS AND TOOLS

3.1. Challenges

When implementing a digital twin for SHM, the following challenges will require robust and flexible methods and tools:

- The maximum sampling rate for most cloud solutions is only 1 Hz, and Gunnerus is frequently outside the 4G/5G range. Hence, the authors had to embed a local and faster 100 Hz edge solution providing real time decision support during crane operations. Such edge solutions are required but in conflict with the interest of most IoT cloud providers!
- Sensor noise and drifting. In this project, Python scripts are custom made to eliminate singularities, noise and drifting of sensor inputs.

- Inverse methods are providing structural loads for the digital twin model based on a minimum number of physical sensors. Most cranes have no force sensors measuring the payload, and the authors had to develop an inverse method based on the hydraulic pressures and crane motions. Strain gages as used by [7] and the authors in [8] are not applicable on a telescopic boom.
- Most digital twin solutions for SHM embed precomputed (FEA/CFD) results. Terms like Reduced Order Models (ROMs), Look-Up tables and Static Twins are often used to describe these solutions. Neural networks are also applicable, and the solutions are robust and reliable when the physical input loads and model configurations are within the precomputed range.
- Real time FEA and CFD are usually too time consuming to run real time and are mainly applied as post-processing tasks in cloud solutions. However, the FEDEM software utilizes various model reduction techniques applicable to real time simulation of flexible mechanisms like knuckle boom cranes. The authors developed a digital twin FEDEM model of the Palfinger crane that calculates stress time histories and structural forces twice as fast as the physical crane moves.

3.2. IoT Framework

In this project, the IoT cloud solution Connected Products (CP) from SAP was preferred which provides a fully integrated solver environment for FEDEM as shown in FIGURE 3.

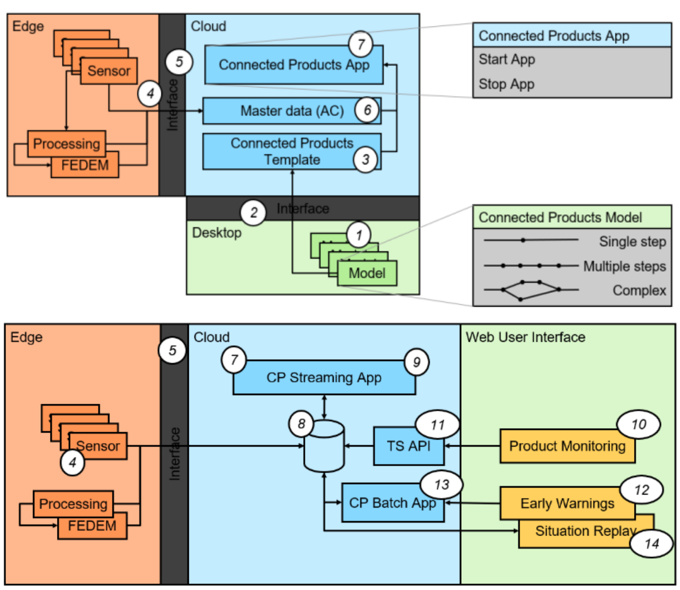

FIGURE 3 CP CONFIGURATION AND OPERATION

1. DT Models used in Connected Products (CP) are developed in a traditional desktop environment. Different DT models are supported. In this study the crane is represented by a FEDEM FMU.
2. Connected Products has a wizard for uploading DT models, and a .zip model is basically a CP Template
3. The CP Template is a non-connected product but with the complete processing logics defined. The Input channels in the template is named with unique names corresponding to the Master Data Model names
4. CP is a cloud product embedding Digital Twins of physical assets. The raw physical sensors itself and/or edge processed signals can be sent to cloud.
5. Data is sent over the IoT messaging protocol MQTT - The Standard for IoT Messaging
6. To receive and store data from edge and Master Data Model, an Asset Central Model, has to be defined. This model binds the edge sent data to a unique name in the CP Tenant.
7. CP Apps can now be paired. The same Template can be combined with multiple Master Data Models, e.g., needed for scaled solutions with many physical crane assets.
8. CP is built on top of AZURE or AWS including data received from edge
9. Streamed micro-batched solutions are achieved by sequentially processing time intervals. The time interval duration is defined by the App developer. Typically, micro-batch durations are from 10s to 60min. Streaming apps must execute faster that real-time.
10. The Product Monitor, i.e., a web page in CP, is a time series viewer for the time series data stored in the database (8).
11. The Time Series API connects the database (8) and the Product Monitor. The Time Series API possesses functionality for aggregating data from the database when too much data is requested. The Time Series API also possesses functionality for frequency transformations of the timeseries when that is requested by the Product Monitor
12. Early Warnings, a web page in CP, shows all the exceedances of defined thresholds.
13. Specific exceedances in Early Warning can trigger tailored batch apps. The Batch Apps do not need real-time execution. An example application is stress contour calculations for extreme conditions. The batch apps start automatically.
14. Situation replay are the CP web page for 3D fields, i.e. stress contour plots.

