

Trade Study to Select Best Alternative for Cable and Pulley Simulation for Cranes on Offshore Vessels

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Cranes on offshore vessels are subjected to crane dynamics, structural couplings to the vessel, and environmental influence by waves and currents. The recent trend has been to use larger cranes on smaller vessels, which makes the lifting operation even more complex. The use of Digital Twins (DTs) are of emerging interest as they enable safer operations, real time simulation and maintenance prediction. On offshore vessels, a DT can monitor the lifting operation to create a safer work environment. The SPADE model has been used as a framework towards the creation of a DT of cranes on offshore vessels. As part of this, several cases involving simulation of cranes revealed the lack of an adequate simulation of cable and pulleys suitable for DTs. This is important for accurate results and for implementation in control systems. A trade study was performed to detect a numerical method adequate for cable and pulley simulation. The trade study identified the Absolute Nodal Coordinate Formulation (ANCF) in the framework of Arbitrary Lagrangian–Eulerian (ALE) as a promising numerical formulation.

KEYWORDS

Digital Twin, MBS, FEM, Crane, Cable, Pulley, Simulation

1 | INTRODUCTION

Offshore vessels with cranes are used for operations such as installation of subsea templates, offshore wind turbine installation, and loading and unloading of equipment. Wind, waves and currents complicates these operations. The recent trend has been to use smaller vessels, with larger cranes, due to cost savings. This makes the lifting operation even more subjected to instability due to the environmental excitations. A Digital Twin (DT) of an offshore crane allows for safer lifting operations. It enables prediction of the load movement and compensation with the control system, improved heave compensation, and monitoring of maintenance and fatigue schemes. Furthermore, a DT support identification of failure states and forecasting the condition, which the project manager can use for the risk analysis. The prediction are sensitive to the accuracy of the model the DT is based on.

A step towards creating a DT of a crane on offshore vessels are to improve the simulations. This paper is set to investigate the requirements for improved simulations. The structure of this paper is as follows: First, the paper presents a context diagram of crane dynamics for a better understanding of physics and dynamics, with the theoretical background for simulation. Then stakeholders are identified to investigate different interests in the project. The main body of the paper then follows with pointing out shortcomings for crane simulation according to cases and previous research. Here it is observed that cable and pulley simulation is lacking accuracy, and a better simulation of cable and pulleys will assist a DT. Based on design requirements a trade study is performed to investigate alternatives for different numerical methods for dynamic simulations of cable and pulleys to create a DT. For a DT the real time simulation aspect is of importance. The paper is wrapping up with a decision making on present results and further work. The paper follows the SPADE methodology as proposed in Haskins (2008).

2 | BACKGROUND

DT is a wide term, so Schluse and Rossmann (2016) lists several companies where the term DT is used differently for industrial practices: Manufacturing flexibility, product design, maintenance, increased lifetime, testing, structural monitoring, efficiency, quality and automation. A DT can be used, not only for engineering and manufacturing, but also operation and service, which according to Boschert and Rosen (2016) makes it more than a Multibody Systems (MBS). This implies that the DT could become a part of the real system, with actionable interactions. In Grieves and Vickers (2017) DTs are divided up into several subgroups. DT Instance, which "describes a specific corresponding physical product that an individual DT remains linked to throughout the life of that physical product", is the most relevant for a crane. Schluse et al. (2017) describes a similar type of DT, which he calls Experimental DT. He claims that "Experimental Digital Twins" seem to have the potential to close the gap between Systems Engineering (SE) and simulation by introducing a new structuring element to configure simulations with virtual test-beds. DTs allows for testing prior to manufacturing, which can lead to significant cost savings. For Product Lifecycle Management (PLM) Tao et al. (2018) has proposed a new method for DT-driven product design, manufacturing and service. The product design phase is divided up into conceptual design, detailed design and virtual verification.

The context diagram as presented in figure 1 is a helpful tool to take a step back and get the bigger picture for creating a DT of an offshore crane. For an offshore lifting operation, the environment with wind and wave induced motions affects the operation. The lifting operation could take place in harsh environments or at the harbour. For lifting operations involving other vessels, the vessels will be in different swing phases. Maintenance is a critical part for the crane to be operational. To allow for a DT it is required to instrument the physical crane with sensors. The draw work of the crane is an essential part of the lifting mechanism. The crane operator is responsible for safe lifting operations,

and therefore could be willing to work in harsher environments with better monitoring. The control system could use an active or a passive heave compensation system to help stabilize the load in waves, and in addition compensating for the relative motion between vessels to keep the load at relative rest. The hydraulics of the crane causing time delays will be included in the DT. The goal is to be able to simulate the whole crane system. This includes how the boom deflects, pulleys, bearings, inertia effects, friction and damping. The inherent dynamics and friction effects in a crane may cause out of phase tension oscillations in the cables, which again leads to control system instabilities. The frequency on the bearings could be influential when it comes to decoupling the crane for simulation, without significant loss of accuracy. The elasticity in the cable, lateral and longitudinal frequencies are affected by the loading condition. Cables has an ability to withstand large axial loads in comparison to bending, compression, and torsional loads. The cable pulley interaction is important, where contact and friction has to be defined. The context diagram highlight that crane dynamics are influenced by cable and pulleys.

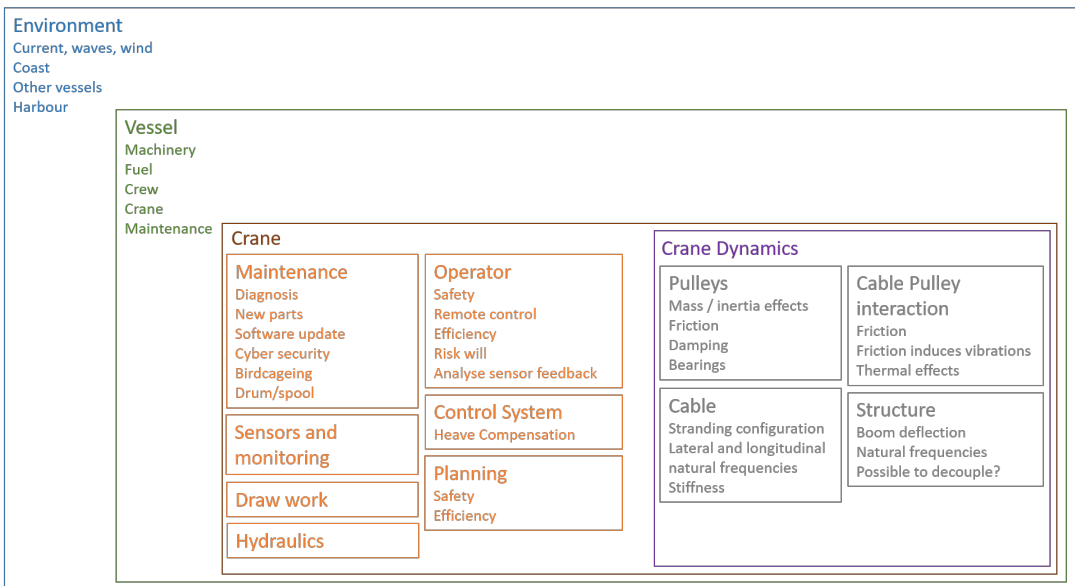


FIGURE 1 Context diagram for the crane dynamics of cable and pulleys.

