Enhancement of Virtual Simulator for Marine Crane Operations via Haptic Device with Force Feedback

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Abstract. This paper presents simulations of marine crane operations using a haptic device with force feedback. Safe and efficient marine crane operations are challenging under adverse environmental conditions. System testing and operation training on physical systems and prototypes are time-consuming and costly. The development of virtual simulators alleviates the shortcomings with physical systems by providing 3D visualization and force feedback to the operator. Currently, haptic technology has limited applications in heavy industries, due to the system stability and safety issues related to the remote control of large manipulators. As a result, a novel 6-DoF haptic device was developed for crane operations allowing for a larger workspace range and higher stiffness. The employment of the haptic device enlarges the interaction scope of the virtual simulator by sending feedback forces to the operator. In the case study, simulations of marine crane anti-sway control suggested that the load sway time and amplitude were reduced with force feedback. Using the haptic device, it also helps the crane operator to prevent problematic operations.

Keywords: marine crane operations, virtual simulation, force feedback

1 Introduction

Compared to land-based cranes, marine cranes are even harder to operate when considering both safety and working efficiency. The movements of the vessel cause many problems in offshore and subsea applications. As a result, it is difficult to achieve stable and accurate positioning of the heavy pendulum load via remote control devices. The load sway results in high safety risks for the object, equipment and personnel on board. In marine crane operations, direct visual information including monitors and sensors in the control room tends to be insufficient for the operators to make quick and adequate response in practice. It demands a lot of experience from the operators, and intensive concentrations during the operation. Haptic device with force feedback can help convey information directly to the operators, leaving them to concentrate on the task in hand. The employment of force feedback in virtual simulations improves the effectiveness of training for operational skill acquisition [1].

Haptic technology has so far few applications in marine industry compared to other engineering fields, such as robotics, medical surgery, and gaming. This is partly due to the remote-controlled mechanisms in offshore and subsea applications are usually much larger and heavier. What's more, the inertial effects of the heavy pendulum create tremendous impacts on the stability of the crane. As a result, the velocity and force mapping between the haptic device and the controlled mechanism are more difficult to achieve. In addition, the operational environment, which is hard to predict, is as equally complex to cope with.

Previous studies on the effects of force feedback in suppressing the load sway during crane teleoperation show that both the sway amplitude and time for stabilizing the load are reduced with force feedback [2-4]. These studies performed experiments on sway suppressing of 1-DoF overhead crane operations, specifically the initiative sway due to the acceleration at start. Takemoto et al [5, 6] presented control system for obstacle avoidance and load sway suppressing using a proposed haptic joystick. The joystick with 2-DoF rotates about X-axis and Y-axis controlling the first rotary joint and the hoisting boom of the crane. However, the flexibility of the proposed system is limited to certain types of crane applications. Load sway in marine crane operations exists in three dimensions, which changes constantly due to the environmental effects. As a result, safe and efficient marine crane operations is highly dependent on the experience and skills of the operators.

In this paper, we present a virtual simulator for marine crane operation with force feedback using a Novel Haptic Device (NHD). The 6-DoF haptic device was developed for large slave mechanisms providing a large working space and high stiffness [7]. Modeling of the crane's physical systems is developed using Bond Graph (BG) method, which is a modeling technique based on identifying the energetic structure of the physical system [8]. A typical 3-DoF offshore Knuckle Boom Crane (KBC) is implemented for the simulations [10]. A special type of bond graph called IC-field is provided for the implementation of the Lagrange's equations, which are used to describe the multi-body dynamics of the KBC [9]. The manipulation of the crane is realized using inverse velocity control instead of joint-by-joint control, i.e., control of the crane end tip movements by solving the inverse kinematics of the joystick and the crane [11]. This provides more flexibility for different types of cranes, and the possibility of implementing the heave compensation and anti-sway algorithms.

