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A software framework for intelligent computer-automated product design

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Background

About NTNU in Ålesund and virtual prototyping

- NTNU in Ålesund (formerly Aalesund University College) has close ties with the maritime cluster of Norway, relating to education, research, innovation, and dissemination
- many past and ongoing research and innovation projects in collaboration with the industry
- bachelor and master engineering programmes in automation, computer, and power systems engineering; product and system design; ship design; simulation and visualisation; management of demanding marine operations; and more
- virtual prototyping (VP) of maritime equipment currently has a strong research focus
- today's presentation: a computer-automated design solution for intelligent virtual prototyping of offshore cranes

What is virtual prototyping (VP)?

Many definitions exists; e.g. [1]:

> *VP refers to the process of simulating the user, the product, and their combined (physical) interaction in software through the different stages of product design, and the quantitative performance analysis of the product.*

or Wikipedia:

> *Virtual prototyping is a method in the process of product development. It involves using computer-aided design (CAD), computer-automated design (CAutoD) and computer-aided engineering (CAE) software to validate a design before committing to making a physical prototype.*

Key aspects of VP

— modelling, simulation, visualisation, analysis, testing, validation, optimisation, process planning, immersive collaborative design, etc.

— typical tools include virtual reality (VR), virtual environments (VE), computer-aided design (CAD), computer-aided engineering (CAE), computer-automated design (CautoD), hardware-in-the-loop (HiL) simulation, etc.

— better chance of reaching targets such as performance, revenue, cost, launch date, quality, bugs and flaws, etc.

— opens possibilities for new and innovative design, including improved performance

What is computer-automated design (CautoD)?

- first (?) occurrence in 1963 [2]: computer programme for design of logic circuits for character recognition
  - do the circuits satisfy hardware constraints?
  - how well do they perform character recognition?
- the general paradigm is optimisation
  $\Rightarrow$ minimise (maximise) a cost (fitness) function
- artificial intelligence (AI) highly suitable for optimisation, e.g., genetic algorithms (GAs), particle swarm optimisation (PSO), ant colony optimisation (ACO), simulated annealing (SA), etc.
- trend: traditional CAD simulation transformed to CautoD by AI
- design problem: find best design within known range (i.e., through learning or optimisation) and find new and better design beyond existing ones (i.e., through creation and invention)
- Equivalent to a search problem in multidimensional (multivariate), multi-modal space with a single (or weighted) objective or multiple objectives

VP at NTNU in Ålesund

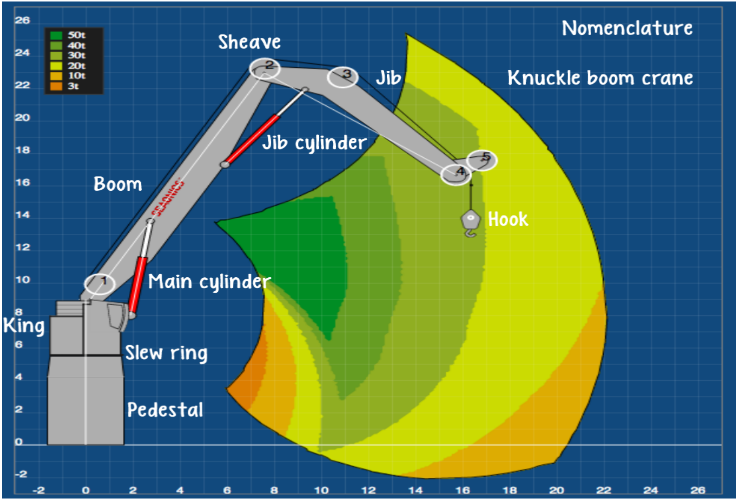
- VP of maritime equipment and operations is an active focus in the research labs at NTNU in Ålesund:
  - Software and Intelligent Control Engineering (SoftICE) Lab
  - Mechatronics Lab
  - Ship Lab
  - Machinery Systems Lab
  - Human Factors Lab
- several ongoing research projects in cooperation with the maritime industry
- focus on VP of ships, cranes, winches, crew training, advanced maritime operations, etc., all of which are complex systems that may involve hydrodynamics, hydraulics, mechanics, electronics, control systems, human factors, etc.