FEA (Finite Element Analysis) as applied in engineering is a computational tool for performing engineering analysis typically for design and optimization. It can be used both for static and dynamic simulations, where dynamic simulations is stepping through a given time interval. An important difference between an engineering simulation and a DT is that a simulation cannot foresee future scenarios and changing circumstances. DT on the other hand takes in real time sensor data and updates the simulation, as it is stepping trough time. This gives the engineer a much better insight in what is actually happening. The real time aspect is a key, and requires fast calculations. Therefore, the purpose of FEA is now to be operational as an estimator, instead of design and optimization. FEA are numerical methods, or formulations, where the Finite Element Method (FEM) is one of them. FEM is commonly used for failure assessment, fracture and crash simulation. FEM is more relevant for crane simulation than other numerical methods, such as rigid body simulation, since it accounts for the flex in the crane boom during heavy lifting, Hong et al. (2016). There are numerous software on

the market doing simulations based on FEM. FEM works by dividing the Computer Aided Design (CAD) model into many small pieces called elements, see figure 2. The elements have material and geometrical properties. Then forces and boundary conditions are included in the model. Mathematical equations describes the behavior of the elements, and how they interact with each other during the simulation. There are numerous elements with different characteristics, specialized for certain simulations.

A MBS consist of several sub-models, which makes up the system being simulated, see figure 2. The different parts have a CAD model, which could be used as a rigid body, or meshed with finite elements for elastic behavior. Mechanism modelling use joints to connect the parts for interaction. Control system modelling is used for actuators, like the hydraulic cylinders and the virtual sensors. The 1D flow chart presents an example of a control system, where real or virtual sensors can be the position input. The applied force will be set according to deviation in measurement and reference value. Cable and pulley modelling is usually simplified to an axial spring.

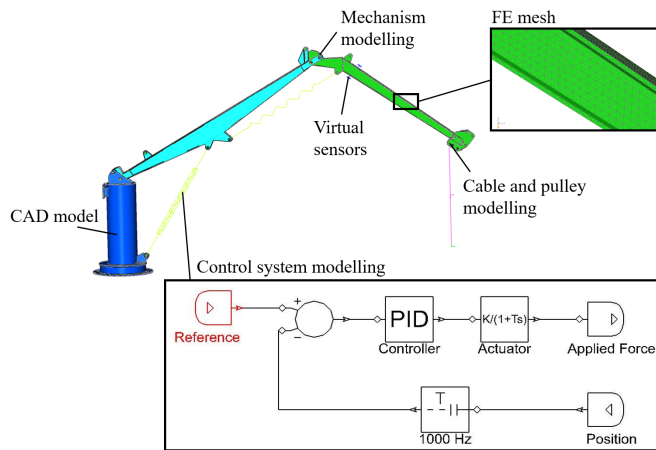


FIGURE 2 The crane system with different sub-modelling requirements indicated.

A simple example of a DT is found in figure 3. In this illustration, the Physical Sensor Data (PSD) from the physical crane is stored in a state vector, which contains turn angle, stroke length of actuators and applied load at the crane tip, $PSD^1 t^0 = \Rightarrow L, L_f, mg$. The state vector is time dependent. The dotted arrow indicates how the state vector is transferred to the server cloud. The digital crane model retrieves the $PSD^1 t^0$ from the cloud, for calculations. Based on the input from the physical crane, the inverse method can be used to extrapolate forces and strains to virtual sensors in the digital model. While the physical actuators are measuring stroke length, the reaction forces can be found in the digital actuators. Also the strain history can be found for any part of the crane, by virtual sensors. This is relevant for detecting fatigue failure. Direction and size of forces are relevant for detecting stability issues and critical loads. The digital model can have an infinite number of states, free of charge. The outputs from the digital crane, Digital Sensor Data (DSD), are stored in the state vector $DSD^1 t^0 = \Rightarrow F, F_f, M, f, \dots$, and sent to the cloud. The data in the cloud could further be used for visualization and presentation of results. The weather and wave forecast are additional data relevant to store in the the server cloud, for risk analysis of the job.

In the video posted by Raftery (2017), a DT is demonstrated by a simple beam with a sensor at the top end, which allows for the whole stress distribution in the beam to be calculated. Different colors indicates the stress level in the beam. The stress is a consequence of the force applied by the hand. The inverse method refer to the numerical equations

&)' 52% 3ENSORS ON THE PHYSICAL CRANE SENDS REAL TIME MEASURED DATA TO THE \$4 "Y THE INVERSE THE \$4 DISTRIBUTES THE INPUTS TO VIRTUAL SENSORS

IN A SIMULATION WHERE THE INPUT DATA IS A MEASURED VALUE AND THE \$4 BEHAVES ACCORDINGLY 4HERE ARE THE INVERSE CALCULATIONS AND THERE IS A NEED FOR INVERSE METHODS THAT ACCURATELY CALCULATE DIS FREQUENCIES OR LOADS IN ORDER TO PREDICT THE STRUCTURAL INTEGRITY 3OLVERS HAVE NO BASIS TO BE TIME OF THE SIMULATION HAS TO BE LESS THAN THE PHYSICAL TIME FOR A REAL TIME \$4 &URTHER DISCUSSION OF OUTSIDE THE SCOPE OF THIS PAPER 4HE FACT THAT PHYSICAL SENSORS ARE EXPENSIVE WHILE VIRTUAL SENSOR WELL AS THE REAL TIME ASPECT MAKES THE \$4 GAIN MOMENTUM #HALLENGES RELATED TO WHAT SENSORS TO U THEM AND HOW TO PROCESSE AND THE DATA FROM THE SENSORS WILL NOT BE ADDRESSED IN THIS PAPER

\ 2%3%!2#(-%4(/\$

7HEN EXPLORING NEW COMPLEX SYSTEMS IT IS USEFUL TO STRUCTURE THE RELEVANT INFORMATION 4HIS INC FOR MAKING GOOD DECISIONS EXPOSE GAPS PROBLEM SOLVING AS WELL AS MOVING FORWARD FASTER 3YS PROVIDE TOOLS TO HANDLE THIS 4O CREATE A RELIABLE AND ROBUST \$4 OF AN OFFSHORE CRANE IS NEW TECH TOOLS HIGHLY RELEVANT AND USEFUL FOR SUCH A DEVELOPMENT PROJECT