The implementation and simulation of the modeling is done by a software tool called 20-sim [12]. A static-link DLL is used in order to connect the haptic device to the virtual crane simulator. The virtual crane simulator alleviates the shortcomings of operating physical systems in terms of time and cost for system testing and operation training purposes. With the employment of force feedback in the simulations, the control algorithms can be tested for the improvement of the working efficiency and safety of operations. Human interaction applications can also be studied to reduce the working stress of the operators.

2 Mapping of the Haptic Device and the Crane

According to the architecture, industrial joystick type of devices for remote-controlled equipment can be divided into two categories, i.e., serial type devices and parallel type devices. Parallel type devices with closed-loop architectures provide higher stiffness and accuracy, but smaller workspace. Application practices of parallel type haptic devices are mostly found in medical surgery, aerospace, micromanipulation and gaming in controlling small manipulators and robots [13]. Parallel type devices are with more compact architectures, hence allow for smaller workspace, more positioning precision, and smaller feedback force to the operator. These are, however, not suitable for controlling of large slave mechanisms with heavy loads like marine cranes, where the requirement on positioning precision is less crucial than on safety and working efficiency. The other category, i.e., serial type of devices are with higher force capability and comparatively larger workspace [14]. As a result, the control of serial type haptic devices usually requires the movements from the forearm of the operator instead of only the waist and fingers. Serial type devices have simpler architectures, which makes it easier to solve the kinematics and more convenient for the installation of sensors and actuators. However, serial type devices have the drawbacks in singularities, low system stiffness and large momentum inertias due to their open architectures.

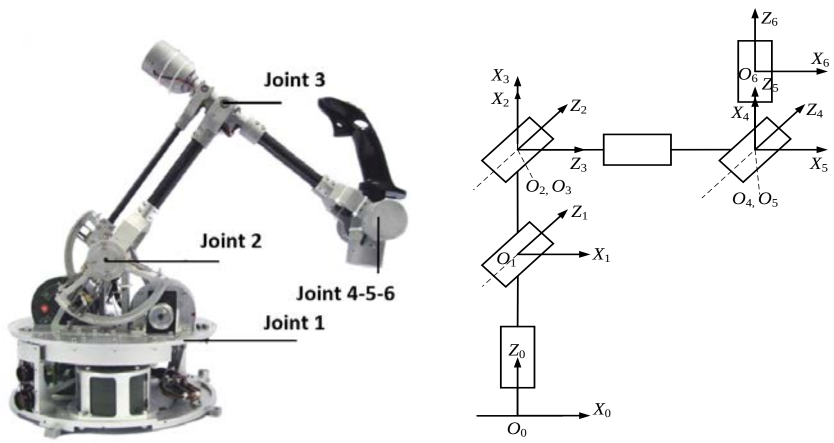

Fig. 1. The NHD prototype and its kinematic coordinates based on the DH method

Based on the above considerations, the NHD was developed for marine operations with the Robotics Institute of Beihang University. The NHD has 6-DoF allowing for the adaption to different types of cranes, as shown in Fig. 1. Marine cranes are usually with serial type architectures; hence it is easier for the velocity and force mapping to serial types of devices and more intuitive for the operators to manipulate the cranes. In order to increase the operational stability of the device, a parallel four-bar mechanism is designed at the second link [15]. The spring wheel mechanism is used to achieve static self-balance of the device at any position. This also means that joint two and three are dependent on each other. From the kinematic point of view, the first three joints determine the positions of the end effector, and the last three joints determine the orientations. The origins of the last three joints are intersecting at the same point in order to make it easier for getting explicit solutions of the inverse kinematics and the allocation of the motors and encoders for static self-balance.

The controlled slave mechanism in the case study is a typical 3-DoF offshore crane with a compact size for storage and maneuvering objects on the deck, as shown in Fig. 2. It consists of a crane base seated via the slew bearing at the pedestal. The two booms bend like the finger knuckles actuated via two hydraulic cylinders. Traditional control of cranes using joysticks is joint-by-joint control, which lacks the flexibility for the adaption to different types of cranes. Through the inverse control of the crane, the NHD can be employed regardless of the types of the cranes, hence more intuitive for the operator to position the load.

