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

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Abstract. This paper presents simulations of maritime crane operations using a haptic device with force feedback. Maritime crane operations are challenging under adverse environmental conditions. System testing and operation training on physical systems and prototypes are time-consuming and costly. Simulation of crane operations in virtual environment alleviates the shortcomings with physical systems by 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 remote control of large manipulators. A novel 6-DoF haptic device was developed for crane operations enabling a larger workspace range and higher rigidity. The employment of the haptic device enlarges the human interaction scope of the virtual simulator for crane operations by sending feedback forces to the operators. Simulations of maritime crane anti-sway control suggested that the load sway time and amplitude were reduced more effectively with force feedback. Using the haptic device, it also helps the crane operator to prevent problematic operations.

Keywords: maritime crane operation, virtual simulation, force feedback

1 Introduction

Compared to land based cranes, maritime cranes are harder to operate considering both safety and working efficiency. It is rather difficult to achieve stable and accurate positioning of the heavy pendulum load via remote control devices. The movements of the vessel cause many problems in offshore and subsea applications. The load sway creates high safety risks for the object, equipment and personnel on board. In maritime 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 time. 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 maritime industry compared to other engineering fields, such as robotics, medical surgery, and gaming. This is partly due to the remote-controlled mechanisms in maritime are much larger and heavier. In particular, the inertial effects of the heavy pendulum create tremendous impacts on the stability of the crane. As a result, the space and force mapping between the haptic device and the controlled mechanism are more difficult to achieve. What's more, the operational environment, which is hard to predict, is also 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. But load sways in maritime crane operations are generally random motions in 3 dimensions, which is hard to be predicted. As a result, the manipulation of maritime cranes is highly dependent on the experience and skills of the operators. 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.

In this paper, we presented simulations of maritime crane operation with force feedback control using a Novel Haptic Device (NHD). The 6-DoF haptic device is developed for maritime crane operations providing a large working space and high rigidity [7]. Modeling of 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 crane called Knuckle Boom Crane (KBC) is implemented for the simulations [9]. Control 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 [10]. This provides more flexibility for the adoption to different types of cranes.

The virtual crane simulator alleviates the shortcomings of operating physical systems in terms of time and cost for system testing and operation training purposes. Modeling of the multi-body dynamics describing the motion of the crane is derived using Lagrange's method [11]. A special type of bond graph called IC-field is provided for the implementation of the Lagrange's equations. Modeling of the hydraulic power system is presented in [12]. These two parts can be directly integrated [13]. The implementation and simulation of the modeling is done by a software tool called 20sim [14]. A static-link DLL is used in order to connect the haptic device to the virtual crane simulator built in 20sim. With the employment of force feedback in the simulations, crane control algorithms can be tested for the improvement of the working efficiency and safety of operations. Human interaction applications can also be studied for reducing the working stress of the operators.

2 Mapping of the NHD and the KBC

According to the structure, industrial joysticks for remote-controlled equipment can be divided into two types, i.e., serial type devices and parallel type devices. Parallel type devices with closed loop structures provide higher rigidity 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 [15]. Parallel type devices are with more compact structures, hence smaller working space and smaller feedback force to the operator. This is not suitable for controlling of large slave mechanisms with heavy loads like maritime cranes. In these fields, positioning precision is less critical than safety and working efficiency. The other category, i.e., serial type of devices provides high force capability and comparatively large workspace [16]. 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 structures, 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 rigidity due to the open structures and large momentum inertias. PHANToM is an alternative serial type haptic device with a parallel four-bar mechanism [17]. The design increases the rigidity of the mechanism and reduces the volume and inertia of the mechanism by using the actuators as counter-weight for static balancing. For applications in heavy industries such as manipulation of cranes and large robotic arms, serial type devices provide a larger workspace and feedback force. Maritime cranes are usually with serial type structures; hence it is easier for the space mapping to serial types of joysticks and more intuitive for the operator to manipulate.