&)' 52% 30!\$% METHODOLOGY FRAMEWORK GRAPHICAL REPRESENTATION (ASKINS

4HE 30!\$% METHODOLOGY WAS INTRODUCED BY (ASKINS GURSE AND WAS USED AS THE RESEARCH METHOD

THIS PAPER 30!\$% IS AN ACRONYM CONSTRUCTED FROM THE WORDS 3TAKEHOLDERS 0ROBLEM !LTERNATIVES AND %VALUATION %VALUATION IS A CONTINUOUS PROCESS AND IS THEREFORE PLACED IN THE CENTER OF THE EVALUATION PROCESS ONE UPDATE IS MADE BY NEW AND RELEVANT INFORMATION 4HIS MAKES THE 30!\$% METHOD USEFUL FOR DEALING WITH PROBLEMS WHERE THE DESTINATION IS UNKNOWN)T ALSO HELPS TO GIVE RELEVANT INFORMATION TO THE STAKEHOLDERS ACTUALLY DESIRE FOR A \$4 OF AN OFFSHORE CRANE AS THE STAKEHOLDERS ARE PARTICIPATING IN THE DESIGN PROCESS \$URING THE EVALUATION PROCESS A CONSULTATION WITH THE STAKEHOLDERS CAN BE DONE THROUGH PROPOSALS .EW STAKEHOLDERS CAN ALSO BE INCLUDED DURING THE EVALUATION PROCESS 4HE 0ROBLEM STATEMENT AND TECHNOLOGY FOR THE CREATION OF A \$4 OF AN OFFSHORE CRANE "ASED ON THE 0ROBLEM STAGE DIFFERENT SOLUTIONS ARE GENERATED IN THE !LTERNATIVES STAGE 4O EVALUATE AND COMPARE ALTERNATIVES FOR A NUMERICAL FORMULATION FOR CABLE AND PULLEY THE TRADE OFF ANALYSIS TOOL BASED ON "LANCHARD AND &BRYCKY GUWA USED IN THE %VALUATION OF THE DESIGN REQUIREMENTSè STEP IN THE TRADE OFF ANALYSIS A TABLE BASED ON THE SUBJECTIVE VALUE METHOD WITH WEIGHTS FROM BOSSIAKOFF ET AL 4HE SUBJECTIVE VALUE METHOD WEIGHTS THE CHARACTERISTICS OF EACH FORMULATION TO FIND THE ONE THAT BEST SUITS THE SYSTEM AS A WHOLE ACCORDING TO DESIGN REQUIREMENTS 4HE SCORING IS DONE ON PAPERS DESCRIBING THE FEATURES %XTENSIVE TESTING OF ALL THE ALTERNATIVES FOR CABLE AND PULLEY IS INADEQUATE DUE TO BEING VERY TIME CONSUMING TO IMPLEMENT MAKING THE TRADE STUDY MORE SUITABLE 4HE DECISION BASED ON AVAILABLE INFORMATION ALLOWS FOR THE PROJECT TO MOVE FORWARD WITH A STEADY PACE THROUGH THE FINAL STAGE IN THE 30!\$% METHODOLOGY WHERE THE BEST ALTERNATIVE FOR A \$4 IS CHOSEN

&)'52% 4RADE OFF !NALYSIS 0ROCESS BASED ON "LANCHARD AND &BRYCKY

\)\$%.4)&)#!4)/. /& 3934%- 34!+%(/,\$%23 !.\$.%%\$3

'RIEVES AND 6ICKERS POINTS TO SILOING KNOWLEDGE OF THE PHYSICAL WORLD AND THE NUMBER OF POSS SYSTEM CAN TAKE AS THE MAIN CHALLENGES FOR A \$4 3ILOING IS REFERRING TO LACK OF COMMUNICATION BE GROUPS WORKING ON THE SAME PROJECT 4HE ISSUE OF SILOING IS NOT ADDRESSED BY TAKEHOLDERS ARE AND INVOLV THEM IN THE PROJECT ! TAKEHOLDERS FOR FREEMAN AND -C6EA AS ANY GROUP OR INDIVIDUAL WHO IS AFEC BY OR CAN AFFECT THE ACHIEVEMENT OF AN ORGANIZATION&s OBJECTIVES 3TAKEHOLDERS HAVE INTEREST IN T OR ANOTHER AND WITH THAT HAVE EXPECTATIONS TO THE OUTCOME 4O DELIVER A PRODUCT THAT ANSWERS T IMPORTANT TO IDENTIFY WHO THE TAKEHOLDERS OF THE PROJECT ARE)F THE TAKEHOLDERS HAVE NOT BE DISCOVERED

4HIS PAPER STARTED OUT BY THE DESIRE TO CREATE A \$4 OF A CRANE ON OFFSHORE VESSELS FOR SAFER L TAKEHOLDERS WAS ENFOR INVOLVING EXPERTISE ON ALL AREA AS WELL AS SOLVING THE RIGHT PROBLEMS NEEDED PRODUCT "ASED ON INSIGHT FROM THE TAKEHOLDERS BOTH APPLICATION FOR \$4S AND CASES WHERE \$4 WAS DISCOVERED

)N GURE THE TAKEHOLDERS FOR A \$4 OF A CRANE ARE LISTED

3&)-ECHATRONICS WHICH REPRESENTS 4HE 2ESEARCH #OUNCIL OF .ORWAY FUNCTION AS A BRIDGE BUILDE OW BETWEEN ACADEMIA AND THE INDUSTRY 4HEIR GOAL IS TO STRENGTHEN COMPETITIVENESS AND INN .ORWAY 4HEY WANT TO DEVELOP HIGH QUALITY RESEARCH GROUPS 4HIS RESEARCH IS PART OF A PROJECT W jADVANCED OFFSHORE MECHATRONIC SYSTEMS FOR AUTONOMOUS OPERATION AND CONDITION MONITORIN SYSTEMS UNDER THE CONTROL OF LAND BASED OPERATION CENTERS CEN SUPERSTATION AND DEEPER WATER AND IN HARSH ENVIRONMENTSz

#RANE PRODUCERS ARE INTERESTED IN MAKING SAFE AND RELIABLE PRODUCTS)MPROVED SIMULATIONS REAL TIME FEEDBACK WOULD HELP TO BETTER UNDERSTAND HOW A CRANE ARE SUBJECTED TO FORCES D WOULD BE VALUABLE INSIGHT FOR TECHNICAL UPGRADES 4HE UPGRADES ARE BASED ON WHAT THE OPERATO OWNERS REQUESTS FOR THE PRODUCTS

/PERATORS OF CRANES WANTS FASTER AND SAFER LIFTING OPERATIONS -ORE AUTOMATION AND CONTROL SAFER LIFTING OPERATION WHERE REAL TIME FEEDBACK IS IMPORTANT &ATIGUE ANALYSIS OF BOTH THE CABLES ARE VALUABLE FOR IMPROVED LIFETIME ASSESSMENT ! \$4 COULD HERE BE A VALUABLE TOOL FOR PREDICTION

