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Development of a Observe-By-Wire System for Forklifts Using Haptic Interfaces

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Abstract: This paper proposes a new concept of a haptic user interface for forklifts. The haptic interface is developed including valuable features and we named it “Observe-By-Wire” (OBW), which can give operators maximum visibility for safe operation. Particularly, the use of a OBW can help human to overcome the problems related to the blind spots caused by the mast configuration of forklifts. The OBW transmits distance information between forks and obstacles to operator in term of force feedback information. It is expected to be useful in emergency cases such as: moving large boxes, lack of illumination in warehouses. We have created OBW system, modeled the fork and its operations. Experiments were carried out with a group of seven subjects. The experimental results indicated that the OBW system can improve the visibility and operating performance of forklift’s drivers. In particular, The OBW could give a haptic-based interaction channel between the drivers and vehicles regardless to the height of masts as well as intensity of illumination.

Keywords: Observe-by-wire, haptic interface, visibility, forklift, mast, forklift, steer-by-wire, human factors.

1. INTRODUCTION

Many advanced systems were developed for forklift applications such as rear combination lights for improved protection and reliability, traction & brake control (TBC), system of active stability™ (SAS). In 1999, The Toyota SAS was first introduced on the 7-series. It is an electronic controlled system, which automatically observe and controls over 3000 key forklift functions, which senses instability and then instantly engages the swing lock cylinder to help reduce the risk of lateral tip-overs [1], [2]. Also, steer-by-wire system was developed in 2002 [3]. However, to have greater productivity and speed, forklift trucks are designed with tall masts. The mast configurations significantly obstruct the operator’s view to the environment and create blind spots. As forklifts are able to stack at higher levels, operators are less able to view the actions occurring at the end of forks. Recently, Trucks offer a commercial solution to the issue of tall masts, which is called tilting cabin. The E Series model is available with tilting cabin that rotates the driver’s compartment allowing the operator to lay back from the vertical which give human a much clearer view of the lift carriage when elevated. This is a standard feature on lift heights above 8.5 meters and optional below [4]. Unfortunately, the angle that the operator’s head has to rotate can lead to serious risks, which are able to cause accidents because of several loads and potential damages over the truck. Together with this, other technical ideas are to use vision system, which can give the operator more visual information about the workspace [5]. However, forklift operations are influenced by many other factors such as lack of illumination, limitation of workspace, driver experience, and so on. Therefore, visibility is always critical issues relate to forklift operation and control. Our research motivation is to take advantage of haptic-based control and steer-by-wire technology, which have been implemented in many fields such as robotics, factory automation, automobiles and so on [6], [7], [8]. The proposed OBW is a system that enables the operator to concentrate on the tasks and accomplish it faster, safer with less overturns. This device can be integrated with the conventional steering wheel or a steer-by-wire system as it allows drivers to perform simultaneous steering and observe distance information with a single steering wheel.

Fig. 1 Driver’s view is significantly reduced by the loads 2, the mast configuration 1, and the rugged overhead guard 3.

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In the following papes, we initially introduce a novel concept of observe-by-wire, which is a haptic-based approach to overcome the mentioned problems. The control strategies are shown in the section 2. The next section, the experimental setups are described in detail. The simulation and experiment results in section 4 have clearly shown that OBW system could improve the visibility as well as forklift performances.

2. OBSERVE BY WIRE FOR FORKLIFTS

2.1 System overview

Operating a forklift is a specialized job. Drivers control forks and its direction through the steering wheel while they use the levels at the front panel to lift up and down the loads. As the forks move up, operators are less able to observe what is going on over their head. To increase visibility, we have implemented a novel method, which can transmit the view of forks' environment in term of force feedback information, and we named it as observe-by-wire system.

The essential components of a OBW system are distance sensors associated with a haptic interface and LabVIEW-based simulation module shown in fig. 2. The control algorithm is applied to implement feedback force, which is a related the measured distance from the sensors.