4. DIGITAL TWIN THEORY

FEDEM is a multidisciplinary simulation system based on a non-linear finite element formulation, CMS model reduction, and control system simulation enabling integrated digital twin modeling and simulation [1]. The nonlinear dynamic FEDEM solver is written on incremental form and solved by the Newmark-β time integration algorithm with respect to the displacement increments $\Delta\mathbf{r}_k$ for time increment k. To achieve equilibrium at the end of the time increment, in the non-linear case, Newton-Raphson iterations must be used to minimize the residual forces:

$$\mathbf{M}_k\Delta\ddot{\mathbf{r}}_k + \mathbf{C}_k\Delta\dot{\mathbf{r}}_k + \mathbf{K}_k\Delta\mathbf{r}_k = \Delta\mathbf{Q}_k \qquad (1)$$

where M_k, C_k, and K_k are the system mass, damping and stiffness matrices respectively at the beginning of time increment k. The changes in accelerations $\Delta\ddot{\mathbf{r}}_k$, velocities $\Delta\dot{\mathbf{r}}_k$ and displacements $\Delta\mathbf{r}_k$ are solved by Newmark-β for each time increment k. The system mass and stiffness matrices M_k and K_k are Component Mode Synthesis (CMS) reduced, which is the main enabler for real time FE simulation of non-linear systems like knuckle-boom cranes [6,9]. Only the external super node displacements $\mathbf{v}_e$ and the fixed interface component mode amplitudes $\mathbf{y}$ are solved for each increment for each component.

The $\mathbf{B}$ matrix can be used to calculate the internal displacements $\mathbf{v}_i$ due to the external displacements $\mathbf{v}_e$ while the eigenvectors in $\mathbf{\Phi}$ is used to scale the calculated modal amplitudes $\mathbf{y}$. The internal displacements $\mathbf{v}_i$ are therefore given by superimposing the contributions from $\mathbf{v}_e$ and $\mathbf{y}$ after the dynamic simulation is completed. The stresses can be calculated based on the component displacements $\mathbf{v}_{comp}$ for each component in the crane assembly.

$$\mathbf{v}_{comp} = \begin{bmatrix} \mathbf{v}_e \\ \mathbf{v}_i \end{bmatrix} = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{B} & \mathbf{\Phi} \end{bmatrix} \begin{bmatrix} \mathbf{v}_e \\ \mathbf{y} \end{bmatrix} = \mathbf{H}\,\mathbf{v}_{sup} \tag{2}$$

The same technique is basically used to calculate the strain / stress time histories at selected hotspots based on super node displacements as described in [13].

$$\boldsymbol{\varepsilon}_{rosette} = \left[\mathbf{T}_{re}\widetilde{\mathbf{B}}\ \mathbf{T}\ \mathbf{A}\ \mathbf{L}\ \mathbf{H}\right]\mathbf{v}_{sup} \tag{3}$$

$\mathbf{H}$ is the CMS matrix mapping external $\mathbf{v}_{sup}$ to internal displacements $\mathbf{v}_{free}$. The L matrix recover the internal displacements from linear couplings (MPCs). The A matrix extracts nodal displacements defining the strain gage from the full displacement vector. T is transferring the extracted nodal displacements to local strain gage directions. The $\widetilde{\mathbf{B}}$ matrix is the strain-displacement matrix given by the derivatives of the strain element shape functions. The optional $\mathbf{T}_{re}$ matrix transforms the calculated rosette strains and stresses to user defined directions.

The $\left[\mathbf{T}_{re}\widetilde{\mathbf{B}}\ \mathbf{T}\ \mathbf{A}\ \mathbf{L}\ \mathbf{H}\right]$ can be precomputed for each strain gauge element which allows fast real time calculations of hot spot strains during crane operations. This formulation is therefore applicable to digital twin / hardware in the loop applications.
The hotspots on the crane support are identified by using a virtual brittle lacquer represented by a surface mesh wrapping the original FE models. Hence, the hotspots are those external element faces with maximum accumulated damage during preselected crane operations [13].

5. THE DIGITAL TWIN MODEL

The FEDEM assembly model shown in Figure 4 is based on a Palfinger PK 65002M CAD assembly model. The CAD assembly was idealized in NX to minimize computational costs without the potential loss of structural failure modes.

The FE assembly consists of 25 structural parts meshed with TETH10 and SHELL elements. RBE2s, RBE3s are used to represent rigid components and super nodes in centre axes of prismatic and revolute joints. The FE assembly model was CMS reduced from more than 3.6 mill. DOFs to 828 DOFs as shown in Table 1.

The rigid body part of the crane mechanism motions is facilitated by 28 revolute, 4 rigid, 1 free and 22 cylindrical joints. Hydraulic cylinders driven by filtered physical sensor signals are modelled by 16 non-linear axial springs and dampers. A total of 45 functions are used to describe nonlinear component properties.