6ESSEL MANUFACTURES ARE INTERESTED IN INSTALLING THE MOST SUITABLE CRANE FOR THE VESSELS 4HEY EXIBLE SOLUTIONS WHICH WOULD BE A COMPETITIVE ADVANTAGE

6ESSEL OWNERS& WANTS TO BEST HANDLE THE REQUIREMENTS FOR THE JOB 4HIS INCLUDES USING THE RIC JOB WHERE THE REQUIREMENTS FOR A SAFE LIFT WITH THE LOWEST COST)T IS COSTLY TO HAVE A VESSEL BETTER WEATHER CONDITIONS)MPROVED SIMULATION ALLOWS FOR BETTER PLANNING FOR THE OPERATION OF THE JOB)F THE WAVES ARE ROUGHER THAN WHAT THE OPERATION WAS PLANNED FOR A \$4 CAN ANALYZ STILL SAFE TO EXECUTE BASED ON REAL TIME DATA 6ESSEL OWNERS& ARE ALSO INTERESTED IN BETTER LI PLANNING THE MAINTENANCE JOBS ! \$4 COULD MINIMIZE DOWNTIME WHICH EQUALS LESS COST #ONTROL S FOR FASTER AND SAFER LIFTING OPERATIONS ARE OF GREAT INTEREST

3SOFTWARE SPECIALIZING IN SIMULATION AND ANALYSIS OF PROBLEMS CONCERNING FAILURE ASSESSMENT ETC ARE INTERESTED IN IMPROVING AND EXPANDING THEIR CAPABILITY OF ACCURATE AND FAST CALCULAT INTRICATE PROBLEMS

3SOFTWARE SPECIALIZING IN \$4 SOLUTIONS WHERE VISUALIZATION AND PRESENTATION OF OUTPUTS ARE RE

USER FRIENDLY PRODUCT

PRODUCERS OF SENSORS AND MONITORING EQUIPMENT USED FOR INPUT TO A \$4 ARE INTERESTED IN DEVELOPING NEW TECHNOLOGIES IMPROVING \$4S. THIS WILL EXPAND THE USE OF SENSORS AND THE MARKET FOR THE PRODUCTION INDUSTRIES WORKING WITH OTHER PRODUCTS THAT COMBINE WITH THE TECHNOLOGY DEVELOPED FOR OFFSHORE CRANES. ELEVATORS, DRAW WORKS, POWER LINES AND ROBOTICS ARE EXAMPLES OF APPLICATIONS WITH SIMILAR CHARACTERISTICS. PULLEY SIMULATION

&)'52% 3TAKEHOLDERS FOR A \$4 OF A CRANE ON OFFSHORE VESSELS

\ -EASURES OF %FFECTIVENESS -/%

WHEN THE PROBLEM HAS BEEN FORMULATED, THEN CRITERIA ARE PUT IN CORRECT TERM AS -EASURES OF %FFECTIVENESS. THESE REPRESENT THE VIEWPOINT OF STAKEHOLDERS AND ASSISTS IN MAKING THE RIGHT CHOICES BASED ON THE SITUATION. PROBLEMS THIS SETS THE SUCCESS CRITERIA FOR WHEN THE END GOAL IS REACHED -/%. FOR THIS PROJECT

! CABLE AND PULLEY SIMULATION IMPROVES THE OVERALL REAL TIME SIMULATION OF A CRANE ON AN OFFSHORE VESSEL. THE \$4 OF A CRANE RESULTS IN BETTER CONTROL SYSTEMS, MAINTENANCE PREDICTION, AND FASTER AND SAFER OPERATION, EVEN IN ROUGH SEAS. I.E. THE NUMBER OF INDUSTRIAL INJURY CONCERNING WORK WITH CRANES ON OFFSHORE VESSELS WHEN USING THE \$4 IS DECREASED. I.E. THE OPERATIONAL TIME FOR CRANES WHEN USING THE \$4 IS INCREASED.

\ 02"/, %- &/2-5, !4)/.

4THE RESEARCH TOPICS CONCERNING SIMULATION OF OFFSHORE CRANES HAS BEEN RELEVANT FOR A LONG TIME. STRENGEHAUGEN AND 'RAN INVESTIGATED THE DYNAMIC RESPONSE AND FATIGUE LIFE OF OFFSHORE CRANES. THEY STATED, "LIMITATIONS IN THE METHOD FOR THIS APPLICATION ARE MAINLY THAT THE METHOD IS LINEAR AND DOES NOT TAKE INTO ACCOUNT COMPRESSION AS WELL AS TENSION." OTHER LIMITATIONS ARE MOSTLY CONCERNED WITH THE ROPES AND CABLES.

IN ROPES AND CABLES WILL ONLY CAUSE THEM TO FOLD NOT TAKE UP BY SIGGIE ET AL PUBLISHED WORK CONCERNING THE DYNAMIC BEHAVIOR OF AN OFFSHORE CRANE 4HE GOAL WAS TO DESIGN OVERLOAD AND FATIGUE 4HE CABLES IN THE SIMULATION WAS REPRESENTED AS AXIAL SPRINGS +U AND 2OH AND (ONG ET AL ARE M STUDIES CONCERNING OFFSHORE CRANES ARE INVESTIGATING THE SAFETY OF INSTALLATION OF OFFSHORE WIN OATING CRANES 4THIS IS DONE BY SIMULATION WHERE WIND HYDROSTATIC AND DYNAMIC FORCES ARE ACTIN LATTER PREDICTS DYNAMIC LOADS ON A CRANE ON AN OFFSHORE SUPPORT VESSEL)T ARGUES FOR THE IMPO BODY MODEL AND NOT A RIGID BODY AS THE RESEARCH ADDRESSING COUPLING MOTIONS BETWEEN CRANE AN HOW EXTERNAL FORCES ACTS ON THE CRANE STRUCTURE EXHIBIT AND THE POINTS FOR STRESS ARE WELL DOCUMENTE MATTER OF SIMULATING -"3 ASSEMBLED WITH CABLE AND PULLEYS SUCH AS CRANES HAS FOR A LONG TIME BEE THE NEED FOR MORE ADVANCED AND ACCURATE CABLE AND PULLEY SIMULATION HAS EVOLVED -OSEID STAR INTRODUCING SEVERAL CHALLENGES RELATED TO THREE DIMENSIONAL MATHHEMATICAL MODELLING OF CABL PULLEY SYSTEMS SUCH AS INHERENT DYNAMICS AND FRICTION EFFECTS IN HIS MASTER'S THESIS

4HE FACT THAT CABLE AND PULLEY SIMULATION IS A SHORT COMING IS ALSO EVIDENT IN THE FOLLOWING 4ECHNOLOGY AND .4.5 SOURCES PRESENTED IN THE NEXT SECTION 4HERE ARE DIFFERENT TYPES OF CRANES AND THE OBJECTIVES OF THE SIMULATIONS VARIES 7HAT THEY HAVE IN COMMON IS THAT THEY ARE ALL LACKING OF A GOOD CABLE AND PULLEY SIMULATION 4HE CASES EXPOSED THE NEED FOR AN IMPROVED CABLE AND PULL WOULD IMPROVE SIMULATIONS IN GENERAL AND ALSO FOR \$4S OF CRANES 4HE CASES WILL FUNCTION AS BEN RESEARCH