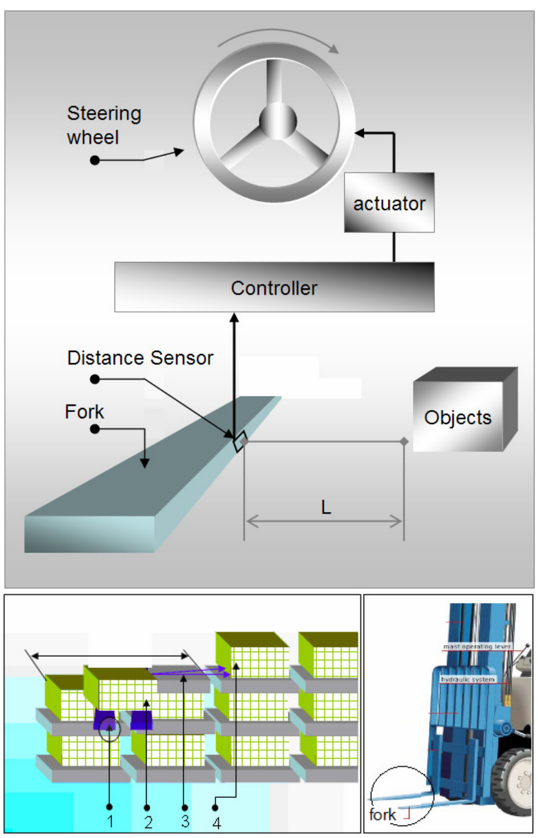

Fig. 2 The OBW system configuration, a forklift lifts loads to the third floor for stacking or storage; (1): fork, (2): package, (3): pallet, (4): package known as an obstacle.

Two sensors are mounted to the forks at the end of outer sides shown in fig. 2. At these positions, the sensor can realize the distance L between the forks to the package (4) or objects along the line, which connect two forks' ending point. It is supposed that the measured distances are L_1, L_2. The measured distances sending to the controller are used in order to create artificial force which is a function of the range from obstacles to the forks. A haptic interface is used to give physical interactions between human and haptic device. It is also one in which the sensors' signals are given to the operator in term of the sense of touch.

2.2 Control strategies:

According to previous researchs [9], [10], the steering system of forklifts is developed. Moreover, driving torque of forklift is calculated as the following equation [11]:

$$F_d = F_{sp} + F_{fr} + F_{in} + F_{alig}. \qquad (1)$$

Where F_{sp} is the side force on the tyre, F_{alig}, F_{fr} and F_{in} are the aligning torque, friction and inertia force, respectively. The driving torque equals a constant value due to the forklift mechanism [11]. As operators turn on the OBW function, basing on the distance measured from the sensors, the force feedback torque is defined by:

$$F = F_d + F_2. \qquad (2)$$

Where F_2 is computed as following:

$$F_2 = \begin{cases} b.L_1, & \text{for the sensor at the left side} \\ (-1).b.L_2, & \text{for the sensor at the right side} \end{cases} \qquad (3)$$

Where:

L_x: is the distance information, which is measured from the distance sensor.

b : is the constant gain.

A operator can observe the operating situations over the forks and its environment by feeling the the magnitude of the torque in the equation (3).

The term -1 is added in order to change force direction, which is physically generated by a DC motor. The physical setup of experimental implementation is shown in the section 3.

3. SEMI-EXPERIMENTAL SETUPS

Our test-bed is a haptic interface as shown in fig. 3 and fig. 4. This interface is used to create the feedback force and give command known as turning angle of forklift's steering system. It consists of a dial as steering wheel 1, maxon motor 2, motor driver 3, universal motion interface UMI 7764 (4), and NI motion control board PCI 7356 (5).