Offshore cranes

VP of offshore cranes

- offshore cranes are complex systems with many components, e.g., cylinders, booms, sheaves, joints, winches, slewing rings, hooks, pedestals, etc.
- design must obey laws, regulations, design codes
- other concerns are durability, installation and operating costs, and workspace characteristics
- design should optimise some desired design criteria, or key performance indicators (KPIs)
  - depends on the components
  - often indirect consequence of a priori design choices
  - traditionally experience-based rules-of-thumb design
  - recent work of colleagues [3] use trial-and-error to improve design $\Rightarrow$ cumbersome, suboptimal method; only a few design parameters are tuned; novelties may not be discovered
- we focus on two particular KPIs in this study:
  1. maximum safe working load (SWL)
  2. total weight of crane

Main components and 2D max SWL chart



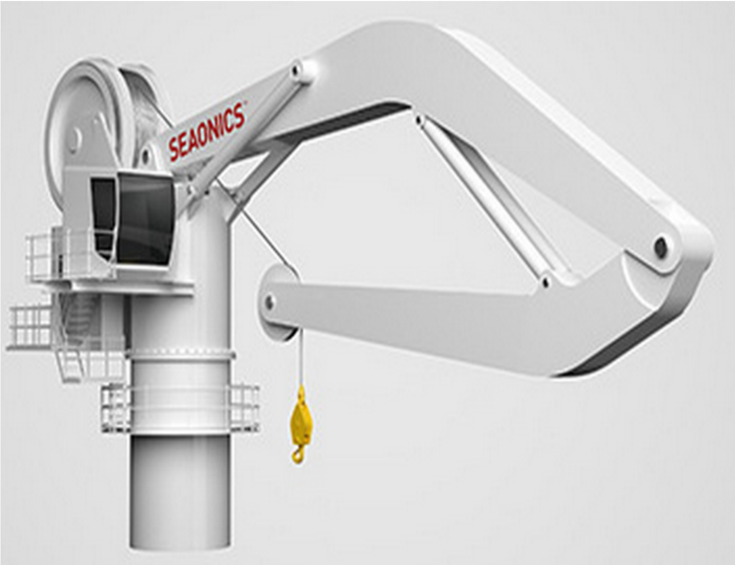
Seaonics and crane types

- Seaonics is industrial partner in our research project
- located in Ålesund, Norway and central to the maritime cluster
- designer and manufacturer of offshore handling equipment for critical lift and handling operations
- offshore/subsea cranes
  - 50T offshore/subsea crane been delivered (80T in 2-fall)
  - crane with 250T SWL has been designed in a pilot project
  - drawings of various crane sizes up to 250T prepared
- marine cranes
  - cranes from 0.5–20T with various reach
  - ship-to-ship operations
  - handling of personnel in baskets

Typical Seaonics knuckleboom crane

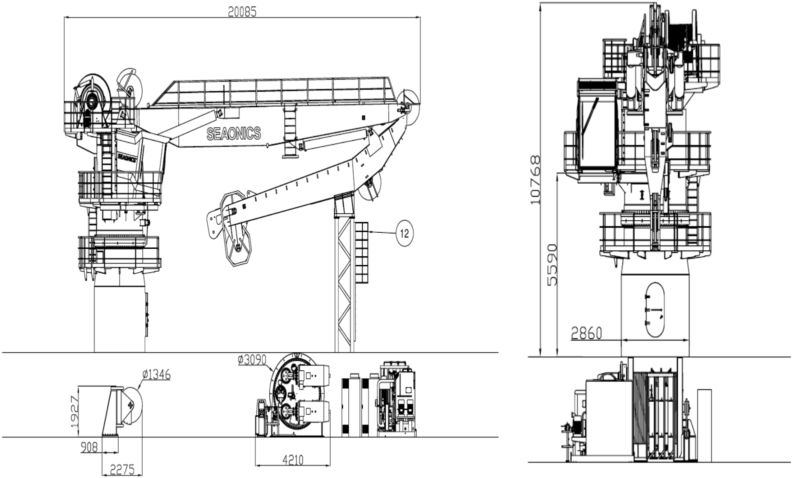
- winch
  - capacity up to 3000m of wire
  - designed according to DNV Standard for certification No. 2.22, June 2013
- operators cabin
  - innovative design, based one the highest quality standards
  - made in Germany
- machinery house
  - location of HPU, starter cabinets and operational valves
  - easy access for maintenance and service
- main boom cylinders lifted to improve sideways view for the crane operator
- walkways/ladders fitted for easy access to maintenance points
- hydraulic piping
  - walform fittings up to and including 42mm pipes
  - stainless steel pipes up to and including 42mm
- “standard” components from recognized European suppliers