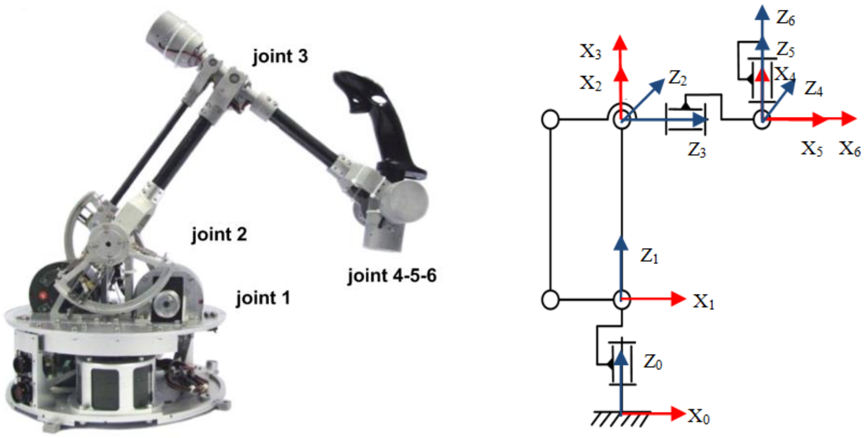

Fig. 1. A prototype of the NHD and kinematic coordinates

A novel haptic device was proposed and developed for maritime operations with Robotics Institute of Beihang University. The NHD has 6-DoF providing the flexibility for the adaption to different types of cranes, as shown in Fig. 1. In order to increase the operational stability of the device, a parallel four-bar mechanism is adopted at the second link. The spring wheel is employed to achieve static self-balance of the device at any position. The first three joints determine the positions of the end effector, and the last three joints determine the orientations. The last three joints are intersecting at one point. This makes it easier for getting explicit solutions of inverse kinematics and the allocation of the motors and encoders for static self-balance.

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

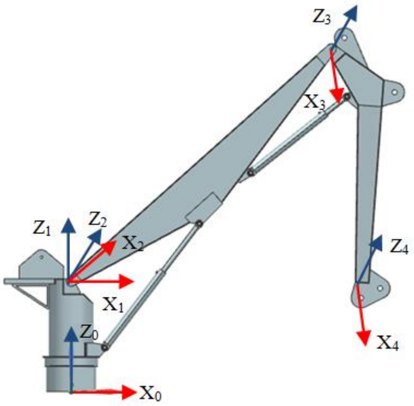

Fig. 2. The KBC and kinematic coordinates

Denavit-Hartenberg (DH) method is a classic systematic approach in robotics describing the mapping from the end tip to the joints of a kinematic chain [18]. The kinematic coordinates of the NHD and the KBC are shown in Fig. 1 and 2. The velocity and force mapping of the joystick and the crane can then be written as Eq. (1) and (2). Due to the size limitation of the paper, the calculations of the transformation matrix and Jacobian matrix are not described.

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

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

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

3 The Virtual Crane Simulator with the NHD

The architecture of the control diagram is shown as in Fig. 3. 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 sensors send the joint positions of the NHD to calculate the end tip position using forward kinematics. By a scale coefficient, the crane simulator calculates the velocities and the positions of the crane joints using the inverse kinematics according to the change of the tip positions of the NHD. The virtual crane simulator calculates the acting force on the crane end tip and sends to the NHD. By a scale coefficient, the NHD controller calculates joint torques from the force on the crane end tip, and sends to the servo motors of the NHD.

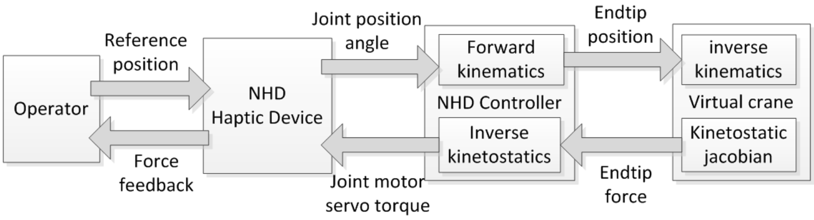

Fig. 3. The control architecture of the virtual crane simulator with the NHD

Fig. 4 shows the setup of the physical systems of the virtual crane operation simulator with the NHD. The crane simulator on the PC is connected to the NHD controller via Ethernet. The following control modes are implemented to increase the usability and stability of the system. Switching between different 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, such as the joint positions and velocity, servo motor current, 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. Control of the crane consists of both position and velocity mapping from the joystick to the virtual crane.
- Emergency mode: In case of emergency, the stop button on the controller can be pressed. 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.