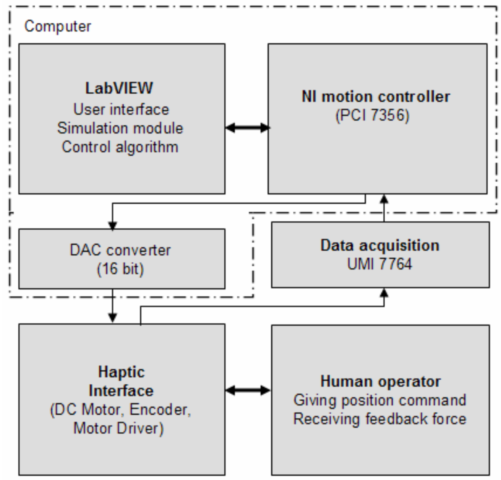

Fig. 3 The haptic interface is developed for OBW system

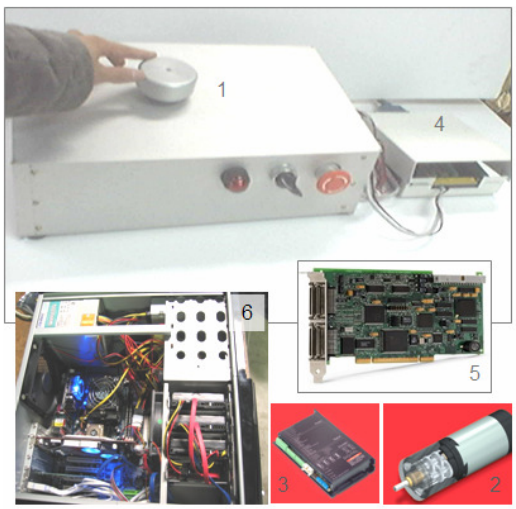

Fig. 4 The haptic interface is developed for OBW system

A fork system and working environment and control algorithm are simulated in LabVIEW. The PCI board includes 16 digital-analog converters (DAC). This feature is useful to convert from binary value to output voltage, which is applied on motor driver 3. This motor diver is connected to the dial 1 (or the motor 2) as shown in fig. 2. Computer 6 is equipped with the motion control board 5.

The value of motor torque is calculated based on current applied to the motor by the following equation:

$$M = K_M . I \tag{4}$$

Where

M : is mecahnical torque.

I : is elctrical current.

K_M : is torque constant

Similarly, the speed constant combines the speed with the voltage induced in the winding. This voltage is proportional to the speed; the following applies:

$$n = K_n . U_{ind} \tag{5}$$

Where

U_{ind} is the voltage induced in the winding.

K_n is speed constant. n is motor speed.

In addition, speed-torque line describes the mechanical behavior of the motor at a constant voltage U is shown in fig 5.

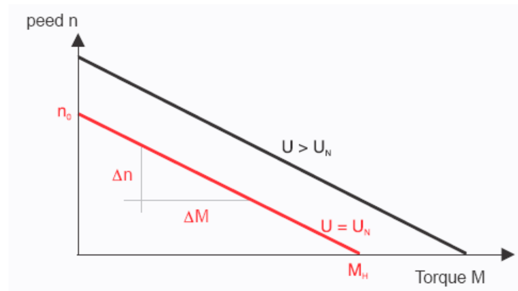

Fig. 5 Speed-torque line of DC motor

With reference to the mentioned equations and motor characteristic and 16bits DAC of motion controller, we can enhance the output voltage range from -10 to 10 volts. The DAC value is the value sent to the DAC. The parameter range is -32,768 to +32,767, corresponding to the full ±10 V output range. Due to the relationship between calculated position from simulation model and the resolution of ADC, it is needed to do scaling before sending value to the motor driver. In this paper, the scaling factor is selected to be equal to 1000.

Let us now turn to describe user interface in fig. 6, and show how the experiments are conducted by using this simulation and the haptic interface.

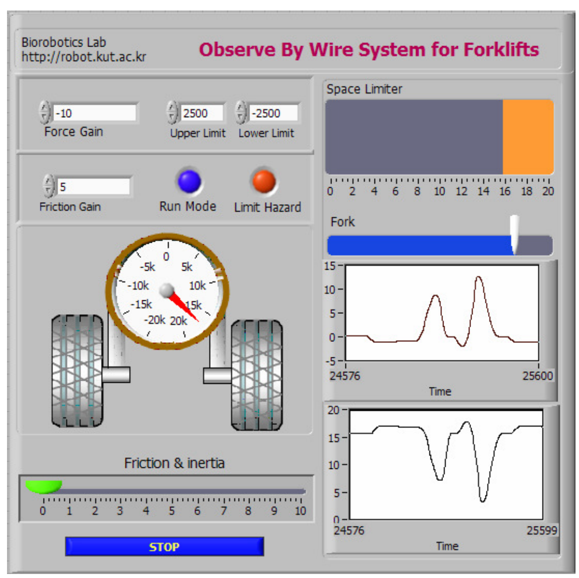

Fig. 6 The LabVIEW-based simulation model and user interface for OBW system.