Virtual strain gages for real time fatigue analysis are positioned in all identified hot spots as described in [12]. In addition to the physical crane sensors, 5 virtual sensors are measuring and displaying additional information about the crane states in optional cloud dashboards [10,11]

TABLE 1: DIGITAL TWIN FEDEM MODEL

FEM Part	EXTERNAL NODES	EXTERNAL DOFS	INTERNAL NODES	INTERNAL DOFS
1	2	12	4 812	4 812
2	9	54	136 829	410 529
3	2	12	14 000	42 006
4	11	66	62 315	186 978
5	4	24	9 912	29 748
6	6	36	12 825	38 493
7	5	30	8 290	24 888
8	5	30	9 063	27 207
9	4	24	11 210	33 648
10	6	36	8 748	26 262
11	5	30	10 637	31 929
12	5	30	8 864	26 610
13	10	60	112 529	337 629
14	7	42	63 815	191 481
15	7	42	55 973	167 958
16	7	42	59 155	177 501
17	7	42	61 388	184 203
18	7	42	59 890	179 706
19	7	42	84 102	252 345
20	7	42	45 355	136 104
21	6	36	40 187	120 597
22	4	24	17 038	51 135
23	2	12	19 856	59 574
24	1	6	6 240	18 723
25	2	12	281 542	844 635
	138	828	1 204 575	3 604 701

Crane payloads are represented by a sensor controlled additional mass located at the crane tip (super node). A simplified inverse method based on the measured hydraulic cylinder pressure is estimating the crane payload. The same hydraulic pressure measurement is used in a trigger function to activate the digital twin simulation.

Environmental wave induced loads acting on the crane support are included by driving a FEDEM free joint with sensor data from the ship IMU transferring heave, roll, pitch and roll motions from the ship to the crane model.

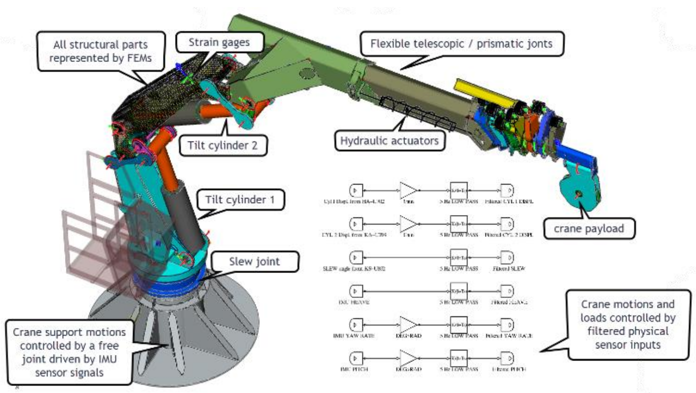

FIGURE 4: CRANE DIGITAL TWIN MODEL

5.1. Virtual sensors

On the Digital Twin the following virtual sensors are defined:

- 6 Virtual strain gauges (see FIGURE 6) located at 3 different crane and pedestal welds.
- 6 Base sensors measuring forces and moments (Fx, Fy, Fz, Mx, My and Mz) (see FIGURE **5**)
- Crane Tip motions in X-Y-Z directions (pully center, not illustrated)

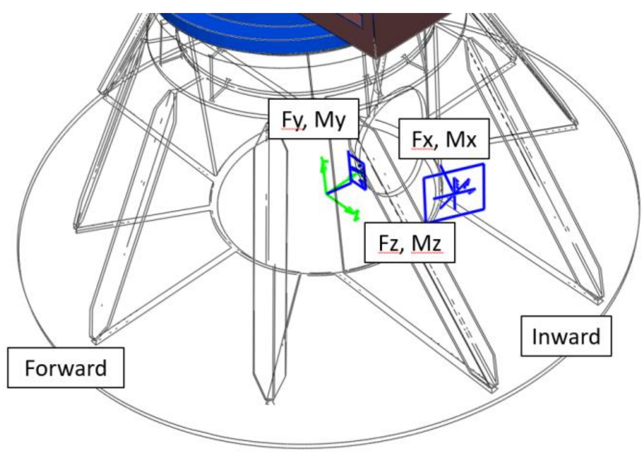

FIGURE 5: BASE FORCES AND MOMENTS

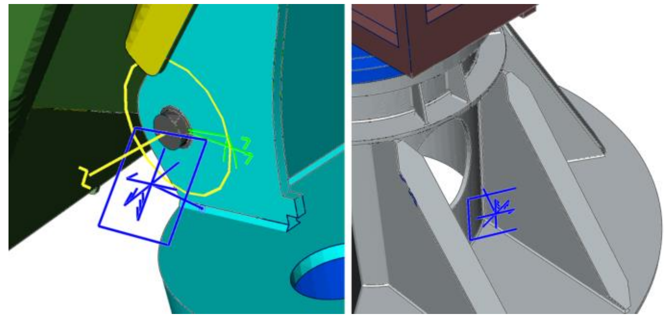

FIGURE 6: VIRTUAL STRAIN GAUGES ON CRANE AND PEDESTAL

6. THE DIGITAL TWIN MODEL VALIDATION

The FEDEM model was calibrated against physical tests to eliminate modelling errors due to limited information about the Palfinger crane hydraulic system. The stiffness was tuned to match the first dominant mode in the stowed and extended positions as shown in this YouTube video [15]

The damping ratio can only be tuned for 2 modes based on the mass and stiffness proportional (Rayleigh) damping in FEDEM [14]. The crane tip oscillations and damping were measured with an iPhone running the SensorLog app at 100Hz sampling frequency.

