Flexible Modeling and Simulation Architecture for Haptic Control of Maritime Cranes and Robotic Arms

F. Sanfilippo, H. P. Hildre, V. Æsøy and H.X. Zhang
Department of Maritime Technology and Operation
Aalesund University College

E. Pedersen
Department of Marine Technology
Norwegian University of Science and Technology

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Summary

Current situation for marine cranes

In the maritime industry, the last few decades have seen a growing interest in developing new technologies for controlling modern vessels and related maritime equipment.

Enormous challenges faced regarding the operation of the cranes:

- load sway
- positioning accuracy
- wave motion compensation
- collision avoidance
- manipulation security

Current situation for marine cranes

- Control approaches based on the concept of teleoperation.
- It is still common to use joysticks to control crane operations.
- Each input device can control only one robotic crane.
- Need of operators with extensive experience and high control skill levels.
- Low control flexibility and non-standardization are two crucial points of current crane control architecture.

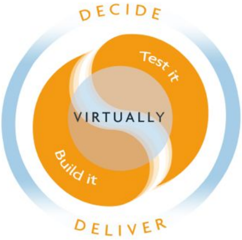
Underlying idea

Since 2012, working on designing and developing a more flexible and safe control system for maritime cranes (MAROFF).

Virtual prototyping is a crucial step during the design process which includes several benefits:

- development time
- validation

Simulations and virtual prototyping are indeed necessary steps to validate the design before committing to making a physical prototype.



Underlying idea

- A modular prototyping system architecture, that allows for modeling, simulating and controlling different robotic arms and cranes.
- A library of rigid bodies, joints, actuators and kinematic models that can be used as modules to simulate different cranes or robotic arms.

Bond Graph modeling technique

- Energy based approach. Robust stability is needed and such a level of stability can be obtained if controllers and controlled systems behave like physical passive systems (Hogan 1984).
- Multi-domain and complex systems. A mathematical model - which also includes the vessel dynamics - is needed.
- Modular approach. The mathematical model have to be flexible enough to easily modify the kinematics and dynamics of the controlled device.
- Physical interaction. The Newton-Euler technique and Lagrange's technique tend to hide the physical interaction between elements involved and do not facilitate the implementation and integration of other subsystems at a later stage.

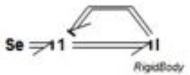
Bond Graph modeling technique

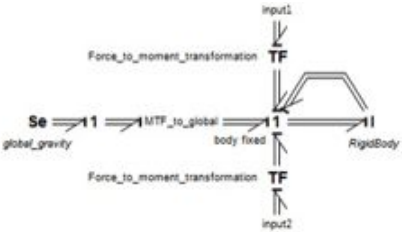
System architecture, Crane beams and rigid body modeling

The idea is to develop a library of rigid bodies, joints and actuators models that can be used as modules to simulate different cranes or robotic arms.

Crane beams and rigid body modeling

- the rigid body equation can be programmed in a modified I-field connected to only one one-junction representing the motion in 6 DOF.
- In order to have a complete BG of the crane beam, the relation between the local coordinate frame and the global reference from which all motion is observed has to be derived. These transformations can be expressed using the Euler angles (Karnopp et al. 2006).

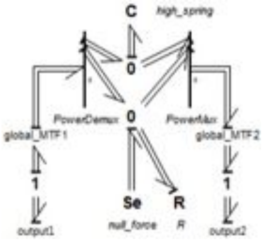




System architecture, Joints

Spherical joints

- The linear velocities are then constrained with a C-element that has a sufficiently high spring constant, which means that translation is forbidden. The Se-element that is attached to the unconstrained angular velocities is a zerotorque element, which means that the effort value is set to zero, thus representing total freedom to rotate.



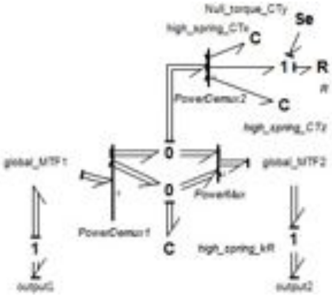
System architecture, Joints

Revolute joints

- Similar to spherical joints but only allow for rotation in one angular direction.