\ ,ABORATORY #RANE +NUCKLE "OOM #RANE

! KNUCKLE BOOM CRANE FOR TESTING IS BUILT IN A LABORATORY 4HE CRANE IS ACCESSIBLE FOR RUNNING EXPERIMENTS AND BENCHMARKING)T IS INSTRUMENTED WITH STRAIN GAUGES FOR DATA COLLECTION WHEN RU WELL AS A DETAILED &%- MODEL 4HE &%- MODEL DOES NOT INCLUDE AN ADVANCED CABLE AND PULLEY SIMULATIO OR VARYING CABLE LENGTH IS INCLUDED 4HE GOAL WITH THE CRANE IS TO DETECT ERROR DURING LIFTING OPERA CALCULATIONS FATIGUE LIFE PREDICTION AND STABILITY MONITORING 4HE INSIGHT COULD BE USED FOR CONDIT

&)' 52% ,ABORATORY #RANE IS A KNUCKLE BOOM CRANE BUILT IN ONE OF THE LABORATORIES AT .4.5 W DETAILED &%- MODEL OF THE CRANE

\ ,ABORATORY #RANE +NUCKLE "OOM #RANE

! KNUCKLE BOOM CRANE FOR TESTING IN A WAVE POOL IS LOCATED IN A LABORATORY 4HE CRANE IS ACCESSIBLE FOR TESTING TO STUDY HOW THE VESSEL MOVEMENTS AFFECTS THE LIFTING OPERATION AND WHAT RESPONSE THIS WILL HA PAYLOAD 4HE HYDRODYNAMICS MUST BE INCLUDED IN THE SIMULATION ,IMITS FOR WHEN THE SYSTEM BECO RELEVANT AND WHAT THE MAIN FACTORS IN THE STABILITY ARE #RITICAL PAYLOADS WAVE AND WIND CO

ARE RELEVANT TO EXAMINE & FURTHERMORE ACTIVE DAMPING CAN BE STUDIED

&)' 52% , LABORATORY #RANE IS A KNUCKLE BOOM CRANE FOR TESTING IN A WAVE POOL

\ *OHAN 3VERDRUP 4OWER #RANE

3STRUCTURAL VIBRATIONS IN THE TOWER CRANES ON THE OIL RIG *OHAN 3VERDRUP HAS BEEN INVESTIGATED. A
MODEL OF THE OIL RIG IS VERY DETAILED & ACCOUNTS FOR INTERNAL DEFORMATIONS IN THE CRANE WHICH IS
ANALYSIS OF STRUCTURAL FLEXIBILITY. THE CRANE IS A COMPLICATED SYSTEM WITH DELAY IN THE SYSTEM DUE TO CABLE
AND TENSION IN THE CABLE SINCE THE FREQUENCY IN THE CABLE CHANGE WITH VARYING LENGTH MASS AND STIFFNESS.
IMPROVED CABLE AND PULLEY SIMULATION COULD MAKE THE OVER ALL RESULTS EVEN MORE ACCURATE FOR THE

&)' 52% 4OWER CRANE INSTALLED ON THE OIL RIG *OHAN 3VERDRUP

\ !,4%2. !4)6%3 &2/- 42!\$% 345\$9

40 IDENTIFY THE BEST ALTERNATIVE FEASIBLE AS A NUMERICAL FORMULATION FOR CABLE AND PULLEY SIMULATION
BASED ON "LANCHARD AND & BRYCKY" HAS BEEN PERFORMED. THE MAIN INTEREST FOR THIS PROJECT IS
IMPROVE THE OVERALL BEHAVIOR OF A CRANE. 40 INCLUDE EFFECTS SUCH AS INTERACTIONS BETWEEN THE STRINGS.
ADDITIONAL COMPUTING POWER. THIS COULD JEOPARDIZE THE REAL TIME ASPECT FOR A \$4 & OR OFFSHORE CRANES
FOR DYNAMICS ARE SET HIGHER THAN FOR ONSHORE CRANES WITH LOWER MOVEMENTS. ! PULLEY ROTATES FASTER
CABLE MOVES OVER IT.) IF THE FRICTION IS TOO LOW THE CABLE WILL SLIDE OVER THE PULLEY INSTEAD OF ROTATING.
WORK STOP PULLING THE CABLE. THE ROTATIONAL INERTIA IN THE SHEAVES COULD CAUSE THE CABLE TO MOVE
EFFECTS. THE NUMERICAL FORMULATION MUST INCLUDE CONTACT AND FRICTION. ! ACCIDENTS DURING LIFTING

SEVERE CONSEQUENCES AND IN WORST CASE FATAL ACCIDENTS ! RISK ANALYSIS IS THEREFORE CRITICAL PRIOR TO THE EQUIPMENT USED MUST BE TRUSTED)F AN OPERATIONAL &%! IS GOING TO BE USED AS AN ESTIMATOR FOR A CRANE IT MUST BE PROVEN RELIABLE AND STABLE PRIOR TO BEING PUT TO USE 4THIS IMPLY THAT THE FORMULATIONS FOR DIFFERENT SIMULATION SCENARIOS)F THE CONTROL SYSTEM FAILS THE CRANE COULD SUDDENLY DROP THE LOAD WHILE RUNNING 4TESTED FORMULATIONS KNOWN TO BE STABLE AND ROBUST SHOULD BE USED TO PREVENT THIS \$DESIGN FORMULATION OF A CABLE AND PULLEY SIMULATION FOLLOWS IN THE NEXT SECTION

\ \$ESIGN 2EQUIREMENTS

4THE SIMULATION METHOD SHOULD BE COMPATIBLE WITH &%- AS &%- IS COMMONLY USED FOR SIMULATIONS OF CABLE DYNAMICS IN THE CABLE WHERE MASS DAMPING AND INERTIA EFFECTS ARE INCLUDED 4THIS IS IMPORTANT TO MODEL CONTACT FORCES THE SHAPE MODE SHAPES AND POSITION OF A CABLE IN MOTION #CONTACT AND FRICTION BETWEEN CABLE AND PULLEY AND BETWEEN DIFFERENT CABLE SEGMENTS 4ACCEPTABLE COMPUTATIONAL SPEED DUE TO THE REAL TIME ASPECT OF A \$4 4TIME VARYING CABLE LENGTH WITH MASS UPDATED ACCORDINGLY 4THIS IS IMPORTANT FOR CORRECT AXIAL DYNAMICS WHERE THE CABLE IS LOWERED OR ELEVATED 2RELIABLE FORMULATION WITH DOCUMENTATION PROVEN TO BE EXTENSIVELY TESTED