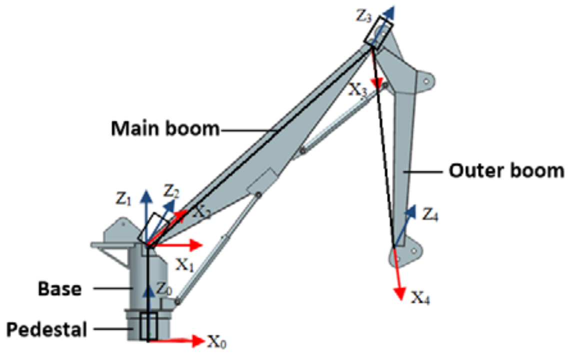

Fig. 2. The KBC and its kinematic coordinates based on DH method

The Denavit-Hartenberg (DH) method is a systematic approach in robotics describing the mapping from the end tip to the joints of a kinematic chain. The kinematic coordinates of the NHD and the KBC are shown in Fig. 1 and 2. The DH tables of the DH parameters are given in Tab.1 and Tab. 2. The transformation matrix and the Jacobian can be derived accordingly. Due to the size limitation of the paper, the computations of the kinematics of the NHD and the KBC are not presented, but can be found in reference [7] and [10]. The velocity and force mapping of the joystick and the crane can then be obtained, as given by Eq. (1) and (2).

$$\dot{\theta} = J^{-1} v \tag{1}$$

$$\tau = J^{T} F \tag{2}$$

Where J is the Jacobian matrix, $\dot{\theta}$ is the joint angular velocity vector, v is the e end tip velocity vector, τ is the joint torque vector, and F is the end tip force vector.

Table 1. DH parameters of the NHD

i	a_i(mm)	α_i(°)	d_i(mm)	θ_i(°)	range of θ_i
1	*0*	*-90*	*197*	θ_1	*[-40,40]*
2	*250*	*0*	*0*	θ_2	*[-135,-45]*
3	*0*	*-90*	*0*	θ_3	*[-45,45]*
4	*0*	*90*	*250*	θ_4	*[-80,80]*
5	*0*	*90*	*0*	θ_5	*[35,135]*
6	*0*	*0*	*0*	θ_6	*[-80,80]*

Table 2. DH parameters of the KBC

i	a_i(mm)	α_i(°)	d_i(mm)	θ_i(°)
1	*0*	*0*	*2560*	θ_1
2	*0*	*90*	*0*	θ_2
3	*7010*	*0*	*0*	θ_3
4	*3500*	*0*	*0*	*0*

3 The Virtual Crane Simulator with Force Feedback

The architecture of the control diagram of the virtual crane simulator with force feedback is shown as in Fig. 3. The force feedback of the NHD uses impedance control, i.e. the operator moves the joystick to control the crane in the virtual simulator, where the feedback joint torques are calculated and sent back to the joystick controller. More specifically, the NHD controller calculates the end tip position according to the joint position increment obtained by the sensor at each joint using the forward kinematics. By a coefficient, the crane simulator calculates the positions of the crane joints using the inverse kinematics. The virtual crane simulator calculates the acting force on the crane end tip and sends it to the NHD. By a coefficient, the NHD controller calculates joint torques from the force on the joystick end tip, and sends them to the joint servo motors of the NHD.