TABLE 2: DIGITAL TWIN FEDEM MODEL

Property	**Physical test data**	**Simulated test data**
First mode in stowed position / damping ratio	1.60 Hz / 6.6%	1.60 Hz / 6.6%
First mode in extended position / damping ratio	0.74 Hz / 8.7%	0.73 Hz / 8.7%

Based on the test results shown in Table 1, the mass and stiffness proportional damping factors α_1 and α_2 were calculated to 0.632 and 0.0069 respectively as shown in this YouTube video [14].

The applied crane payload is therefore currently the main error source. Even though SAP embeds an inverse method for payload detection [10], pulley and wire friction and elasticity will damp the peak loads and hence the worst load cases. To improve the accuracy a force transducer will be installed on the crane hook in 2022. However, the payload was known in advance for the 4 crane operations documented in this paper (see FIGURE 7), and the applied loads are therefore correct. The applied strain gage calculations are validated in [8,13].

7. DIGITAL TWIN PROCESSING

The Digital Twin processing at the edge consists of several steps.:

- The physical pressure sensor (4) is used to trigger the crane simulation when a lifting operation has started.
- Physical sensor data is sampled at 100hz and dumped to digital twin input files in 200 increment batches, equivalent to 4s of operation.
- Calculate individual outer boom segment strokes from the total outer boom stroke sensor (1). When extending the outer boom, the telescopic cylinders and hence boom segments, are sequentially driven (FIGURE 4)
- Use crane kinematics to calculate the main and secondary cylinder strokes based on the physical tilt angle sensors (2)
- Execute Digital Twin simulation driven by physical input sensors and dump virtual sensor outputs i.e., virtual strain gauges, base forces/moments and tip motions.

The digital twin input drivers are then the crane slewing angle directly measured by physical slewing encoder, tilt cylinder stroke 1 and 2 derived from physical tilt angle sensors on lower and upper tilt arm as well as cylinder Stroke 1-7 derived from the wire sensor measuring total boom length.

Both physical sensor data, processed data output as results from the digital twin execution and the digital twin model and results are stored locally on the edge computer. The local storage directory structure is standardized for easy, fast and robust access the data.

The digital twin model and native results can optionally be persisted and downloaded for more in dept investigations.

The edge computer is wired to the vessels network but is not setup with backup capabilities. This is acceptable for a R&D setup, but not for an industrial IoT solution. The data uploaded to cloud are though secured to the extent that the cloud provider secures the data.

8. RESULTS

Four lifting operations, hereby called events, have been selected for this work. These are moving a 1300kg frame internally on the vessel (1), a 800kg cable drum (2), a 1700kg ROV (3) and a 3000kg container (4) from the vessel to the Trolla quay as shown in FIGURE 7.

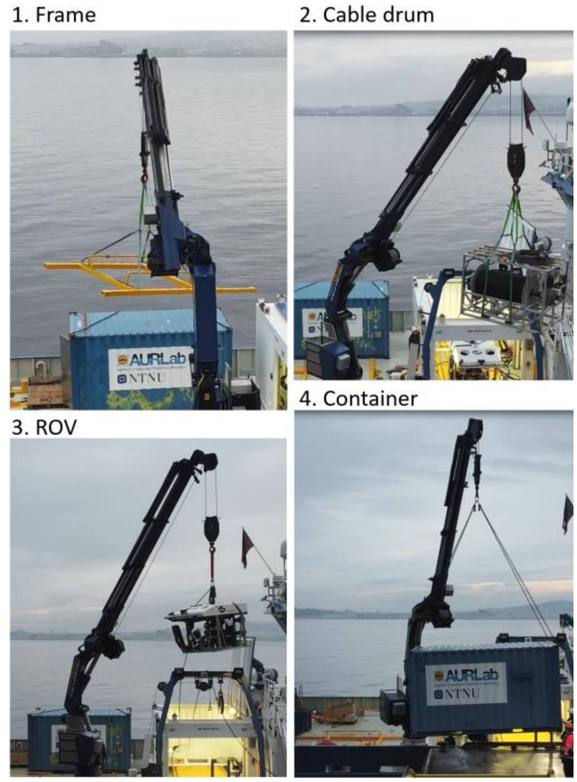

FIGURE 7 DRONE PICTURES OF FOUR CRANE LIFTS

The processing capabilities on the edge computer and the in the cloud supports a variety of solutions and only one of the data and processing flows are presented in this section.

8.1. Edge results

The edge processing capabilities do in addition to execution the digital twin itself and option to dump a summary report of the event. What to persist are also user controlled. The following options applies

- A data file containing the data sent to cloud
- The FEDEM model with dynamic results and stresses
- The automatically generated summary report.