\ !LTERNATIVES FOR #ABLE AND OULLEY 3IMULATION

"BASED ON THE -/%S STAKEHOLDERS AND DESIGN REQUIREMENTS ALTERNATIVES FOR CABLE AND PULLEY SIMULATION

\ 3RING

)N &%! A CABLE HAS COMMONLY BEEN REPRESENTED AS AN AXIAL SPRING ,ANGEN ET AL AND IRENA ET AL DERIVED FROM (OOKE'S LAW x WHERE F IS THE FORCE AND x IS THE AXIAL DISPLACEMENT &FOR MORE ADVANCED BEHAVIOR THE SPRING CHARACTERISTIC CAN BE TABULATED DEPENDENT ON THE CABLE LENGTH 4THIS APPROACH NEGLECTS MASS AND INERTIA FORCES /NLY AXIAL STIFFNESS IS INCLUDED IN THE CABLE DYNAMICS 4THE NORMAL MODES OF WORK AND PULLEYS ARE THEREFORE NOT CONSIDERED 4THE APPROACH RESULTS IN FAST CALCULATIONS AND QUANTITATIVE RESULTS FOR CERTAIN SIMULATIONS 4THE FORMULATION IS RELIABLE AS IT IS SIMPLE AND HAS BEEN EXTENSIVELY TESTED

\)SOGEOMETRIC !NALYSIS)!

2AKNES ET AL USE)SOGEOMETRIC !NALYSIS)! TO DESCRIBE LARGE DEFORMATIONS IN A \$ CABLE 2IBS OF A CABLE AND BOW AND ARROW ARE NUMERICAL EXAMPLES USED 4HAI ET AL PUBLISHED A PAPER CONCERNING STATISTICAL ANALYSIS OF CABLES WITH)! 4THE TEXTBOOK #OTTRELL ET AL DESCRIBES HOW)! RELATES TO &%-)NSTEAD OF GENERATING QUANTITATIVE RESULTS DO CALCULATIONS DIRECTLY ON THE #!\$ GEOMETRY)T IS POSSIBLE TO HAVE)! AND &%- TO INTERACT BUT IT WOULD BE MORE ADVANCED MODELS WHERE NODES IN THE MESH AND #!\$ GEOMETRY NOT NECESSARILY COEXIST AND QUANTITATIVE RESULTS SUFFERS FROM SOME NUMERICAL CHALLENGES AND THE MAJOR DRAWBACK IS THAT IT STRUGGLES TO HANDLE CONTACT AND !DETORO 4THE USE OF)! WOULD INVOLVE A RISK AS THE FORMULATION IS LESS MATURE THAN &%- AND QUANTITATIVE RESULTS COMPLICATIONS WHEN COMBINING WITH &%!

\ 4HE "AR &INITE %LEMENT FOR #ABLE

4HE BARNITE ELEMENT AS DESCRIBED IN ORIOUR IS BASED ON A PRINCIPLE TO SPLIT THE BAR ELEMENT INTO PER
HOMOGENEOUS ELEMENTS 4HE ELEMENTS HAVE ELASTIC PROPERTIES WITHOUT ROTATIONAL \$EGREES OF &REED
COUPLING BETWEEN CONSECUTIVE BAR ELEMENTS BENDING STIFFNESS IS INCLUDED 4HIS LEADS TO FORCES
THESE TWO ELEMENTS WHEN A CURVATURE OCCURS ON THE MODELLED CABLE !LARGE AMOUNT OF ELEMENTS IS
REPRESENTATION OF THE CABLE 4HE FORMULATION INCLUDES DRAG FORCES FROM WATER AND HAS BEEN TEST
CAGES AND SHING GEAR

\ !0ARAMETRIC 3UPER %LEMENT

*U AND #HOO PRESENTS A SUPER ELEMENT FORMULATION FOR A CABLE PASSING THROUGH SEVERAL PULLEY
THE ABILITY TO REPRESENT COMPLEX GEOMETRIC PATHS FOR A LONG CABLE !TOWER CRANE HAS BEEN ANALYZE
3TATIC SIMULATIONS IS THE PRIMARY TARGET FOR THIS FORMULATION THEREFORE IT NEGLECTS THE DYNAMIC

\ 4HE &LOADING &RAME OF 2EFERENCE &ORMULATION &&2&

!CCORDING TO 3HABANA B &LOADING &RAME OF 2EFERENCE &ORMULATION &&2& WAS THE MOST WIDELY USE
FOR SIMULATION NEBLE -"3 IN)N &&2& THERE ARE TWO SETS OF COORDINATES USED TO DESCRIBE CON
OF THE DEFORMABLE BODIES THE RIGID IS DESCRIBED IN THE GLOBAL COORDINATE SYSTEM WHILE THE LOCAL
COORDINATE SYSTEM 4O COMPENSATE FOR THE DISTANCE BETWEEN THE GLOBAL AND LOCAL COORDINATE S
#ORIOUS TERMS MUST BE TAKEN INTO ACCOUNT 4HIS LEADS TO A NON CONSTANT MASS MATRIX 4HE INERTIA
EXPRESSIONS WHILE THE ELASTIC FORCES ARE SIMPLE &&2& ARE SUITABLE FOR SMALL DEFORMATION AND L
#HAMORRO ET AL USE &&2& FOR SIMULATION OF RAILWAY TRACKS WHICH HAVE SIMILAR GEOMETRY AS A C
TO 3UN ET AL ONLY THE 6ARIABLE DOMAIN &INITE %LEMENT 6&% VARIANT OF THE &&2& AS PRESENTED IN
(ORIE ET AL ARE GOOD FOR -"3 4HE 6&% CANNOT ACCOUNT FOR LARGE DEFORMATIONS AND LARGE OVER
VARIABLE LENGTH BODIES DUE TO THE INHERENT NATURE OF &&2&

\ 'EOMETRICAL .ON LINEAR "EAM &ORMULATION '."&

*ONKER AND -EIJAAARD PROPOSED THE 'EOMETRICALLY .ON LINEAR "EAM &ORMULATION '."& FOR LARGE DE
PROBLEMS IN ANALYSIS IDEE -"3 4IMOSHENKO BEAM THEORY SERVES AS THE FOUNDATION FOR THE DEFORMATION
THE FORMULATION 4HE BEAM IS SHEAR DEFORMABLE !CABLE IS A VERY SLENDER GEOMETRY WHERE SHEAR FOR
SIMULATION OF CABLES FOR ERRORS 4HE '."& IS COMPARED TO SEVERAL METHODS INCLUDING THE DISCRETE
"ATHE AND "LOURCHI GEOMETRICALLY EXACT FORMULATIONS 2OMERO NATURAL COORDINATE FORMU
ET AL AND A CO ROTATIONAL FORMULATION #RIS WHERE IT SHOWS GOOD RESULTS #OMPARED TO !.#& SEE
SECTION IT IS MORE ACCURATE AND LESS COMPUTATIONAL DEMANDING 2OMERO POINTS OUT THAT A C
EXACT FORMULATION REQUIRES A SPECIAL TIME STEPPING METHOD 4HIS MAKES THE GEOMETRICALLY EXAC
COMPLICATED TO IMPLEMENT THAN !.#& ELEMENTS