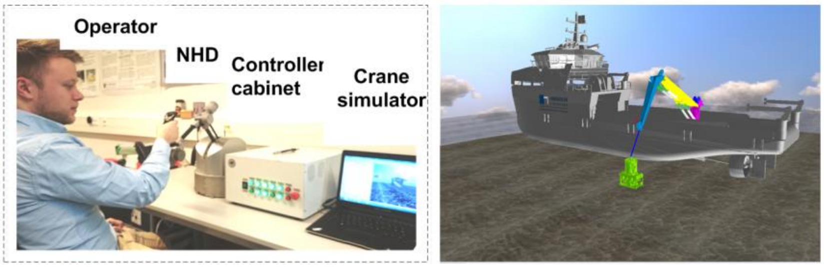

Fig. 4. The virtual maritime crane simulator with the NHD

Modeling and simulation of the crane are developed using BG method and implemented in 20sim. The BG representation of the crane model implemented is presented, as shown in Fig. 5. Due to the size limitation of the paper, the development of the component sub-models in detail can be found in the reference [11-12], including the multi-body dynamics of the crane body, 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 formulas. Two types of bonds are used in BG method, i.e., power bond and signal bond. A power bond, which contains bi-direction physical energy, is represented by a harpoon with a short stroke indicating the causality between the two sub-models. A signal bond is represented by an arrow, which contains uni-direction of information without transferring energy. Double-lined arrows indicate vectors of power or signal variables.

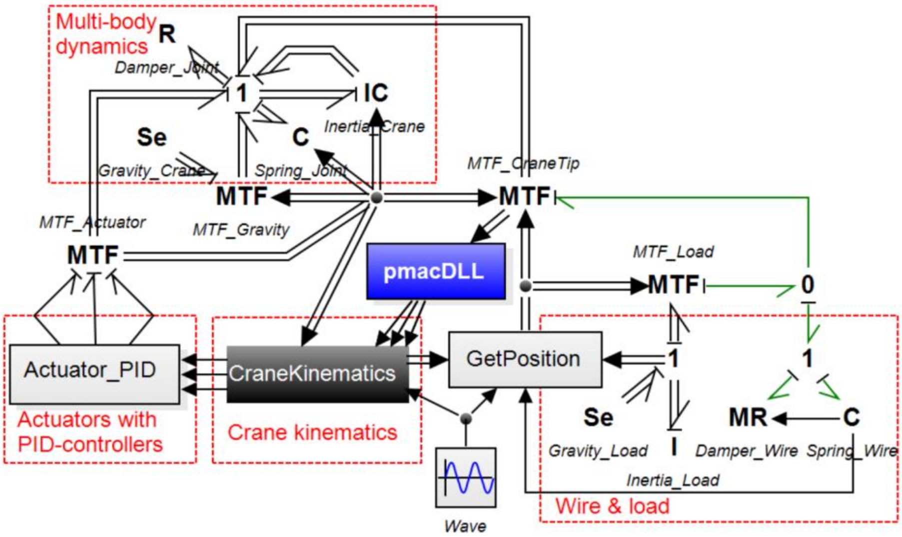

Fig. 5. BG model of the KBC with the NHD

A static-link DLL is implemented in order to connect the haptic device to the virtual crane simulator (the pmacDLL sub-model in Fig. 5). 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 program code of calling the pmac.dll implemented as the pmacDLL sub-model in 20sim is presented.

```
//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[48];
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;
```

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 to reduce the sway of the pendulum load caused by the movements of the wave, external forces, system instability and problematic human operations. But load sway is hard to be predicted or avoided in practice. 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 operator training in crane operations. The following setup shows the simulations of using the NHD for anti-sway crane lifting operations.