The first three figures below are persisted simulation input FIGURE 8 and FIGURE 9) and output data (FIGURE 10) on the edge computer from the container lift event. FIGURE 11 is showing stress results that can be computed on edge.

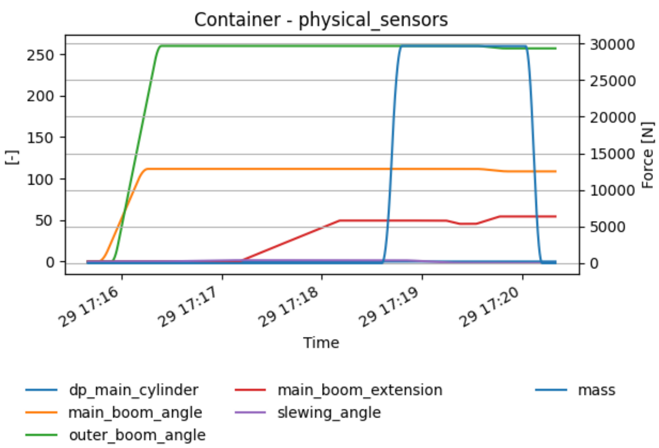

FIGURE 8 PHYSICAL SENSOR READINGS - EVENT 4

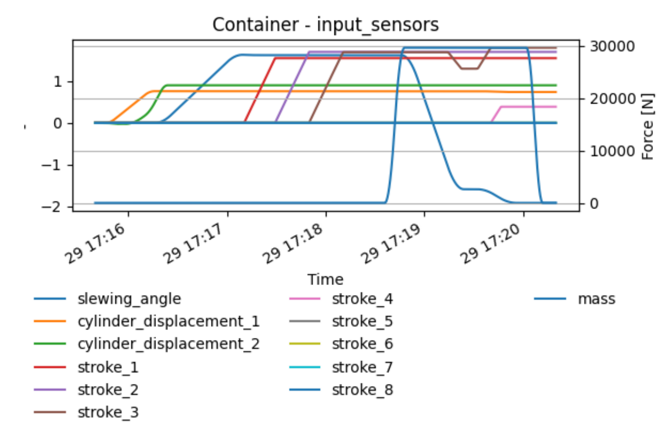

FIGURE 9 INPUT SIMULATION DRIVERS - EVENT 4

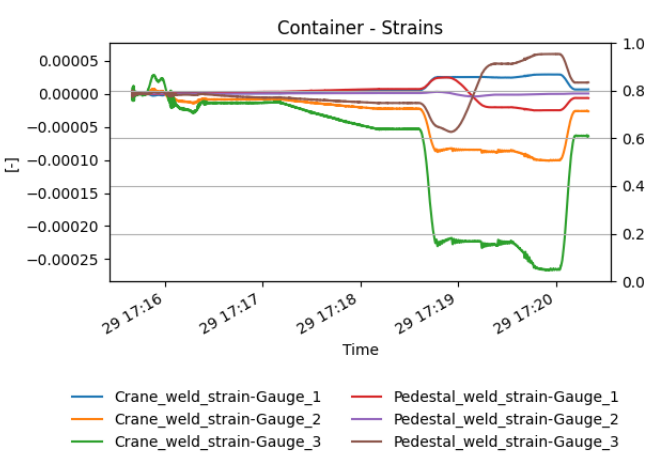

FIGURE 10 STRAIN GAGE OUTPUTS - EVENT 4

The dynamic simulation is conducted automatically for every new event. The detailed stress calculations are though not automated. As the FEDEM solver uses super-element techniques the detailed stress calculations are a separate solver process from the dynamic solver process. Dependent upon the level of detail the stress analysis requires the work can be conducted on the edge computer, but in most cases a transfer of the model to a local workstation is beneficial.

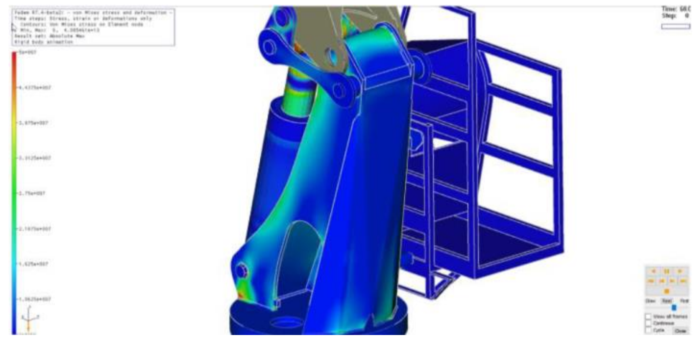

FIGURE 11 VON MISES STRESSES – EVENT 4

8.2. Cloud results

The virtual sensors are sent to Connected Products [10] and presented in the Product Monitor. The Product Monitor is setup with two views, one for the Trolla lifting operations and one for visualizing online visualization. The only difference between the two are that that the Trolla case are fixed to the actual time interval of the operation, while the online view is set up to show the last 30min. The time delay between the actual operation and the visualization in the online view are dependent upon duration of each micro-batch to be processed.