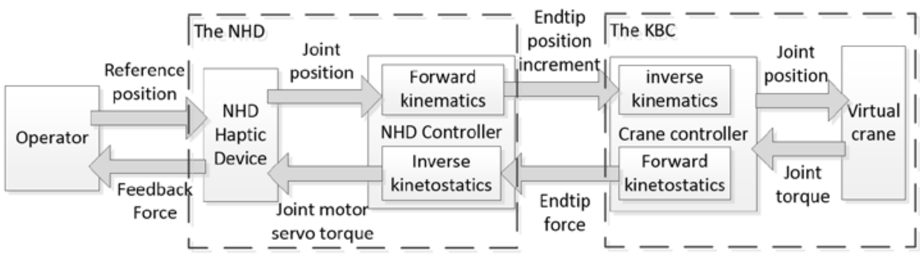

Fig. 3. The control architecture of the virtual crane simulator with force feedback

Modeling of the crane are developed using BG method and implemented in 20-sim. The complete model is shown in Fig. 4 using a combination of bond graphs for representing the crane dynamics and block disgrams for the control algorithms. The development of the component sub-models in detail can be found in the reference [11], including the multi-body dynamics of the crane, the wire and the pendulum load, the actuators with PID-controllers, and the kinematic control of the crane. All the bond graphs and sub-model blocks are equation-based implementations of the physical laws.

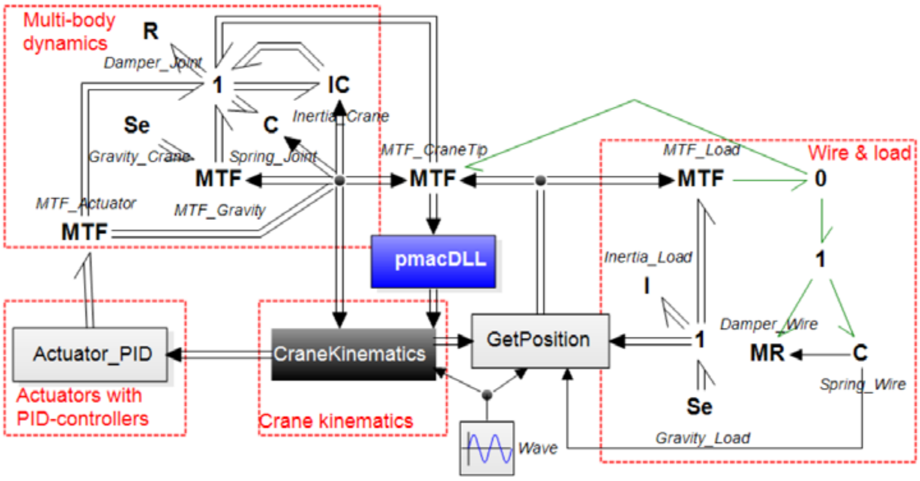

Fig. 4. BG model of the KBC with the NHD

A static-link DLL, i.e., the pmacDLL sub-model, is implemented in order to connect the haptic device to the virtual crane simulator. The static DLL calls a "pmac" function at each simulation time-step to read the end position of the NHD, and record the force on the crane end tip to calculate the torques of the servo motors. The input for the controller sub-model is the end tip force for the NHD, and the output is the end tip velocity for the KBC. The program code of calling the pmac.dll in 20-sim is presented. The frequency for the discrete signals is set at 20Hz, in consideration of the real-time performance and computation accuracy of the simulations.

```
//This sub-model calls a function called 'pmac'
parameters
   string dll_name = 'pmac.dll';
   string function_name = 'pmac';
variables
   real dll_input[6], dll_output[6];
code
//Prepare the DLL function inputs
   dll_input = [ feedback_fx; feedback_fy; feedback_fz;
   feedback_gamma; feedback_beta; feedback_alpha ];
//Call the 'my_custom_20simfunction' function in the DLL
   dll_output = dll(dll_name, function_name, dll_input);
//Read the DLL function outputs
   [tip_delta_pos_px; tip_delta_pos_py; tip_delta_pos_pz;
   tip_delta_pos_gamma; tip_delta_pos_beta;
   tip_delta_pos_alpha] = dll_output;
```

Fig. 5 shows the setup of the physical systems of the virtual crane operation simulator with force feedback. The crane simulator on the PC is connected to the NHD controller via the Ethernet. The following control modes are implemented to increase the usability and stability of the system. Switching between the alternative modes is realized using buttons on the joystick, and indicated by LED lights on the NHD controller cabinet.