First of all, the red space limiter is created to mimic the workspace of stores. This space can be easily changed by clicking and moving to the desired position. The red area is referred to any package, which is assumed that this package is placed before the driver's performance. Therefore, driver must stop at the position set by the red marker. Second, the white pointer indicates where the fork is during the experiment. Upper and lower limit are programmed in order to ensure safety of the electronic and mechanical systems of the test-bed. Force gain is used to give adjustable feedback torque. This is essential because of the variety of human sensitivity. As the force gain increasing, the feedback force is reduced. Friction and inertia term are modeled as the conventional steering system of a forklift truck. Finally the two graphs show the current position and the error between desired position and current position.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

In order to validate and investigate the possibility of proposed control strategy and examine the observe-by-wire system, seven subjects were asked to participate in experiments. The task for the subject is to move the fork (white slider) from 0 position to the limitation where is supposed as the obstacle at the third floor. They were trained several times to get acquainted with the tasks. The experimental results, which are the moving time, and errors, are automatically recorded with two different modes: The first mode has no OWB function. And the OWB is activated in the second mode. Both of the two modes, users look at the set point and turns the dial until the white slider reaches the set point. Subjects are suggested to perform the tasks as fast as possible. Also, they need to minimize the error as small as they can do.

The experiment results are shown at fig. 7~ fig. 10. The fig. 7 is randomly selected from one subject's result. It showed that the user could complete his or her task three times without using OBW system while she or he can complete her or his task five times with OBW system shown in the fig. 3b. In particular, at point (1) in the fig 7a, some vibrations were occurred due to their attention to the set mark. However, this unwanted result was improved with OWB system shown at (1) in the fig. 7b. The error at point 2 of fig. 3a is -2. This tumble was happened due to the lack of feedback force because it has been reduced to 0.2 when we activated the OBW system shown at (2) in the fig. 7b.

The fig 8 shows the experimental results of seven subjects in the same tasks. The thick line shows that the number of completion is smaller than the thin line for all subjects. The seventh subject even could accomplish this taks seven times by using OBW mode.

The fig.9 is the distance error results calculated by the following:

$$Error = \frac{\sum_{1}^{N} e_i}{N} \quad (6)$$

Where, e_i is the error of each completion. N is the number of completion of each subject.

The thin line clearly proves that OBW mode could improve the subject's controllability. Therefore, they achieved more accuracy of performances. The error is rapidly leap from 1.7 to 6.4 in the case of the first subject. For the second subject, the error of non-OBW mode is quite small. However, the error of OBW mode is still smaller.

More specially, it has been investigated with the final experimental data that the adjustable gain is useful and valuable. The magnitude of feedback force also effect on the user's performance shown in fig. 10. This figure is the result of a randomly seleted subject with four different gains of feedback force (FF gain). First, force gain is set to be equal to 7. The thin black line is the results of seven subjects. This line shows the increasing error due to too much feedback force on the steering wheel. In other word, the drivers have to apply too much effort in order to reach the desired position. Second, the thick black line indicates that errors were minimized if the force gain was only increased to 12. This finding suggests the need of adjustable feature mentioned in section 3. Third, the gain force is set to be equal to 20. however, the errors of all subject are much more lager than the second case. Finally, the force gain is increased to 10000. It means that system now working as a steering system without OBW features. (The feedback toque was so small that driver could not sense)

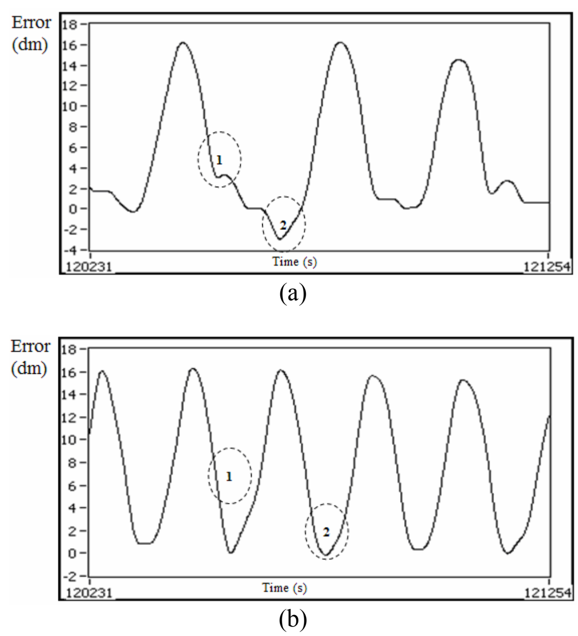

Fig. 7 Results of a subject, (a): without OBW mode, (b): with OBW mode.