The following figures are all screen dumps from the Trolla view. The first four plots show all four events, while the next plots zooms into the container lift (event 4).

FIGURE 12 shows the EPD Dashboard. the event 4 shows the highest Mx value i.e., the moment contributing to the roll motion. The relative small difference in the MX Values are due to the different tip motions in X direction (FIGURE 15)

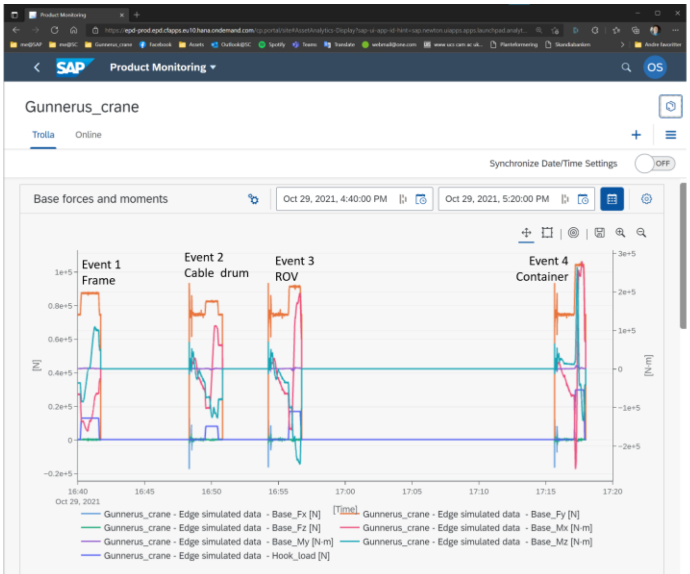

FIGURE 12 FORCES AND MOMENTS- ALL EVENTS

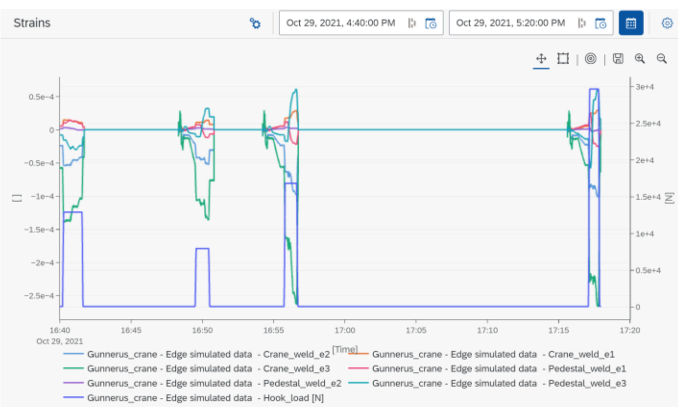

FIGURE 13 ALL EVENTS – STRAIN GAUGE STRAINS

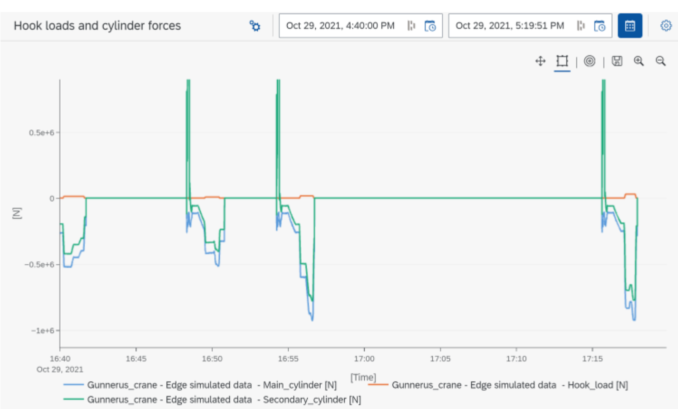

FIGURE 14 HOOK LOAD AND CYLINDER FORCES – ALL EVENTS

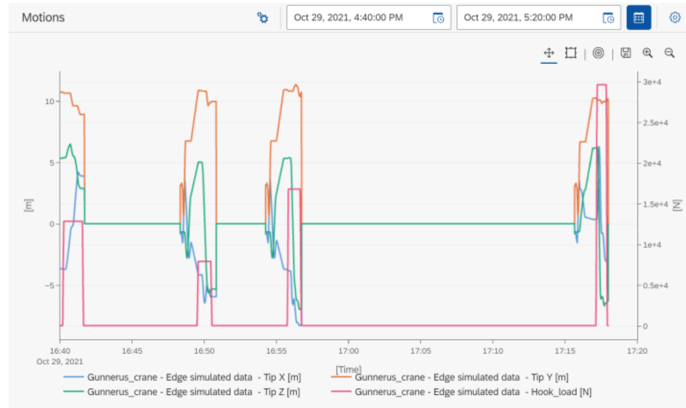

FIGURE 15 TIP MOTIONS - ALL EVENTS

The below four plots show the container lift. The startup transients in FIGURE 16 has not been investigated, hence the fraction of true physical behavior from this are not quantified.