- Check mode: The NHD controller checks all the safety factors of the system, including the joint positions and velocity, the servo motor current, the communication to the virtual crane simulator, etc. The end tip position and feedback force are both set at zero. The servo motors remain at open-loop until all the checking conditions are passed.
- Idle mode: The servo motors are switched to close-loop after all checking conditions passed at the check mode. The end tip position and feedback force remain at zero. The virtual crane doesn't follow the control of the joystick. The joystick doesn't receive feedback force from the crane.
- Work mode: Work mode includes Uni-direction and Bi-direction control, i.e., the crane in the virtual simulator is controlled either with or without feedback forces sent to the joystick.
- Emergency mode: In case of emergency, the stop button on the controller can be pressed down. The end tip position and feedback force are set to zero. The servo motors are set to open-loop. The controller remains at check mode until the emergency stop button is released.

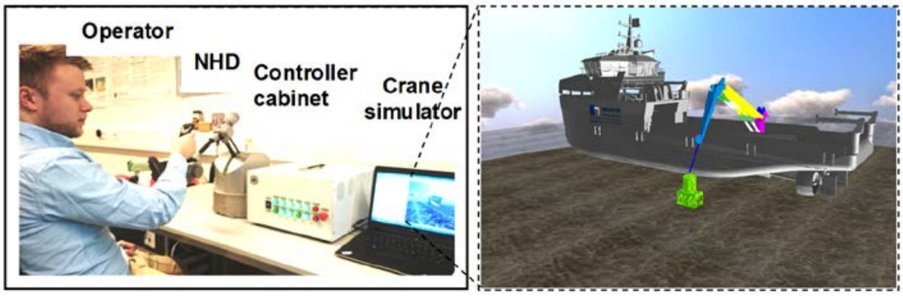

Fig. 5. The virtual marine crane simulator with force feedback

4 Load Anti-sway Control Using the NHD

Load sway is one of the most challenging problems in offshore lifting operations. Inteligent control algorithms have been proposed in order to reduce the sway of the pendulum load caused by the movements of the vessel, external forces, system instability and problematic human operations. However, load sway in offshore operations is hard to be predicted or effectively avoided in practice as many external factors affect the sway. As a result, it requires the interference of the operators whenever the sway occurs. Experience and skills from practice is an essential part of the crane operator training. Virtual crane simulators for training have been used and proved of great values in the aspects of improving the operators' skills, hence improving the operation safety and efficiency. The following experimental setup presents simulations of using the NHD for anti-sway crane lifting operations.

The test was carried out by inexperienced lab technists as the crane operators, provided with 30 minutes training. Load sway in offshore operations could occur in three dimensions; however, the sway in the transverse direction of the vessel is the most dominate and dangerous. To simplify the problem for the experiment, the load is given an initial load sway of ±20 degrees in the transverse direction of the vessel with 10 meters lifting wire. External environmental impacts were not included in the simulation model, nor any automated intelligent anti-sway control algorithm. The load sway angle was suppressed by manipulating the crane with and without force feedback using the NHD. The testing results on three individual subjects suggested similar results. According to the simulation results, it took 30 seconds to reduce the load sway to less than ±2 degrees without force feedback, i.e., Uni-direction control. The amplitude of the sway was reduced to 12 degrees after the first sway cycle. Simulations of anti-sway operations with force feedback, i.e., Bi-direction control, indicated both reduced time and amplitude of the load sway by average, as shown in Fig. 6. However, the effectiveness of the introduction of force feedback in addition to the 3D animation to suppress the load sway is trivial. In the case of 3D visualization unavailable, force feedback could help to prevent problematic operations that would result in accidents, e.g., move the crane in the wrong direction out of panic, and consequently generate more sway of the load.