Example of a knuckleboom crane



50T knuckleboom crane delivered to Baku, Azerbaijan

Some engineering drawings for Baku crane



Some Baku crane facts

— delivery price: 28 MNOK (ca. 3.25 MUSD)

— total crane weight: $\approx$ 50T

— maximum SWL: 100T

— four important design parameters affecting weight and SWL:

- boom length: 15.8 m
- jib length: 10.3 m
- max pressure of main cylinder: 315 bar
- max pressure of jib cylinder: 215 bar

How can we optimise the design parameters to minimise total crane weight while maximising max SWL?

Motivation and aim

Motivation

- traditional methods use “calculators” or spreadsheets to determine crane properties and behaviour based on pre-determined design parameters
  $\Rightarrow$ analogous to “forwards kinematics” in robotics
- the inverse problem is much harder and analytical solutions are generally infeasible
- the research question becomes:

How can we choose appropriate, and possibly conflicting, values for numerous offshore crane design parameters such that the resulting cranes have the desired properties and behaviour that we want?

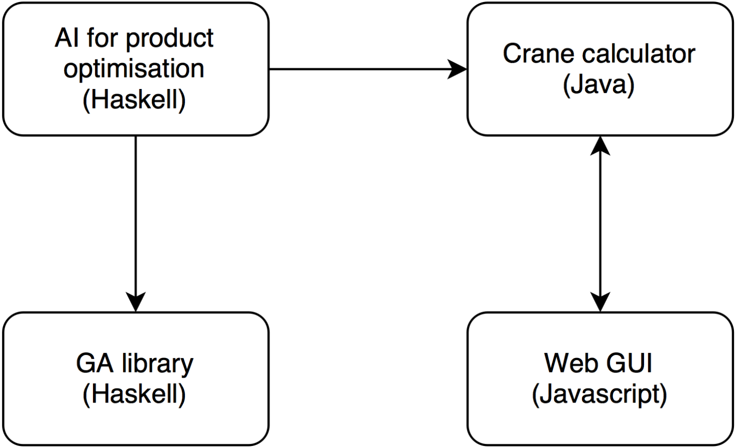
Aim

Create an intelligent CautoD solution that includes

1. a black box crane calculator implemented in Java that calculates a crane's properties for a given set of design parameters or specifications
2. a web graphical user interface (GUI) implemented in Javascript that enables a crane designer to manually input design parameters and calculate the corresponding crane and its properties
3. an AI for product optimisation (AIPO) module implemented in Haskell that employs a GA library, also implemented in Haskell, using the crane calculator to determine optimal design solutions
4. communication interfaces using WebSocket (WS) and HTTP between the crane calculator and the web GUI and AIPO module