\ 4HE !BSOLUTE .ODAL #OORDINATE &ORMULATION !.#&

&OR THE LAST TWO DECADES THE !BSOLUTE .ODAL #OORDINATE &ORMULATION !.#& HAS GAINED ATTENTION FOR LARGE DEFORMATIONS AND LARGE ROTATIONS IN MULTIBODY DYNAMICS WITH SIMULATION OF TIRES AND BELT DRIVERS. 3HABANA AND 3HABANA RST PROPOSED THIS ELEMENT IN 3HABANA A)N CONTRAST TO &&2& !.#& HAS A CONSTANT MASS MATRIX AND NO CENTRIFUGAL AND #ORIOLIS FORCES 4HIS MAKES IT EASY FOR THE !.#& TO STAY IN CONTACT AND CONTINUITY OF THE DEFORMATION GRADIENT FOR DYNAMIC SIMULATIONS !.#& ELEMENTS USE NODAL DISPLACEMENTS AS \$/&S INSTEAD OF ROTATIONAL PARAMETERS AS IN &&2& \$IBOLD ET AL 1998 FOUND THAT !.#& IS LESS CPU INTENSIVE AND CONVERGES FASTER THAN &&2& IN LARGE DEFORMATIONS ESPECIALLY WITH AN INCREASING NUMBER OF ELEMENTS. IN THE FRAMEWORK OF !.#& THERE ARE SEVERAL ELEMENT FORMULATIONS INCLUDING SPECIAL CABLE ELEMENTS !.#& IMPORTANT FEATURES AND APPLICATIONS OF !.#& IS GIVEN IN 'ERSTMAYR ET AL 2005 AND .ACHBAGAUER 2006. 'ACHBAGAUER ET AL ADDRESS THE DIFFERENCES BETWEEN DIFFERENT !.#& ELEMENTS 3HE ENDS UP PROPOSING WHAT SHEA SEES AS THE BEST !.#& ELEMENT TO USE 'ERSTMAYR ET AL 2005 PRESENTS !.#& ELEMENTS WITH AND WITHOUT TORSIONAL STIFFNESS AND CROSS SECTION DEFORMATION "UL-N ET AL 2007 PRESENTED A CABLE PULLEY SYSTEM WHERE THE CABLE ELEMENT AND CONTACT FORCES CAUSED THE PULLEY TO ROTATE !QUADROSPHERE CABLE MECHANISM WAS SIMULATED WITH A FORMULATION WITH REALLY PROMISING RESULTS IN "UL-N ET AL 2007 40 SIMULATE CONTACT BETWEEN THE CABLE AND PULLEY THERE ARE DIFFERENT APPROACHES 7ESTIN AND)RANI 2004 DEVELOPED A METHOD FOR \$ CASES WITH A LARGE DYING POINT IN THE WRAP ANGLE AND CABLE TENSION)T IS COMMON TO USE (ERTZ AS THE CONTACT FORMULATION WHILE 40 USE 1UINN METHOD 7ANG ET AL 2008 HAS STUDIED THE CONTACT BETWEEN CABLE AND CABLE WITH A CONTINUOUS CONTACT A MASTER SLAVE TECHNIQUE HAS BEEN USED IN 7ANG ET AL 2008 AND 7ANG ET AL 2009

\ !RBITRARY ,AGRANGIAN %ULERIAN !,% !.#&

4HE !RBITRARY ,AGRANGIAN %ULERIAN !,% FORMULATION IS COMBINING THE ,AGRANGIAN FORMULATION AND THE CONTACT FORMULATION AS THE NAME SUGGESTS)N THE ,AGRANGIAN FORMULATION THE NODES IN THE %&- MESH AND THE MATERIAL ARE CONNECTED TO EACH OTHER 4HIS IS THE COMMON FORMULATION TO USE FOR SIMULATION OF STRUCTURES)N THE %ULERIAN FORMULATION THE NODES IN THE %&- MESH ARE IN SPACE AND THE MATERIAL IS CONNECTED TO THEM THROUGH THE !.#& ELEMENTS 7ITHOUT THE !,% FORMULATION THE ELEMENT WOULD BEHAVE AS A)REGULAR ARROW POINT !,% OPENED UP FOR THE POSSIBILITY TO HAVE STATIONARY NODES AROUND THE PULLEYS AS A STRATEGY TO BE USED IN CONTACT BEING THAT FEWER ELEMENTS CAN REPRESENT THE CABLE 4HE REASON FOR THIS BEING THAT CONTACT IS NOT EASY TO SIMULATE ESPECIALLY THE MOMENT CONTACT OCCURS 7HEN ANY RANDOM CABLE ELEMENT CAN HAPPEN TO BE IN CONTACT WITH A PULLEY AT SOME POINT OF TIME ALL THE CABLE ELEMENTS MUST BE SMALL 7ITH !,% FREE CABLE ELEMENTS CAN BE USED FOR FEWER ELEMENTS AND FASTER SIMULATIONS !NOTHER ADVANTAGE IS THAT FOR SIMULATION OF REELING AND UNREELING REMOVE EXCESSIVE CABLE "ASED ON (ONG AND 2EN 2005 0ENG ET AL 2006 A CAME UP WITH AN !,% FORMULATION FOR CONTACT AND PULLEY SIMULATION HANDLING VARIABLE CABLE LENGTH !DEPLOYABLE MESH ANTENNA WAS SIMULATED BY 0ENG ET AL 2006 B %SCALONA 2007 DISCUSS \$ \$ AND \$!,% FORMULATION WITH AND WITHOUT TRANSVERSE DEFORMATION AND TWIST 4HE !,% FORMULATION IS SUITABLE FOR REAL TIME SIMULATIONS DUE TO ITS

\ #OUPLING -OTION BETWEEN #ABLE AND #ULLEY

11 ET AL 2008 AND 7ANG ET AL 2008 POINTS OUT THAT FEW STUDIES PROPOSE A GOOD FORMULATION OF COUPLING BETWEEN CABLES AND MOVABLE PULLEYS PULLEYS PLAY AN IMPORTANT ROLE WITH TENSIONING OF THE CABLES AND THE CONTACT BETWEEN THEM ON THE

52% MODEL OF AN ELEVATOR MECHANISM WITH AGRANGIAN VS !, % FORMULATIONS
 A CABLE PULLED OVER A PULLEY WITH TWO MASSES ATTACHED AT TWO DIFFERENT TIME STEPS !, AGRANGIAN
 REQUIRES MANY NODES TO CAPTURE INTERACTION BETWEEN THE CABLE AND PULLEY WHILE AN !, % FORMULA
 A HIGH DENSITY OF ELEMENTS AT THE PULLEY AS THEY ARE STATIONARY THIS ALLOWS FOR FEWER ELEMENTS
 THE GURE IS BASED ONRE IN %SCALONA