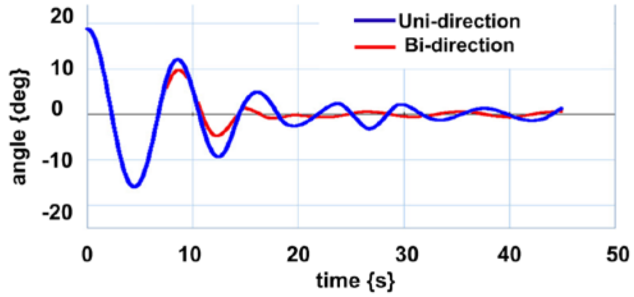

Fig. 6. Load sway angles of crane anti-sway control using the NHD

As shown in Fig. 7, the feedback forces decreased as the sway was reduced until 15s. From 25s, load sway was generated intentionally by moving the crane in opposite direction of the load. Consequently, the feedback forces to the operator via the NHD increased. The NHD provides resistance forces to the operator guiding the correct movements of the NHD, hence the crane. In the case of the crane reaches to its limits or collides with other rigid objects, the operation will stop to ensure the safety.

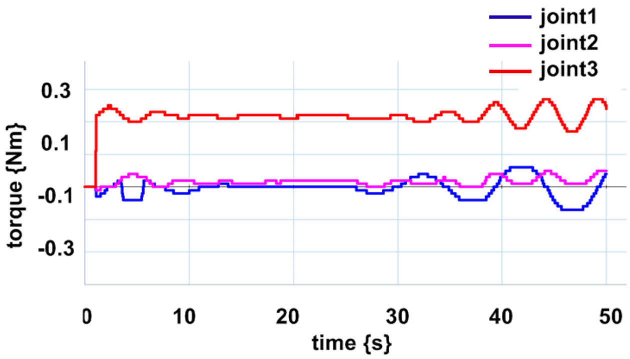

Fig. 7. Feedback forces due to the load sway

It is also noted that continuous operation with force feedback can be exhausting, especially when the feedback force is big for the operator to hold stable grip of the joystick all the time. According to the recent research and design of flexible haptic devices, such as PHANToM and Force Dimension, the maximum output force is usually set within the range of 10-25N. The NHD is designed with the maximum force of 12N and the maximum torque of 0.15Nm. On one hand, the operator needs to overcome the feedback forces to move the crane. On the other hand, the feedback force cannot be too small to provide sufficient perceptions to the human hand. Improved feedback force algorithms to the operator via the NHD needs to be studied in order to reduce the stress during long period operations.

5 Conclusion

A virtual simulator with a haptic device for marine crane operations is introduced in the study. Simulations in virtual environment provide a flexible and cost effective approach for the testing of crane operations and the training of operators. 3D visualization and force feedback send direct information to the operator during the operations. Haptic device with force feedback adds another sense of feeling to the operator besides the visual information.

Experiments on using the NHD for load anti-sway control showed both the sway time and the amplitude was reduced with force feedback. The experiments were performed in the laboratory by inexperienced users as the crane operators. The results suggested that the introduction of force feedback for suppressing the sway is trivial in addition to the provided 3D visualizations. However, using the haptic device with force feedback helps to prevent problematic operations, which may result in disastrous consequences, especially in the case of visual-blind areas. It is also noted that continuous operations with force feedback can be exhausting for the operators after relatively short periods. On one hand, the NHD is designed with the maximum output force allowing for continuous operations of master-slave mechanisms. On the other hand, small force feedback fails to provide insufficient perceptions for the human hand.

As has been pointed that offshore crane operations are far too complicated in terms of unpredictable factors, the test of using the NHD for training purposes needs a systematic design for the operation scenarios. Quantitive study on the stress induced by the feedback force to the operators during operations is important for the optimization of the force feedback via the NHD. For example, the experiments on the individual subjects could be performed in a larger sample and evaluated by the time used for suppressing the load sway, the continuous time period for operations, and compare these with different scales of the feedback force, and the operation position of the operator, the NHD and the visualization monitor.

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