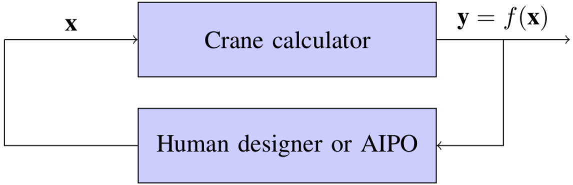
Method

CautoD software dependencies



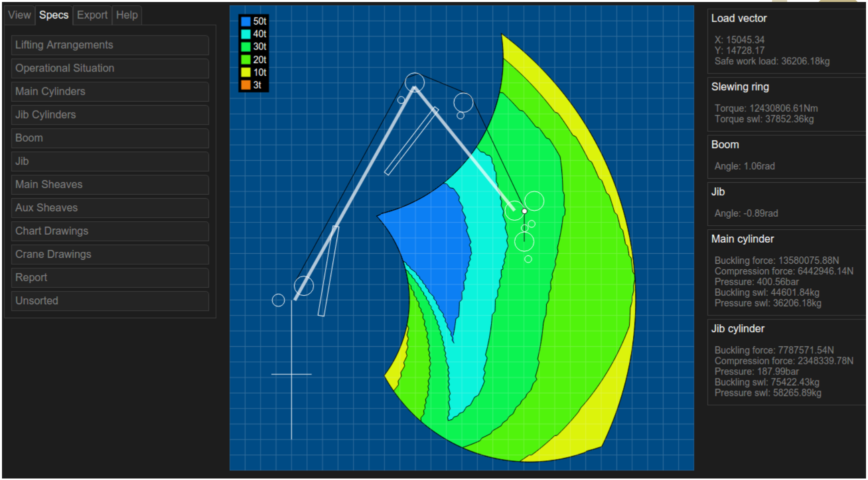
Crane calculator

- cannot include all parameters in crane calculator
  $\Rightarrow$ reduce to 120 design parameters for feasibility
- calculator calculates a number of outputs **y** dependent on a number of parameter inputs **x**



- outputs are a set of KPIs (design criteria) such as max SWL, load chart, total crane weight, etc.
- calculator accuracy been verified with current in-use industry crane calculators
- use web GUI for manual interaction with calculator

Web GUI for manual design



Manual design by trial-and-error

- may use a default crane such as the Baku crane as a starting point
- can manually tune 120 design parameters one by one in the web GUI and observe effects on design criteria (forward solution)
- finding suitable design **x** that yields desired **y** analytically is not possible (inverse solution)
- improve design by repeated trial-and-error using web GUI
  $\Rightarrow$ time-consuming, suboptimal, may miss novelties

What if we automate the trial-and-error process by an AI for product optimisation (AIPO) module that uses a GA to optimise the design?

AIPO module

- defines objective functions $f(\mathbf{x})$ for optimisation
- $f(\mathbf{x})$ called cost (fitness) function if minimised (maximised)
- uses an AI method such as a GA to find $\mathbf{x}$ that optimises an objective function $f(\mathbf{x})$
- AIPO repeatedly interrogates calculator with candidate design solutions from GA until optimised solution is found
- 120 input parameters means search space is huge
- difficult to find appropriate objective function
- tradeoff in optimising conflicting KPIs/design criteria
  $\Rightarrow$ may require multiobjective optimisation (MOO) with a set of several objective functions
- MOO returns a set of Pareto optimal solutions
  $\Rightarrow$ improving one solution degrades another

The genetic algorithm (GA)

- bio-inspired stochastic search heuristic for search and optimisation problems
- inspired by natural evolution and uses inheritance, mutation, selection, crossover
- excellent for combinatorial and nonlinear problems where analytical solutions are difficult or impossible to obtain
- usually attributed to Holland and popularised by Goldberg
- several applications at NTNU in Ålesund, including dynamic resource allocation, adaptive locomotion of caterpillar robots, universal control architecture for maritime cranes/robots, machine learning, optimisation of boid swarms, etc.
- suitable for parallel computing

Functional implementation of AIPO and GA

We use the programming language Haskell for the AIPO and GA modules:

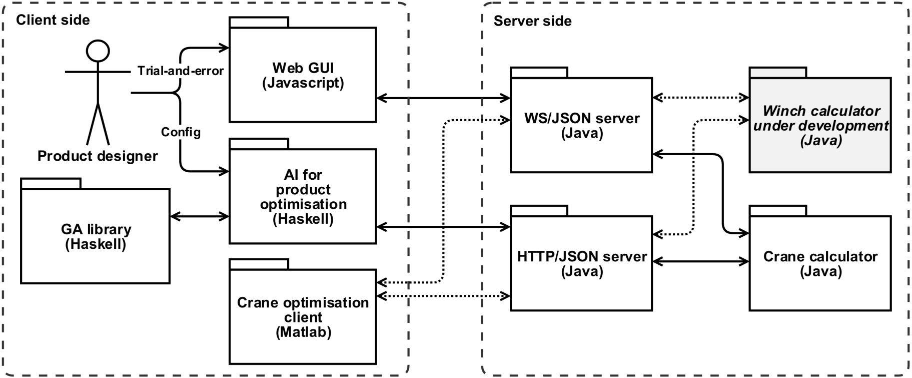
- purely functional ⇒ no global state, no side effects
- declarative, expressing the logic of a computation without describing its control flow ⇒ code closer to mathematical specifications
- pure/impure separation ⇒ easier debugging, less error-prone
- typically more concise, compact, and readable than imperative languages
- highly suitable for parallel programming
- lazy evaluation can reduce unecessary overhead
- modular, extendable, and maintainable code
- our GA library supports parallelisation

Parallel coming

- objective function evaluations can be computationally expensive ...
- ...but is an “embarrassingly parallel problem”
  $\Rightarrow$ many similar but independent simultaneous calculations
- can speed up GA by outsourcing objective function evalution to computer clusters and/or computing clouds
- commercial off-the-shelf computers with general purpose GPUs provide a cheap, local solution
- large number of design parameters may require parallel computing for suitable solutions in reasonable time

Results

Architecture of software framework



About the software framework

- server-client architecture using WS/HTTP and standardised JSON messages
- generic and modular framework:
  - caen easily replace crane calculator with winch calculator (under development) or other product calculators/design tools
  - easily replace AIPO module with other product optimisation clients ⇒ Matlab crane optimisation client (MCOC) has been developed in parallel and accepted for ECMS 2016 [4]
  - easily extend AIPO module with other AI methods, e.g., PSO, ACO, SA, etc.
- crane calculator and web GUI for manual crane design already adopted for professional use by crane designers
  - incorporates highly detailed mathematical crane models
  - accuracy verified with industry crane calculators
  - adheres to laws, regulations, standards, design codes

Proof-of-concept case study

- use designed and delivered Baku crane as benchmark
- objective functions based on two KPIs:
  1. maximum SWL, $\mathrm{SWL}_{\mathrm{max}}$
  2. total weight of crane, W
- optimise four design parameters:
  1. boom length
  2. jib length
  3. max pressure of boom cylinder
  4. max pressure of jib cylinder
- remaining design parameters kept the same as for Baku crane
- intelligent CautoD outperforms Baku crane for chosen objective functions

Objective function f_1

- objective: maximise $f_1 = \mathrm{SWL}_{\max}/\mathrm{W}$
- rationale: increase max SWL while reducing crane weight (weight may also serve as surrogate for price of crane)
- GA settings: population size 100 for 50 generations
  $\Rightarrow$ 5,000 evaluated designs & 98.4 minutes[1] processing time
- results:
  - max SWL increased from 100T to 142T (+42.2%)
  - weight of crane reduced from 50.8T to 44.0T (-13.5%)
  - 64.3% increase of evaluated fitness function f_1