ROTATION OF THE PULLEY THEY PROPOSED A FORMULATION FOR EXHIBIT CABLES WITH TIME VARYING LENGTH AND
 COUPLING MOTIONS BETWEEN CABLE AND PULLEYS THE CONTACT SEGMENT OF THE CABLE IS MOVING TOGETHER
 POINT ON THE PULLEY WITH A SHAPE CONSTRAINT SPATIAL DESCRIPTION #UBIC SPLINE INTERPOLATION IS USED TO
 WHICH CAN BE REGARDED AS AN AXIALLY MOVING MEDIUM THE SIMULATION INCLUDE TENSILE STRAIN INERTIA AND
 FORCES OF THE CABLE PULLEY AND WINCHES THE BENDING STIFFNESS AND TORSIONAL STIFFNESS ARE NEGLECTED
 EXIBLE CABLES ARE EASY TO BEND AND TWIST THE PAPERS PRESENTS EXAMPLES OF SIMULATIONS OF CABLE PULLEY
 MOVABLE AND FIXED PULLEYS WITH GOOD RESULTS COMPARED TO !\$!-3 SOFTWARE SIMULATIONS 4HERE HAVE NO
 STUDIES VERIFYING THE FORMULATION

\ %VALUATION OF !TERNATIVES

IT IS NOT STRAIGHTFORWARD TO DECIDE FOR THE BEST ALTERNATIVE OF A NUMERICAL FORMULATION TO USE
 SIMULATION TO IMPLEMENT IN A \$4 OF AN OFFSHORE CRANE 4HERE ARE MANY ASPECTS TO TAKE INTO CONSIDERATION
 TIME DYNAMICS AND CONTACT FORMULATIONS ! TABLE BASED ON THE SUBJECTIVE VALUE METHOD ACCORDING TO
 ARE PRESENTED IN FIGURE 4THIS WAS USED FOR CROSS REFERENCING DESIGN REQUIREMENTS AND OPTIONS
 OF THE DIFFERENT FORMULATION CANDIDATES %ACH OF THE CRITERIA WERE WEIGHTED EQUALLY WITH THE SCORES
 POOR FAIR SATISFACTORY GOOD AND SUPERIOR

FOR THE ALTERNATIVES OF FORMULATIONS FOR CABLE AND PULLEY SIMULATION EVALUATED IN THIS PAPER
 COMMONLY USED BUT IS LACKING BOTH A GOOD DYNAMIC REPRESENTATION AND CONTACT FORMULATION)! A
 IS NOT %- COMPATIBLE AND THE FORMULATION IS NOT EXTENSIVELY TESTED)IT MIGHT BE VERY RELEVANT IN
 ET AL FOUND THAT !.#& CONVERGES FASTER THAN &&2& !, !.#& HAS THE HIGHEST SCORE)T CAN REPRESENT
 BETWEEN CABLE AND PULLEY WITH STATIONARY NODES IT ALLOWS FOR MODELS WITH FEWER ELEMENTS AND
 MAKES IT SUITABLE FOR REAL TIME \$4S !, !.#& ALSO ALLOWS FOR VARYING CABLE LENGTH 4HE #OUPLING -OTION
 AND PULLEY IS A PROMISING METHOD WITH THE SECOND HIGHEST SCORE 4HE METHOD HAS A LOW SCORE ON RESEARCH
 RESEARCH GROUP HAS PUBLICATIONS ON IT %VEN THOUGH THE FORMULATION SEEMS PROMISING IT SHOULD BE U

FURTHER TESTING HAS BEEN DONE

&)'52% 4HE ALTERNATIVES FOR CABLE AND PULLEY SIMULATION EVALUATED ACCORDING TO THE SUB. METHOD BASED ON +OSSIAKOFF ET AL WHERE NOT KNOWN POOR FAIR SATISFACTORY GOOD AND SUPERIOR

\ \$%#)3)/. -!+).'

\$4 APPLICATIONS IN 3% TEND TO FOCUS ON MANUFACTURING OR MAINTENANCE OF OBJECTS WHERE THIS PAPER REQUIREMENTS TO CREATE A \$4 OF AN OFFSHORE CRANE FOR SAFER LIFTING OPERATIONS 4HE \$4 SHOULD PRE COMPENSATE WITH THE CONTROL SYSTEM IMPROVE HEAVE COMPENSATION AS WELL AS MONITORING FOR MA)DENTCATION OF FAILURE STATES AND FORECASTING ARE IMPORTANT TO PREVENT ACCIDENTS 4HERE ARE SEVE TO GET A SATISFACTORY FUNCTIONING \$4 4ROUGH DIFFERENT CASES IT WAS EVIDENT THAT THE SIMULATIONS WORK FOR CABLE AND PULLEY REPRESENTATION ! SATISFACTORY CABLE AND PULLEY SIMULATION IS CRITICAL FOR AN O A REAL TIME \$4

! TRADE STUDY WAS PERFORMED TO INVESTIGATE ALTERNATIVES FOR CABLE AND PULLEY SIMULATIONS 4H !,% !.#& HAD THE HIGHEST SCORE IN THE EVALUATION BY THE SUBJECTIVE VALUE METHOD 4HIS METHOD IS VE REAL TIME SIMULATIONS DUE TO RELATIVELY FEW ELEMENTS NEEDED AND THAT NODES CAN BE STATIONARY / THE PULLEY)T ALSO HAS GOOD DYNAMIC REPRESENTATION OF THE CABLE AND CAN INCLUDE CONTACT AS WELL !,% !.#& IS THE RECOMMENDED FORMULATION TO IMPLEMENT IN A \$4 OF AN OFFSHORE CRANE

3% HAVE PROVEN TO BE A USEFUL APPROACH FOR CREATION OF A \$4 4OOLS TO EXPOSE LACKS SETTING DESI NDING ALTERNATIVES ALREADY HAVE A FRAMEWORK READY TO USE &OR STRUCTURING COMPLEX SYSTEMS T THE CREATION OF \$4 OF OFFSHORE CRANES HAVE NEVER BEEN DONE BEFORE 3% IS HIGHLY RELEVANT

\ &524(%2 7/2+

4O VERIFY THE SELECTED FORMULATION FOR CABLE AND PULLEY SIMULATION A \$4 OF THE LABORATORY KNUCK BE MADE FOR BENCHMARKING 4HIS WILL VERIFY IF THE SELECTED ALTERNATIVE IS FEASIBLE 4ESTING WILL REQUIREMENTS FOR HAVING A FULLY FUNCTIONING \$4 OF AN OFFSHORE CRANE

A DT requires software for processing of sensor data, calculations, simulations and visualization. There are a large amount of software available, where some are specialized for certain tasks, while others are generalized. Further work involves investigation of software alternatives to use for a DT of an offshore crane.

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