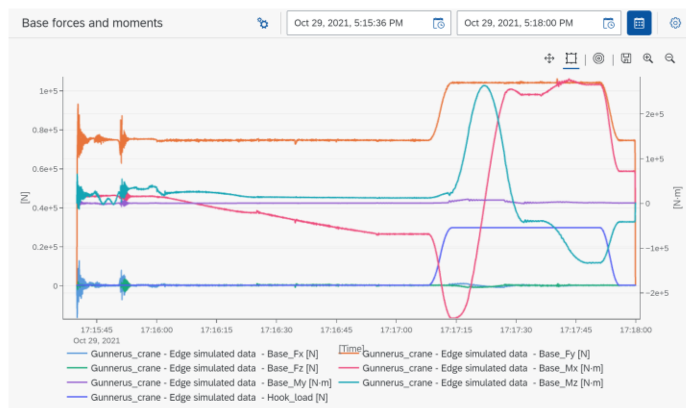

FIGURE 16 BASE FORCES AND MOMENTS - EVENT 4

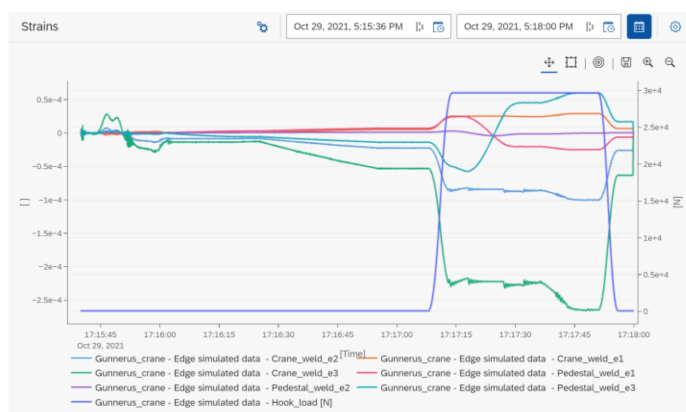

FIGURE 17: STRAIN GAUGE STRAINS - EVENT 4

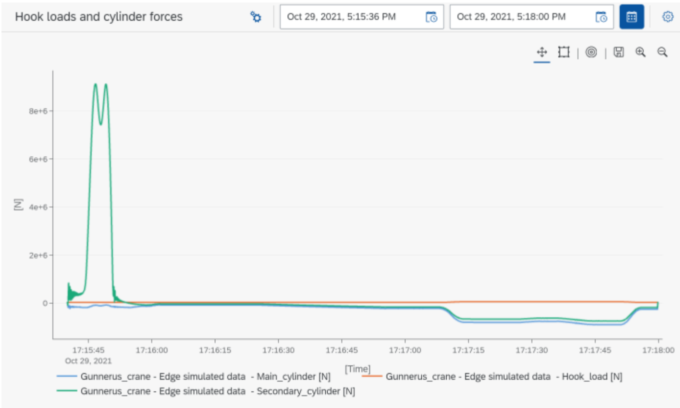

FIGURE 18 HOOK LOAD AND CYLINDER FORCES – EVENT 4

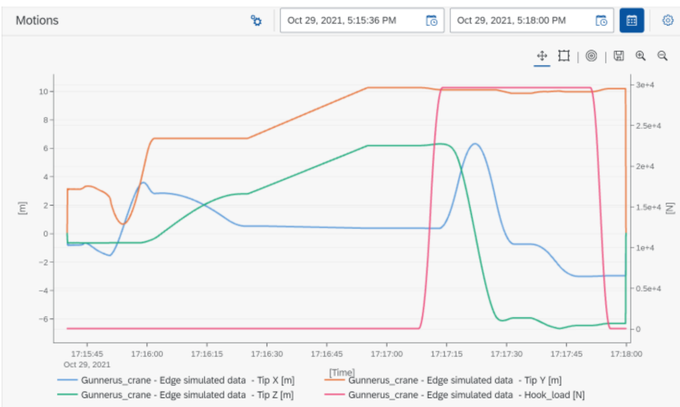

FIGURE 19 TIP MOTIONS – EVENT 4

8.3. Alerting and automated stress analysis

Time series managed by Connected Products [10] can be subject to thresholding and subsequent alerting. FIGURE 20 shows the Connected Products Early Warning view. The threshold limit in this case are tuned for this study. Different types of thresholds severity notification can be defined (Left). The time series that is exceeded and the actual interval with overlap is show to the left.