Experiments were carried out by inexperienced lab technist as the crane operator, provided 30 minutes training practice. External environmental impacts were not included in the simulation model, nor automated intelligent anti-sway control algorithms. Given an initial load sway of ±20 degree with 10 meters lifting wire, the load sway angle was suppressed by manipulating the crane with and without force feedback using the NHD. According to the simulation results, it took 30 seconds to reduce the load sway to less than ±2 degree 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 reduced time and amplitude of the load sway by average, as shown in Fig. 6.

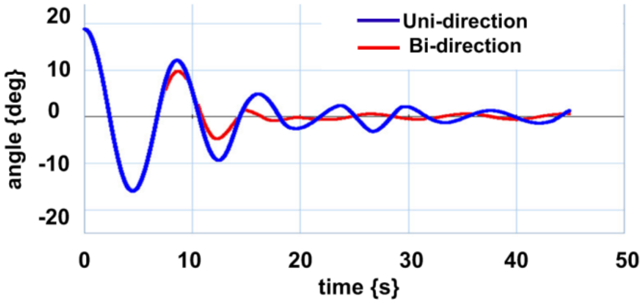

Fig. 6. Load sway angles of crane anti-sway control using the NHD

Force feedback also helps to prevent problematic operations, such as moving the crane in wrong directions that would increase the load sway. The NHD generates resistance forces to the operator guiding the movements of the NHD. When the crane reaches to its limits or collides with other objects, the operation will stop to ensure the safety. Fig. 7 shows that the feedback forces decreased as the sway was reduced until 15s. From 25s, load sway was generated by moving the crane in wrong directions intentionally. As a result, the feedback forces increased accordingly.

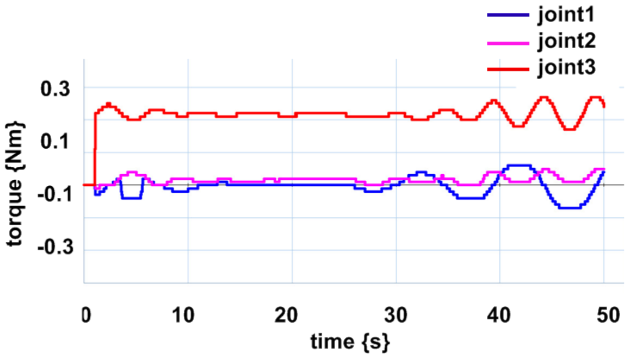

Fig. 7. Feedback forces due to load sway

It is noted that continuous operation with force feedback can be exhausting, especially when the feedback force is big for the operator. On one hand, the operator needs to overcome the feedback force to control the crane. On the other hand, the feedback force cannot be too small to provide adequate sensitivity to the human hand. Continuous steering the crane to suppress the sway without any automated anti-sway control algorithm is stressful.

5 Conclusion

A virtual simulator with a haptic device is developed for maritime crane operations. Simulations in virtual environment provide a flexible and cost effective approach for testing and training of crane operation. 3D visualization and force feedback send direct information to the operator during operations. Haptic device adds a 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 more effectively with force feedback. The employment of haptic device helps to prevent problematic operations in the case of visual-blind areas, which may result in disastrous consequences. It is also noted that continuous operation with force feedback can be exhausting for the operator. Future work involves studies on human interaction of using the NHD, including optimizing the anti-sway control algorithms.