Prismatic joints

- They allow for translation in one direction while the other two translational DoFs as well as the all three rotational movements are constrained. The unconstrained power bond has a zero effort source meaning total freedom to translate.



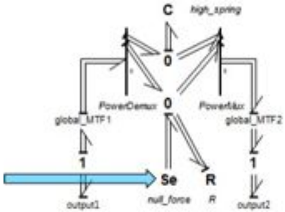
System architecture, Actuators

Rotary actuators

- The effort value can simply be applied to the joint Se-elements, which previously represented zero efforts.

Linear actuators

- A possible approach involves using the existing Se-element that models the gravity force or adding a new Se-element to the global one-junction, thus representing a force in the positive global z direction for instance. This solution is quite close to representing the physical actuator since the torque in the global x direction will decrease as the beam is elevated.



System architecture, Control

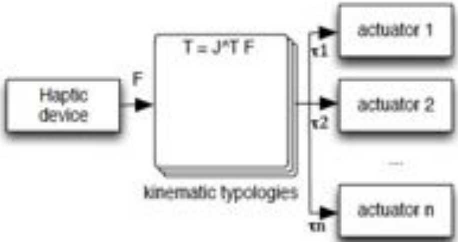
Control

- Several beam models can be connected using different joint models and various cranes or robotic structures can be implemented. However the control of the system is still missing.
- To implement the control part, instead of using simple effort sources as inputs for the actuator models, the actual actuator forces can be calculated according to the dynamic model of the arm that has to be controlled.
- The force that the user applies on the haptic device can be used to calculate the actual actuator efforts. To do this the principle of virtual works (Zhang and Song 1993) can be applied.

System architecture, Control

Control

- A set of different Jacobian matrices which correspond to a set of different kinematic typologies was included in the proposed library.
- The parameters of each generic Jacobian matrix, such as for instance the length of the links, have to be set according to the specific crane to be controlled.



System architecture, Force feedback and Vessel Model

Force feedback

- In order to provide the user with valuable force feedback, a BG effort sensor can be used to measure forces and torques exerted on the end effector of the controlled arm.
- These efforts can be scaled and sent to the haptic device that will actuate them.

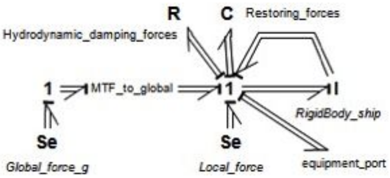
Vessel model

- The vessel model may take into account radiation-induced forces (added mass, hydrodynamic damping and restoring forces), environmental forces (ocean currents, wind and waves) and propulsion forces (propeller/thruster forces and control surface/rudder forces).

System architecture, Force feedback and Vessel Model

Vessel model

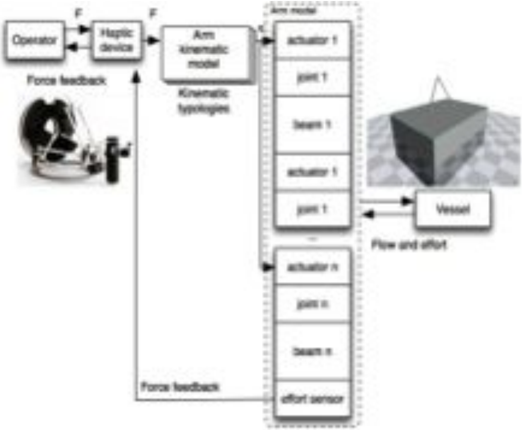
- As shown by Pedersen in (Pedersen 2012) and Fossen in (Fossen 1994), the vessel can be also modeled as a rigid body with the addition of a C-element representing the restoring forces and an R-element representing the hydrodynamic damping.
- To fully complete the vessel model, an effort source is connected to the one-junction for the earth-fixed coordinate system representing gravity. There is also another effort source connected to the local one-junction, which can be used to simulate local forces on the vessel. Finally there is a port that can be used to attach some equipment to the model, it will be used to attach the crane.