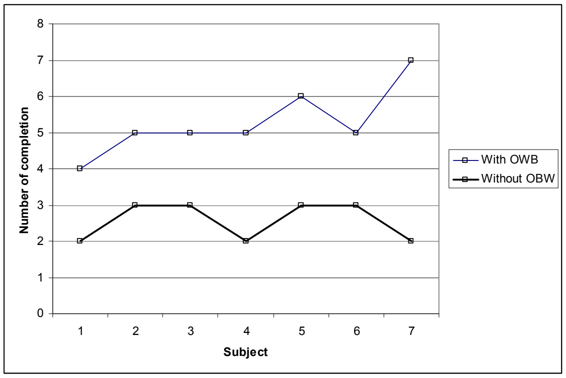

Fig. 8 Experimental results of seven subjects with OBW mode and without OBW mode.

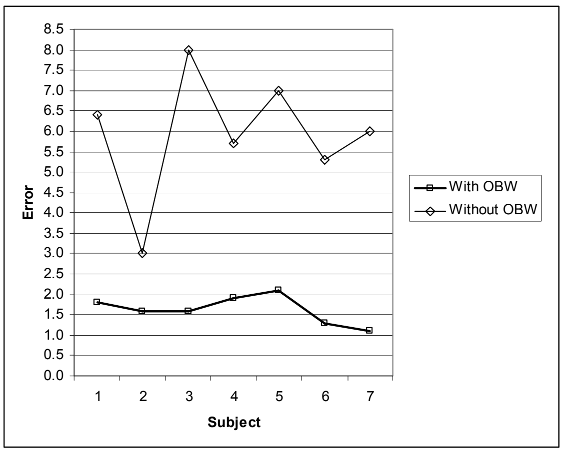

Fig. 9 Overage errors of seven subjects with OBW mode and without OBW mode.

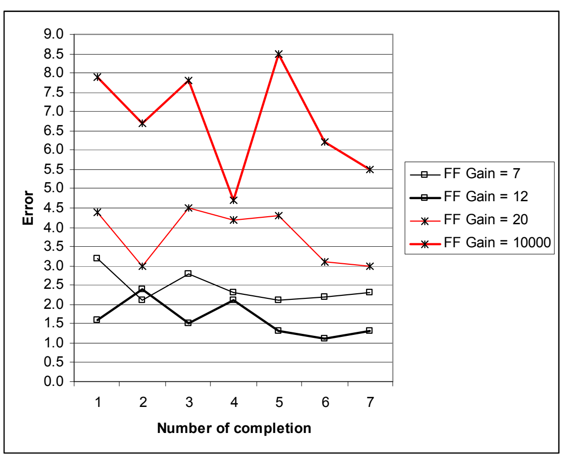

Fig. 10 Experimental results of a subject with four different feedback force gains (FF Gain).

5. CONCLUSIONS

From the research that has been carried out, we can conclude that:

The concept of obsever-by-wire is given and a systematic study of observe-by-wire is provided in order to give a possible method for improving the forklift's visibility.

The haptic interface is developed to implement the proposed control approach. The control strategies have been discussed, which is used in the OBW system.

In addition, the experimental results demonstrated that OBW system not only increases productivity but also improves the forklift operating performance. In particular, it could give one more interaction channel between the drivers and vehicles regardless to the height of masts, vehicle's roof as well as intensity of illumination. Therefore, the drive could also reduced risk of damaging the load and the warehouse by activating OBW mode.

The discussion in section 4 indicates that the feedback force is needed to be adjustable due to the different sensitivity of each subject.

This paper has only been able to touch on novel technical solution for problems of forklift's visuality and main features of an observe-by-wire system as well as its possibility of implementation. In order to validate the work we have done, a more in-depth study and investigation on real forklift trucks is necessary.

Our future works are to extend this research on other types of heavy-duty vehicles or engineering vehicles such as excavators, cranes, telescopic handlers.

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