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References

1. Y. Kado, Y. Pan, and K. Furuta, “Control System for Skill Acquisition — Balancing Pendulum based on Human Adaptive Mechatronics,” in Proc. of IEEE International Conference on Systems, Man, and Cybernetics, 8-11, Oct. 2006, Taipei, Taiwan, pp. 4040-4045.
2. A. F. Villaverde, C. Raimúndez, and A. Barreiro, (2012), “Passive internet-based crane teleoperation with haptic aids,” J. of Control, Automation and Systems, Vol. 10 (1), pp. 78-87.
3. R. Sato, Y. Noda, T. Miyoshi, K., Terashima, K. Kakihara, Y. Nie, and K. Funato, "Operational support control by haptic joystick considering load sway suppression and obstacle avoidance for intelligent crane," in Proc. of IEEE Annual Conference of Industrial Electronics, Porto, Portugal, 3-5 Nov. 2009, pp. 2301-2307.
4. I. Farkhatdinov and J. H. Ryu, (2008), A study on the role of force feedback for teleoperation of industrial overhead crane. In Haptics: Perception, Devices and Scenarios, Springer Berlin Heidelberg, pp. 796-805.
5. A. Takemoto, K. Yano, K. Terashima, "Obstacle avoidance control system of rotary crane using proposed haptic joystick," in Proc. of Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint, 18-20 Mar. 2005, pp.662-663.
6. A. Takemoto, K. Yano, T. Miyoshi, and K.Terashima, "Operation assist control system of rotary crane using proposed haptic joystick as man-machine interface," in Proc. of 13th IEEE International Workshop on Robot and Human Interactive Communication (ROMAN), 20-22 Sept., 2004, pp.533-538.
7. Y. Liang, X. Li, Y. Chu and W. Li, (2015), Kinetostatics and Spring Static Balancing for a Novel Haptic Device, Journal of International Journal of Advanced Robotic Systems, submitted.

8. D. C. Karnopp, D. L. Margolis and R. C. Rosenberg, (2012), “System dynamics: modeling, simulation, and control of mechatronic systems,” John Wiley & Sons. New Jersey, US.
9. M. K. Bak and M. R. Hansen, (2013), “Analysis of Offshore Knuckle Boom Crane - Part One: Modeling and Parameter Identification,” Journal of Modelling, Identification and Control, 34(4), pp.157-174.
10. Y. Chu, F. Sanfilippo, V. Æsøy, H. Zhang, “An effective heave compensation and anti-sway control approach for offshore hydraulic crane operations,” in Proc. of IEEE International Conference on Mechatronics and Automation, Tianjin, China, 3-6 Aug., 2014, pp.1282-1287.
11. Y. Chu and V. Æsøy, “A multi-body dynamic model based on bond graph for maritime hydraulic crane operation,” in Proc. of International Conference on Ocean, Offshore and Arctic Engineering 2015, St. John’s, Newfoundland, Canada, 31. May – 6 Jun., 2015, No. 41616.
12. Y. Chu, Ø. Bunes, V. Æsøy, and H. Zhang, “Modelling and simulation of an offshore hydraulic crane,” in Proc. of European Conference on Modelling and Simulation, Brescia, Italy, 27-30 May, 2014, pp. 87-93.
13. Y. Chu, V. Æsøy, S. Ehlers, and H. Zhang, (2015), Integrated multi-domain system modelling and simulation for offshore crane operations. Journal of Ship Technology Research-Schiffstechnik, 62(1), pp. 36-46.
14. Controllab Products B.V., available online at: http://www.20sim.com/, 2015.
15. S. Khan, Design and optimization of parallel haptic devices: Design methodology and experimental evaluation, Doctoral thesis, Trita-MMK, 2012.
16. M. Ueberle and M. Buss, “Design, control, and evaluation of a new 6 DOF haptic device,” in Proc. of IEEE International Conference on Intelligent Robots and Systems, 2002, pp. 2949–2954.
17. C. Cruz-valverde, O. A. Dominguez-ramirez, E. R. Ponce-de-león-sánchez, I. Trejo-Mota and G. Sepúlveda-Cervantes, “Kinematic and Dynamic Modeling of the PHANToM Premium 1.0 Haptic Device: Experimental Validation,” Electronics, Robotics and Automotive Mechanics Conference (CERMA), 28 Sept. - 1 Oct., 2010, pp. 494–501.
18. J. J. Craig, Introduction to Robotics. New York: Addison-Wesky, 1989.