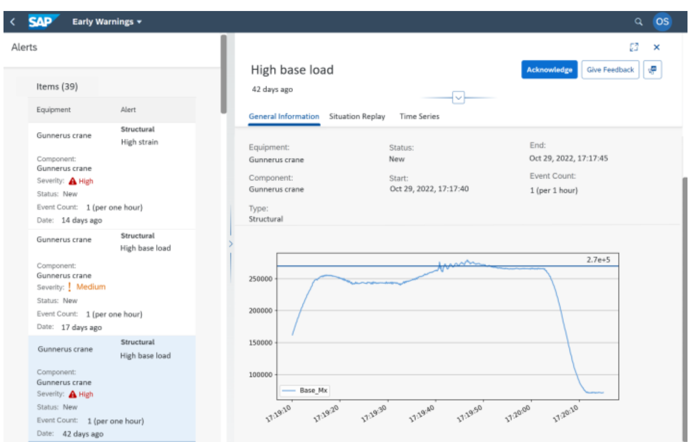

FIGURE 20 ALERTS DUE TO EXCEEDANCE OF BASE MOMENET

The threshold specification also included parameters to execute automated stress calculations for the time interval shown in FIGURE 21, These stress animations are investigated in the Connected Products Situation Replay functionality. Stress evaluation is performed on the altered time interval. Only a snapshot of the time animation is presented below.

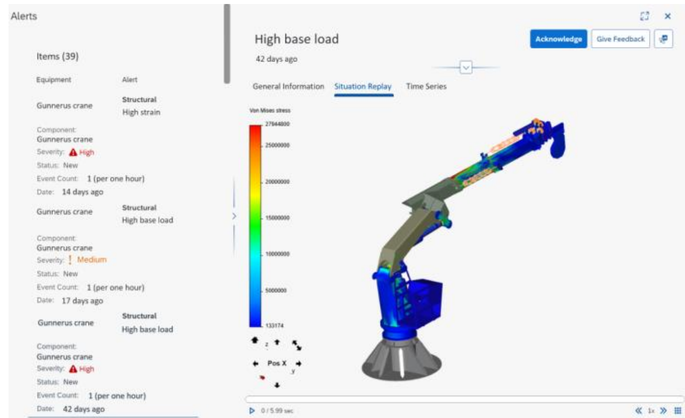

FIGURE 21 ALERTED STRESS CALCULATION

9. DISCUSSION

Implementing an industrial SHM system for offshore cranes is a rather time consuming and error prone process. The main challenge was expected to be creation and validation of a digital twin crane model for real time co-simulation. Even though the 3D CAD model was not applicable to meshing without time consuming editing and idealization, the final 3D FE models were rather easy to assemble, validate and run. The FEDEM solver also performed better than expected due to embedded model reduction techniques. Simple techniques and tools were applicable for model tuning.

The new Palfinger crane was instrumented with cylinder pressure, yaw angle, tilt angle and total arm length sensors. These were not providing the required digital twin simulation inputs, and tilt angle sensors suffered from singularities within the crane workspace. Hence, Python scripts were developed for singularity removal, and the total arm length measurement was split into 7 individual cylinder stroke lengths.

The key achievement of this work has been achieving real time simulation of crane events on a small edge computer with subsequent transfer of data to various cloud solutions. One the cloud solutions (SAP) also included alerting and automated detail stress analysis upon threshold exceedance.

Benefits of such a solution.

- The alerting capabilities are applicable for responsible personnel during crane operations. Warnings against overload and possible vessel instability can be given real time on hand hold devices

- Better asset performance information feedback to OEM (e.g., Palfinger). Crane operational time is continuously updated for predictive maintenance
- Real time Structural Health Monitoring is enabled supporting remaining life assessments used in predictive maintenance
- Identification of component degradation by FFT analysis of time series from virtual and physical crane responses. This can be automated to capture
- Effects of ship/wave induced motions on the dynamic crane loads and stresses can be used by the OEM in design and optimization of future offshore-cranes.
- Root causes of crane failures can be traced from historical cloud data stored in long term (STEP) repositories
- The digital twin provides root causes and detailed information resolving lawsuits between OEM and ship owner

Even though the solution developed and used for this study shows great usability and value, there are still areas to pursue in further work:

- The kinematic relations and singularity issues caused by the tilt angle sensors can be eliminated by cylinder stroke sensors
- Using the dynamic pressure to separate between parked and operated crane seems unstable and should be replaced with a more robust sensor.
- Develop and embed a more adequate hook load assessment. Invers solutions with hydraulic pressures or strain gauges are considered but a hook load sensor is the ultimate solution enabling a more robust force driven digital twin.
- Implement a more flexible configuration control. The digital twin should always follow the real crane and hence start the simulation from the physical crane configuration. The crew does not always run the crane back to its stowed position as expected, and power failures might cause the initial digital twin position to be out of synch.

10. CONCLUSION

This study has proven that digital twins of such complex nonlinear structures can execute real-time and hence enable predictive maintenance of real offshore knuckle boom cranes with minor additional costs. The presented approach is described in a general manner and is applicable for offshore cranes used in the industry. The study also shows a complete setup including a hybrid edge and cloud solution. The solution includes detailed simulations on both locations, combining speed (edge) and scalability (cloud). Such a digital twin solution can be implemented as an aftermarket product. However, in an optimal implementation process, the digital twin model should evolve with the OEM crane design and instrumentation.

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