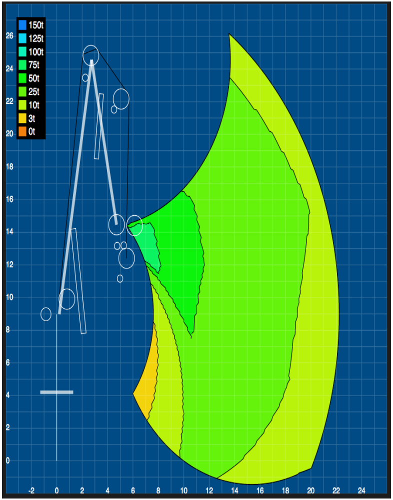
measure	units	nominal	limits (min, max)	optimised	difference	change
boom length	mm	15,800	(12,000, 26,000)	12038	-3,762	-23.8%
jib length	mm	10,300	(6,000, 16,000)	6124	-4,176	-40.5%
boom cylinder max pressure	bar	315	(100, 400)	383	68	21.6%
jib cylinder max pressure	bar	215	(50, 300)	262	47	21.8%
$\mathrm{SWL}_{\max}$	kg	99,978	-	142,138	42,160	42.2%
W	kg	50,856	-	44,014	-6,842	-13.5%
$f_1 = \mathrm{SWL}_{\max}/\mathrm{W}$	-	1.97	-	3.23	1.26	64.3%

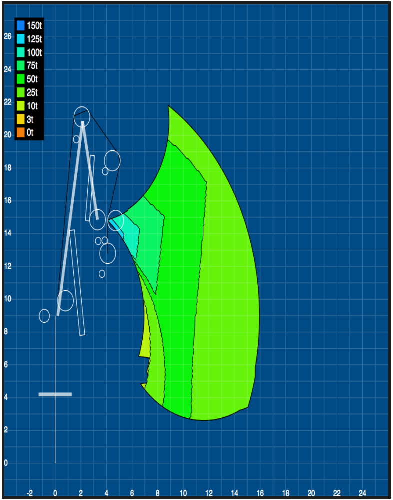
Table 1: Optimised crane design compared with a nominal benchmark crane.

[1] when paper submitted; now reduced to about 3–4 mins.

Load charts of Baku crane and f_1-optimised crane

Tradeoff: higher SWL values in workspace but
size of workspace is reduced





Discussion

Summary

- a software framework for intelligent CautoD of offshore cranes has been presented
- the framework employs a generic and modular server-client architecture
- both server-side and client-side modules are easily replaced, e.g., for
  - other product design problems, e.g., winch systems
  - other AI methods for product optimisation
- the framework has been tested by a case study optimising a real knuckleboom crane
- choice of objective function is crucial to obtain desirable designs

Other potential objective functions

Additional objective functions studied in Hameed et al. [4]:

— objective function f_2

- maximise $f_2 = \mathrm{SWL}_{\mathrm{max}} \cdot w_1 + 1/\mathrm{W} \cdot w_2$
- rationale: maximise max SWL while punishing crane weight

— objective function f_3

- minimise $f_3 = 1/\mathrm{SWL}_{\mathrm{max}} \cdot w_1 + |\mathrm{W}_{\mathrm{target}} - \mathrm{W}| \cdot w_2$
- $\mathrm{W}_{\mathrm{target}}$ is set to the weight of the Baku crane
- rationale: maximise max SWL while punishing deviation from the Baku crane weight

— objective function f_4

- minimise $f_4 = |\mathrm{SWL}_{\mathrm{target}} - \mathrm{SWL}_{\mathrm{max}}| \cdot w_1 + \mathrm{W} \cdot w_2$
- $\mathrm{SWL}_{\mathrm{target}}$ is set to the max SWL of the Baku crane
- rationale: minimise crane weight while punishing deviation from the max SWL of the Baku crane

— w_1, w_2 are scaling factors (function weights)

— multiobjective optimization of $\mathrm{SWL}_{\mathrm{max}}$ and W

Current and future work

- implement more and refine existing objective functions
  - incorporate functions of workspace area/load chart
  - use many more design parameters
  - obtain delivery price estimate of crane designs
  - involve Seaonics designers in process for realistic objectives and quality assurance
- develop easy-to-use complete software package with high-level GUI for end-users without domain expertise in AI or programming $\Rightarrow$ software to be tested and adopted by Seaonics
- develop new server-side design tools/calculators for other products
  - plug'n'play with existing AIPO and MCOC client modules
  - current ongoing project for winch design
    $\Rightarrow$ great synergy with existing crane project
- parallelisation of objective function evaluation
- publications at ECMS 2016 [4, 5], AISI 2016, and later in renowned journal

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Thank you for listening!

Questions?