System architecture, Complete model

Complete model

- The arm joint angles can be calculated at runtime according to the specific kinematic model.
- A BG effort sensor is used to measure forces and torques exerted on the end effector of the controlled arm. These efforts are then scaled and sent to the haptic device that will actuate them.



Simulations and experimental results

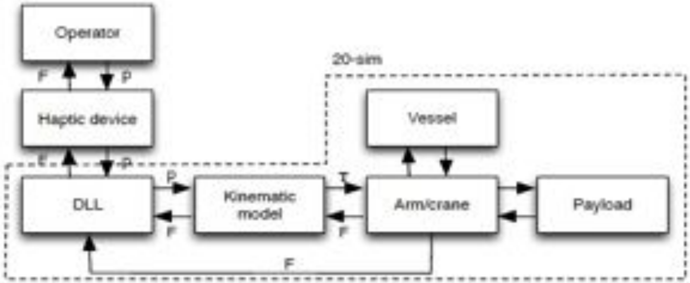
Omega.7 and 20-sim

- A commercial haptic device, the omega.7 from Force Dimension, was used as universal input for the system. The omega.7 is a 7 DOF haptic interface with high precision active grasping capabilities and orientation sensing. Finely tuned to display perfect gravity compensation, its force-feedback gripper offers extraordinary haptic capabilities, enabling instinctive interaction with complex haptic applications.
- Thanks to the modularity of the proposed system, the same input device can be also used to control several different models.
- The system was implemented by means of a BG and simulated in 20-sim (Broenink 1999). 20-sim is a modeling and simulation package that provides a large library containing all standard BG elements. Next to standard elements 20-sim supports custom user made BG models.

Simulations and experimental results

Omega.7 and 20-sim

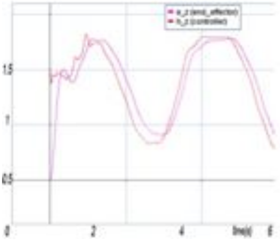
- A static-link DLL library was implemented in order to connect the omega.7 haptic device to the simulator environment. At each simulation time-step the static dll sub-model calls a specific function to read the position of the input deviceÕs end effector and to write down the efforts that are used to give force feedback to the operator.

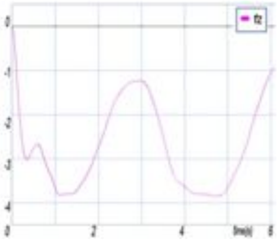


Simulations and experimental results

Results

- The plot shows the motion of the crane end-effector along the z axis as a result of the haptic input deviceÕs movements which is operated by the user. In this particular case, the operator maneuvers the crane model to lift the end effector up at first, then down and up again. Similar results were obtained for the x axis showing that the system is quite responsive to the userÕs inputs. The operator also perceives a force feedback that is proportional to the end effectorÕs elevation.





Simulations and experimental results

Conclusion

- In this work, the so-called Bond Graph Method was used to introduce a modular system architecture that allows for modeling and simulating different maritime cranes or robotic arms.
- The resulting models can be simulated and controlled by using the same input haptic device which provides the user for a valuable force feedback. The arm joint angles are calculated at runtime according to the specific dynamic model of the robot to be controlled.
- Using the proposed approach, each arm model can be connected to a simplified model of a vessel, providing a complete model.
- Related simulations were carried out to validate the efficiency and flexibility of the proposed architecture.

Future work

- Model, simulate and compare different crane configurations to prove the flexibility of the proposed architecture. A comparison with traditional modeling methods will also be necessary to prove the advantage of using Bond Graphs over other modeling techniques.
- Another issue that has to be better investigated in the next future concerns the effectiveness of using such a haptic device on board of a vessel from a human factor point of view.
- The proposed system architecture could be used for finding dynamic responses in complex marine operations or for controlling a real crane on a vessel. However, for such applications, the level of accuracy in the model must be raised and a more accurate tuning of all the involved parameters has to be carried out.

Thank you for your attention